Improved glued wood composites - modeling and mitigation of moisture induced stresses (Improved moisture)

FINAL REPORT

Title of the research project	**Improved glued wood composites- modeling and mitigation of moisture induced stresses**
Coordinator of the project	**Tomi Toratti**

BASIC PROJECT DATA

Project period	1.1.2008-31.12.2010
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URL of the project	www.buildingwithwood.eu (internal site)

FUNDING

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Finland Tekes - Finnish Funding Agency for Technology and Innovation	210 000 EUR
Germany Federal Ministry of Education and Research (BMBF)/	255 000 EUR

Project Management Agency Jülich (PtJ)

Sweden
Swedish Governmental Agency for Innovation Systems (VINNOVA) 160 500 EUR

Other public funding:

Austrian Research Promotion Agency (FFG) 113 300 EUR

Other funding:

CEI-Bois, Belgium	205 000 EUR
VTT, Finland	87 500 EUR
MPA, Germany	31 000 EUR
Harbin institute of technology, China	20 000 EUR
Association of wood industries, Austria	56 700 EUR
Casco adhesives AB and Linotech AB, Sweden	78 000 EUR
Hitreiter holzbau GmbH and Grossman Bau GmbH and Hess Wohnwer GmbH and Feyler Holzleimbau GmbH, Germany	4 000 EUR

PROJECT TEAM (main participants)

Name, degree, job title	Sex (M/F)	Organization, graduate school	For a visitor: organization & country of origin	Funder
Toratti T., PhD, Senior research scientist	M	VTT		
Fortino S., PhD senior researcher	F,	VTT,		
Henriksson M., PhD post doc	F,	KTH,		
Hofstetter K. PhD University assistant	F	TUW		
Dill-Langer, G, PhD, Senior research scientist	M	MPA		
Zhu, E. PhD, Professor	M	HIT		

DEGREES
Degrees earned or to be earned within this project.

Year	Degree	Sex (M/F)	Name, year of birth and year of earning M.Sc.,	University	Supervisor of thesis, supervisor's organization
2008	MSc	M	Mirianon F.	IFMA	Toratti T., Fortino S., VTT
2009	PhD	M	Zagari, G.	Univ. of Calabria, It	Fortino S., VTT
2008	MSc	M	Xu C.	HIT	Zhu E., HIT
2008	MSc	M	Eitelberger, J.	TUW	Hofstetter K.& Eberhardsteiner J.
2008	Msc	F	Hassel I.	Kyoto Univ. Japan	Berglund L., KTH
2010	MSc	M	Sundström, T.	Aalto univ. Fin	Toratti T., Kevarinmäki A., VTT
2010	MSc	M&F	Tononi D, Usardi I.	Univ. Brescia, It	Fortino S., Toratti T., VTT
2010	MSc	M	Lipeng, Q.	HIT	Zhu E., HIT
2010	MSc	F	Jingyu D.	HIT	Zhu E., HIT
2011	PhD	M	Mendicino L.	Univ. of Calabria, It	Fortino S., Toratti T., VTT
2010	PhD	M	Zhou H.	HIT	Zhu E., HIT
2011	PhD	M	Bader, T.	TUW	Hofstetter K. TUW
2011/June	PhD	M	Eitelberger, J.	TUW	Hofstetter K. TUW
2011/Dec.	PhD	M	Gloimüller, S.	TUW	Hofstetter K., TUW)

ABSTRACT

A summary of the project.

The present project contains research work on wood as a structural material as affected by moisture in a multi-scale and multi-physical manner. The models applied have ranged from the wood micro-structural level to full scale level and from a multi-physical point of view when solving for mechanics, fracture, moisture and temperature transfer simultaneously. The project contains large efforts both in developing calculation methods and in testing. A consistent set of micromechanical approaches for the effective hygro-mechanical behaviour of wood was developed. A material model for wood has been implemented to Abaqus FEM software. This is partly based on the micromechanical approaches. This enables the calculation of stresses and strains in variable humidity conditions. The modelling of moisture transfer and the novel testing of moisture distributions are utilised in the overall understanding of the performance of timber structures in variable climates. Full scale tests revealed that moisture induced stresses are mostly affected in curved glulam structures, where perpendicular stresses may also develop from mechanical loads. It seems that the variable humidity environment, which creates internal stresses, does not affect the shear resistance of glulam. Straight beams did not show any sign of strength loss. The test period was one year and it may be possible that this was a too short time to reveal such findings. The coatings applied at present perform poorly against RH variations. Better moisture resistance in coatings should be developed. The best ways to manage moisture induced stresses would be to apply moisture resistant coatings and to produce glulam with material which is of a moisture content as close as possible to the equilibrium of the mean service conditions. The number of publications (35) and the number of Phd (6) and MSc (8) degrees obtained through this project is very high. This is due to the scientific level of the work carried out.

1.1 Introduction

1.1.1 Background

Describe the background of the project and the basic problem that it sought to address.

Moisture variation has a significant effect on product performance of wood and wood composites. As structural elements, the first critical period to them is during the construction of building, when glued components may first be exposed to weather followed by fast drying. The second critical period is during the long full service life of building, when variations of air humidity due to natural weather changes or due to changes of usage will induce moisture variation and gradients and consequent stresses into wood, which will affect the performance of the composites and lower their capacity to carry external loads and cause cracking. Failures of glued laminated timber beams have taken place, which cannot be explained without considering the effect of moisture induced stresses due to natural weather variations or due to changes of relative humidity at indoor conditions. Such stresses are not yet considered in the current structural design practice, which may pose potential risks to the use of such wood products as load bearing structures.

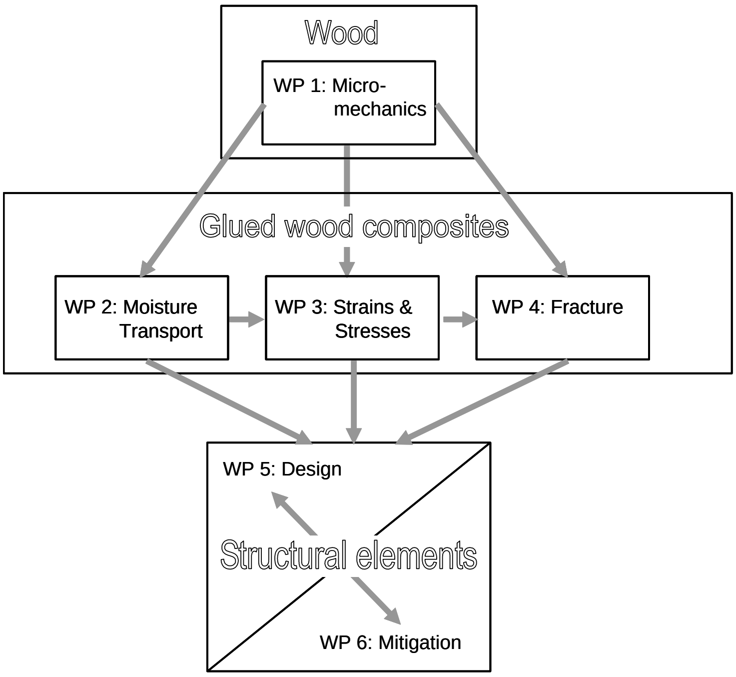

Figure 1. Work package structure of the project

1.1.2 Objectives

Describe the project objectives.

The objective of this project is to find ways to manage the performance of load bearing timber structures in variable humidity conditions to which they are by nature exposed to in real conditions. This includes developing design methods, detailing methods (including connections) and building instructions in such a way that adverse effects related to moisture can be avoided and/or controlled. A good example is the control of cracking of glulam.

The objective as stated in the applications is as follows:
The objective of this research is to facilitate the understanding of the nature of moisture induced stresses, and to develop new computational tools to assess strength of structures, and cracking of wood under weather exposure. The ultimate goal is to enable the development of innovative wood composites which are significantly less sensitive to moisture variations. Specific objectives are:
1. Improvement of safety, credibility and market share of wood in construction;
2. development of new wood products for markets where wood is not commonly used, and
3. improvement of durability and extension of service life of wood products by solving the problem of cracking during end-use.

1.2 Results and discussion

Main achievements of the project, quality, innovativeness, industrial relevance and contribution to competitiveness, environmental and societal impact.

WP1 Micromechanics

WP1 focused on the development of physically-based multi-scale models for the hygro-mechanical behavior of wood. These models allow for prediction of mechanical and moisture transport properties of wood under consideration of hygro-mechanical couplings from microstructural characteristics of the material. Emanating from the elementary wood components cellulose, hemicellulose, and lignin makes the model applicable to arbitrary wood tissues. These components are arranged in a universal manner in these tissues: Hemicellulose and lignin form an amorphous matrix, in which partly crystalline cellulose fibres are embedded. This fibre-reinforced material builds the wood cell wall in layers with different chemical compositions and orientations of the cellulose fibres. The wood cells themselves are arranged in a honeycomb fashion, where the cell axis is aligned with the direction of the stem.
Homogenization techniques such as continuum micromechanics and the unit cell methods are employed in order to link structural features and physical phenomena at different length scales. Thereby, an effective homogeneous material which shows the same behaviour under mechanical and/or moisture loading as the micro-heterogeneous material is determined. Specific formulations for homogenization of different aspects of the material behaviour are explained in more detail below.
Validation of the model is based on comparison of model predictions with corresponding experimental data. These were derived from the literature or determined in own tests (e.g. nanoindentation tests for cell wall stiffness) and tests by project partners (e.g. NMR tests for moisture diffusion by KTH in the framework of WP2). For all investigated hygro-mechanical characteristics, the model predictions show good agreement with the corresponding experimental data. Finally, the micromechanical models are evaluated in order to obtain input data for the numerical simulations of glulam beams performed by VTT in the framework of WP3.

The influence of the moisture content on elastic properties and elastic limit states of wood is predicted by a poro-micromechanical formulation. The poromechanical framework allows to consider the pressure state of the water adsorbed into the wood cell wall and its different effects on the mechanical behaviour under tension and compression.

Effective hygro-expansion coefficients of wood are derived by extending the poro-micromechanical model for the elastic behaviour. Thereby, the swelling pressure is introduced at the level of the polymer matrix of hemicellulose and lignin at a length scale of a few nanometers. Homogenization methods enable to determine the resulting macroscopic swelling pressure in case of constrained conditions or the resulting macroscopic expansion in case of unconstrained conditions. Concepts for upscaling of eigenstrains are exploited for this purpose.

Macroscopic viscoelastic deformations originate from the viscoelastic behavior of the matrix polymers hemicellulose and lignin. Upscaling of their viscoelastic properties can be accomplished by means of the correspondence principle: After a Laplace-Carson transformation, the relaxation and creep equations exhibit an identical structure as the constitutive equations for elastic behaviour. Thus, the same multiscale model can be applied for upscaling of Laplace-Carson transformed viscoelastic properties as for upscaling of elastic properties. A back-transformation of the homogenized properties finally yields the sought effective viscoelastic material characteristics in terms of effective relaxation moduli and creep compliances. Mechanosorpive effects were not considered in the developed model.

Under stationary conditions, moisture transport in wood can be described by Fick's first law. The according relations then show the same mathematical structure as those for the elasticity problem. Hence, also in this case the multiscale model for elasticity only requires small adaptations in order to be applicable for determination of effective diffusion characteristics for stationary moisture transport. In case of instationary processes, the moisture fluxes in the cell walls (bound water diffusion) and in the lumens (water vapour diffusion) are not in equilibrium, so that homogenization is not possible anymore. In this case, a numerical finite element scheme was established, in which the two fluxes are considered as separate though coupled state variables. Also the heat transport has to be taken into account then in order to accurately represent instationary moisture transport problems. The micromechanical model provides the required material properties for both diffusion processes as well as for the heat transport process in this case.

The developed micromechanical models delivers estimates for effective hygro-mechanical properties of clear wood depending on microstructural characteristics, the most important ones being mass density and moisture content and – for moisture transport – also temperature. In particular, the following properties were derived, all in a three-dimensional orthotropic framework:

- elastic constants,
- elastic limit states in terms of six-dimensional critical stress states,
- linear hygro-expansion coefficients,
- linear creep compliances,
- diffusion coefficients for stationary moisture transport,
- thermal conductivities.

In an exemplary manner, the influence of moisture content on the elastic modulus in longitudinal direction, fig. 1, and the micromechanical model for the diffusion coefficient and comparison to literature experiments on different species and directions is shown in fig.2.

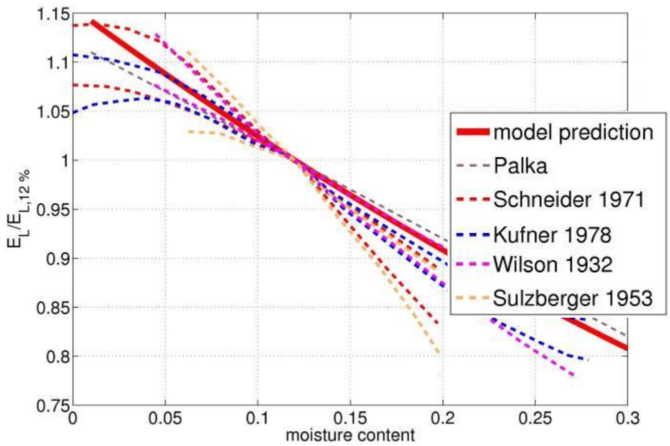

Figure 1. Influence of moisture on elastic modulus in longitudinal direction; comparison of model predictions and experimental data from the literature

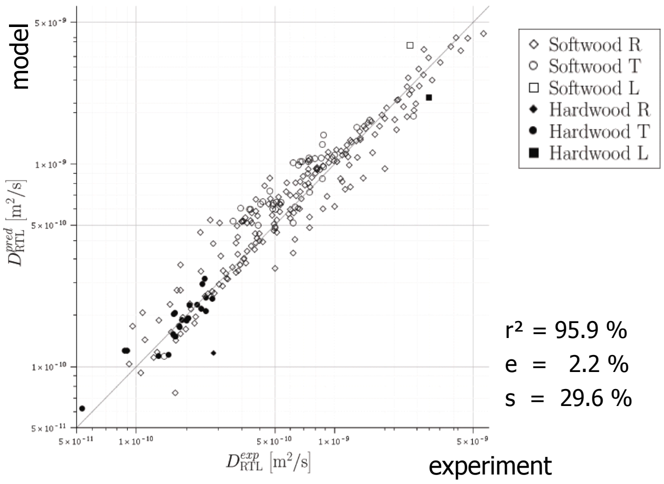

Figure 2. Comparison of modelled Diffusion to experiments from the literature

The main achievement of the modeling work in WP1 is the derivation of a consistent set of models for different aspects of the hygro-mechanical behaviour of wood, delivering consistent sets of effective material properties for specific wood tissues. Also all hygro-mechanical couplings are covered in the micromechanical models on an appropriate physical basis. This had not been accomplished before.

WP2 Moisture transport

A moisture transport model has been developed in collaboration with WP3. At first the moisture transfer was modelled on the basis of a three dimensional Fickian equation.
Secondly a model for moisture transport based on the Frandsen et al. (2007) multi-Fickian theory has been implemented in Abaqus by using: 1) the Abaqus/sequential analysis approach for the two differential equations involved (water vapour and bond water); 2) the Abaqus/HetVal subroutine for the definition of the sorption rate.

A novel method for spatial distribution of water in wood by using NMR imaging (MRI) has been developed. Wood samples adsorbed heavy water (D2O) and were subjected to optimized MRI imaging experiments. For the first time, spatial distributions of water content (2H MRI) and the macromolecular wood tissue density (1H MRI) could be obtained separately from the same sample with the same type of experiments. In the radial direction, the obtained distributions have sufficient resolution to show details on the scale much below the annual ring width. This was used to confirm the very close correlation between local water content and polymer density within the wood tissue. The present technique has a high potential because it makes possible measurement, with accuracy and high resolution, of moisture concentration gradients and diffusion mechanisms, for example. This method is presented in Dvinskikh et al (2011a).

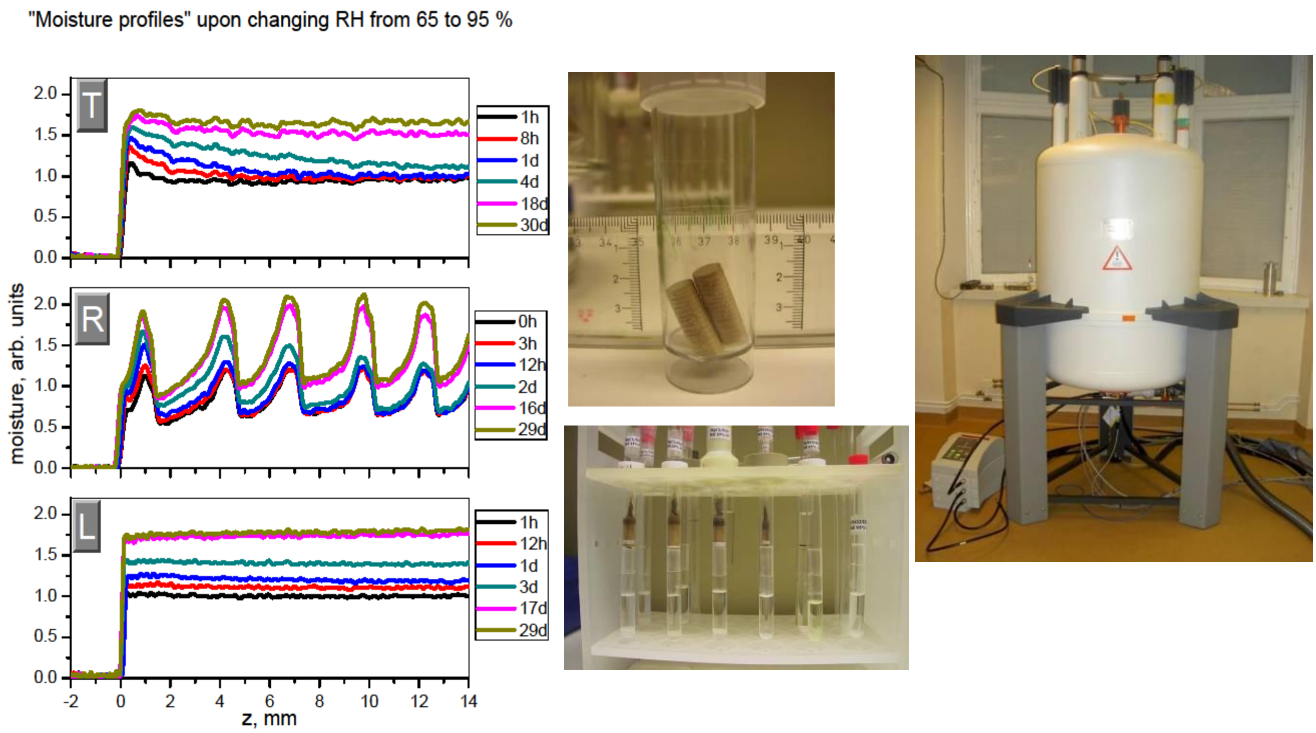

Figure 3. Moisture profile measurements and experimental setup

Based on this method, 1D moisture profile measurements for Norway spruce (Picea abies) have been measured in three directions: radial, tangential and longitudinal. Coated specimens and a specimen with adhesive bond line were also measured in radial and tangential directions. The coatings used were acrylic lacquer and linseed oil. The adhesive was melamine-urea-formaldehyde (MUF). The above performed measurements were done on 20 mm long specimens. I addition measurements on a longer (58 mm), uncoated sample with mixed radial and tangential direction was also performed (supposed to represent a transverse cross section of a glulam member). The diameter of the samples was 8 mm. Detailed information about the density distribution, microfibrillar angle etc for the radial samples and the sample with mixed directions were measured by SilviScan measurements.

There are no indications that the use of the coatings in this study would significantly mitigate the moisture absorption. The rate of moisture absorption is similar for coated and uncoated specimens. Thicker layer of the acrylic coating or coatings with larger filler content would possibly have worked better. This acrylic coating is however presently used in the glulam industry. A better coating is definitely needed. The MUF adhesive studied did not act as a moisture barrier either.

The experimental moisture profile data obtained by MRI has been used for evaluation of the moisture transfer modelling in collaboration with WP3. The numerical results obtained by both the single-Fickian and the multi-Fickian methods are compared with the NMR experimental data in the directions T, L and

R for the uncoated cases. The numerical results are in good agreement with the experimental data. This work will be presented at the final conference of COST E55 and has been submitted to a special edition of Engineering Structures (Dvinskikh et al. (2011b)).

The micromechanical model developed within WP 1 is currently validated with the experimental moisture profile data obtained by MRI. This activity will extend beyond the project end. The FE Models have been successfully used to simulate moisture-induced dimensional changes of both individual laminations and glulam members.

FE models to simulate moisture induced dimensional changes of individual laminations and glulam have successfully been developed. The following work has been conducted.
(1) Dimensional changes of an individual lamination in consideration of the boundary conditions of MC exchange (due to different positions of lamination in glulam), effect of location of pith and width and thickness of the lamination were investigated;
(2) Dimensional changes of glulam beams in relation to the cross-sectional dimensions of beam and lamination, location of pith were investigated. The most unfavourable dimensional changes of beams in the depth and width directions due to arrangements of laminations were revealed. The correlation between glulam dimensional changes and the dimensional changes of individual laminations was developed. Comparison of the numerical results with further experiments is still needed.

During the spring of 2010 the study of Hergenröder on glulam beam cross-sections subjected to transverse compression was complemented with additional experiments with different compression rates and lamella stacking. HIT are currently using these experimental results for validation of numerical modelling. The experimental results are summarized in the report “DSP compression” available on the Building With Wood-web portal.

The low shear modulus (G_{RT}) in spruce has been studied by the single cube apparatus. The full-field in-plane shear strains (ε_{RT}) were measured in a direct manner by digital speckle photography DSP and the homogenised shear stress distribution was evaluated by a FE model. There was a good agreement between the measured and computed shear strains. This part of the work is presented in Hassel et al. 2009a and 2009b.

WP3 Stresses and strains: Modelling moisture induced stresses in wood

Within WP3 several computational tools for the calculation of moisture induced stresses in the presence of varying relative humidity conditions and mechanical loads have been developed:

1. A three-dimensional orthotropic-viscoelastic-mechanosorptive constitutive method has been specialized on the basis of previous 1D-models. A single-Fickian approach for moisture transfer has been used. The model is implemented into Abaqus FEM code and verified with respect to experimental data for small wood specimens and glulam beams taken from the literature.
2. A multi-Fickian model for moisture transfer proposed by Frandsen et al. (2007) has been implemented into Abaqus by using a sequential-analysis approach. The method has been validated with respect to experimental data for solid wood specimens and glulam beams taken from the literature and also with respect to the NMR experiments performed at KTH within this research (WP2).

3. Improved moisture-stress analysis: Model 1 has been improved by using Model 2 for moisture transfer.

These tools are suitable to analyze full size three-dimensional timber structures under real environmental conditions and can be further improved by using more accurate values of material properties obtained within WP1 on the basis of micromechanics. Some improvement of the method by using the stiffness coefficients calculated in WP1 was done.

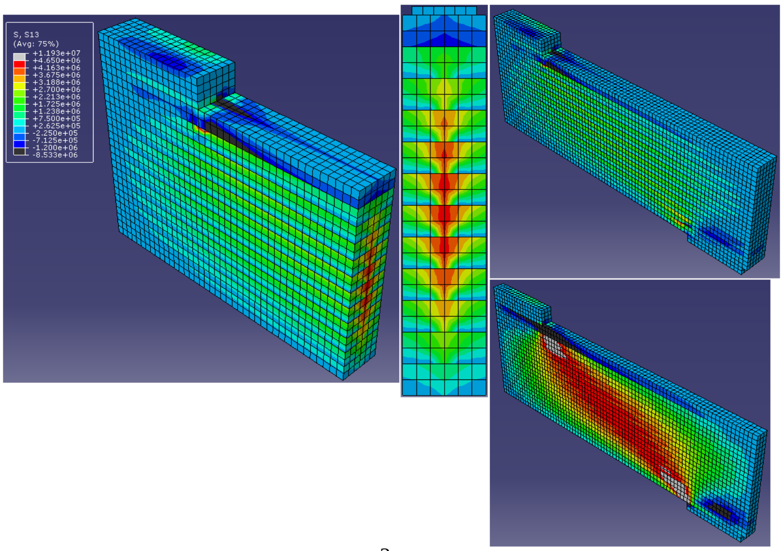

Figure 4. Shear stress τ_{rl} [N/m^2] of a beam half tested in WP5.

Application of the proposed models to practical engineering problems are as follows:

- Simulation of the short-term crack growth in solid wood and glulam under constant humidity, growing loads and in the presence of different adhesives (research performed in collaboration with WP4 Fracture).
- Simulation of the long-term crack initiation in solid wood and glulam under moisture variation and sustained loads (research performed in collaboration with WP4 Fracture).

- Numerical evaluation of shear strength of glulam beams under varying humidity conditions (fig 4 and WP5).
- Calculation of moisture gradients, moisture variations and moisture induced stresses perpendicular to the grains in timber sections under different European climates (research performed in collaboration with COST E 55 action).

WP4 Fracture

An experimental programme was conducted and a modelling work part was done at a later stage. A thorough literature survey revealed that hardly any fracture parameters can be found on glue-lines of glued wooden products. Two new specimen lay-ups have been designed for modes I and II fracture. More details may be found from the reference publications.

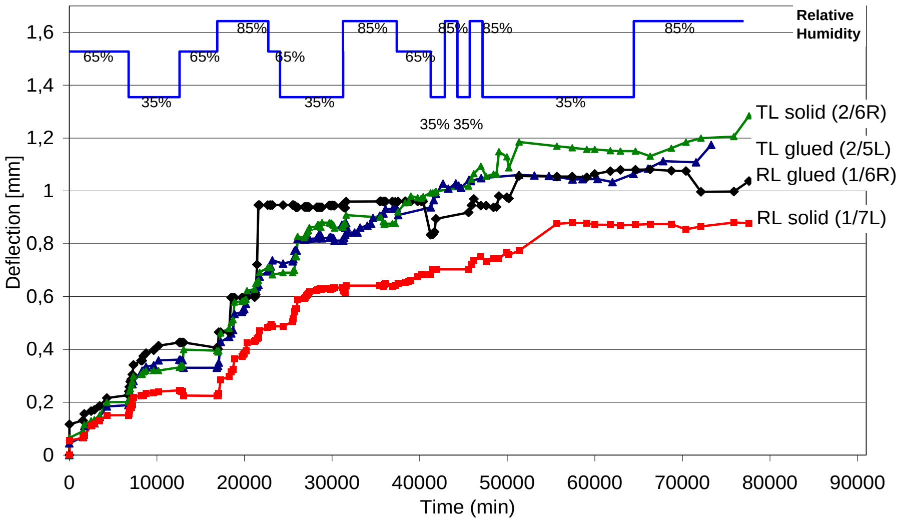

Figure 5. Deflection results of one set of mode II-specimens at varying humidity conditions

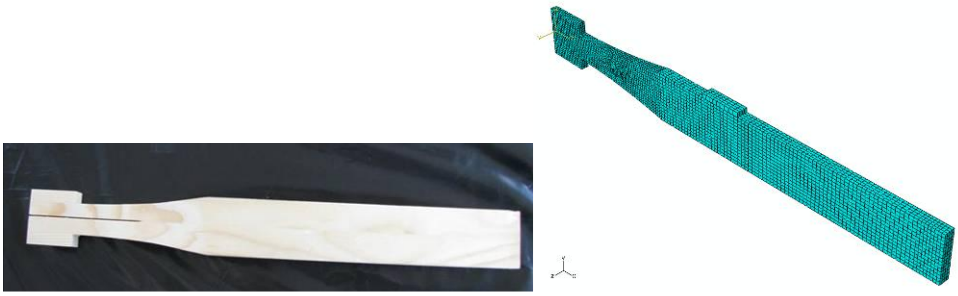

Figure 6. Photograph of the PTENF-specimen and meshed 3D (ABAQUS) model of the geometry

The calibration of model parameters was carried out. The cohesive zone model in Abaqus was applied for the short-term case of opening mode in DCB specimens (see Figure 8). Figure 7 shows an example comparison of test results to model results for the long-term case (PTENF specimen) where a linear elastic fracture mechanics approach (J integral based) was used to calculate the critical time of crack initiation.

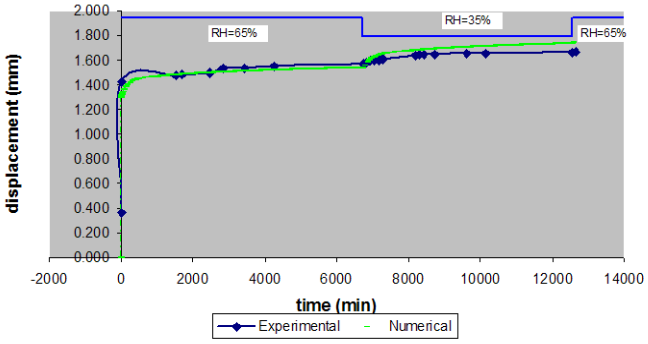

Figure 7. Load-displacement curve for the RL solid specimen. Experimental and numerical results at crack growth initiation (t_{crit}=2839.8 min). Sustained load: 0.8 P_{crit}=1.483 kN.

There are still some open questions mainly with respect to identification of model parameters and partly also with respect to experimental methods.

Figure 8a. Modified DCB specimen in RL crack configuration of wood.

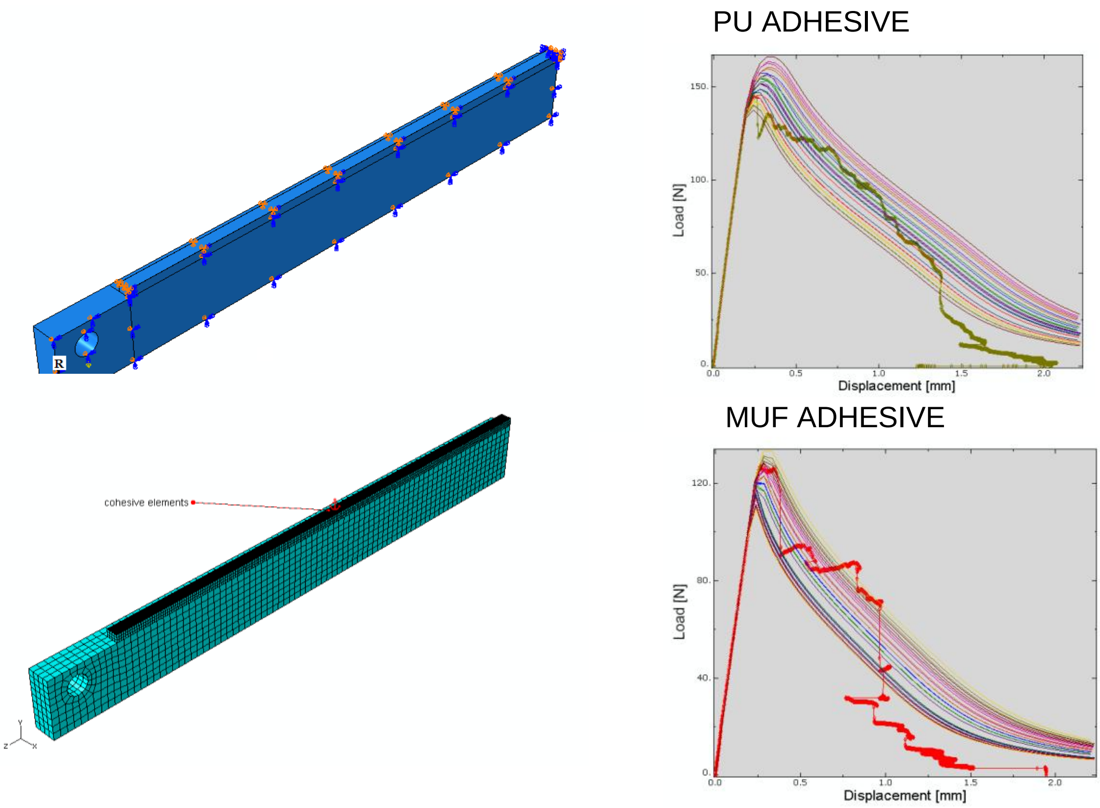

Figure 8b. Mode I DCB specimen. Modelling of fracture with two adhesives.

WP5 Design, glulam experiments

A total of 104 glulam beams were tested in a three point beam-shear test configuration to determine the shear resistance of glulam under varying humidity conditions. The cross-section dimensions of the beams were 540 mm x 115 mm and the total length was 3200 mm. The beams were first conditioned from RH65% to high humidity, RH90%, for three months. In a next stage the remaining beams were conditioned to a dry condition of RH30% for a period of three months. Four similar samples of 24 beams were tested to failure at different stages of the conditioning. Three different coatings were used in the test specimens.
The general objective of this study is to find out if moisture induced strains and stresses affect the shear resistance of conventional sized glulam beams. The effect of coatings in varying humidity conditions is also under study.

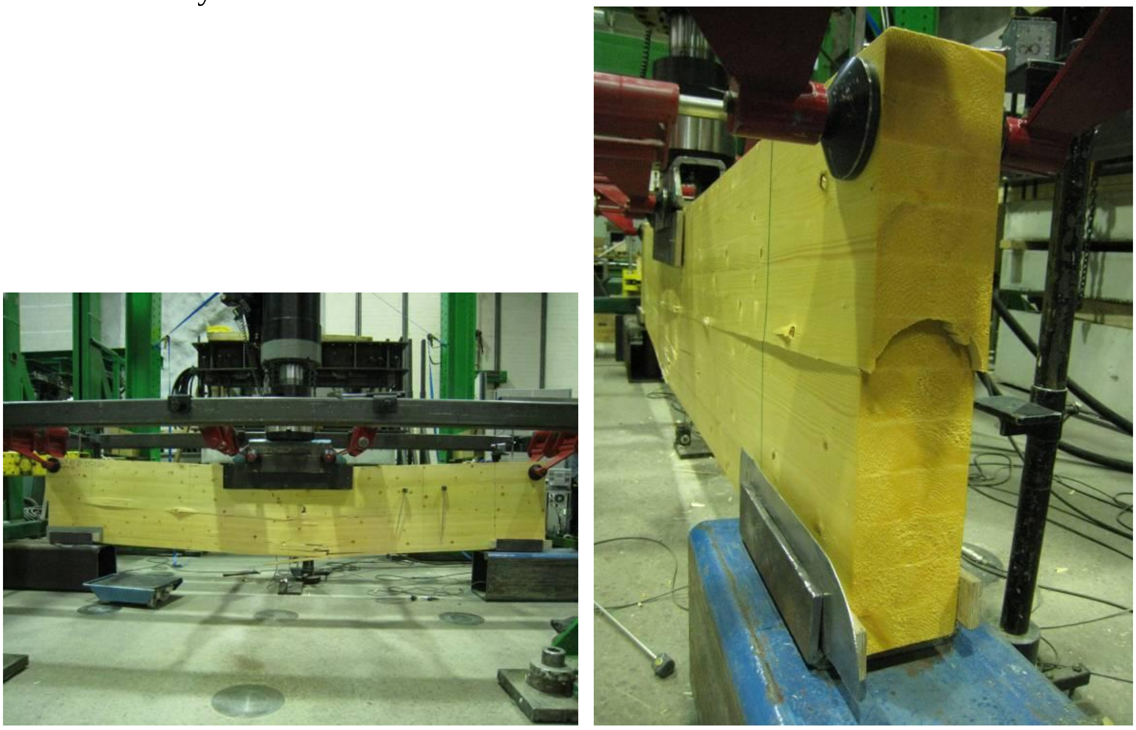

Figure 9. Typical shear failure of the beam experiments.

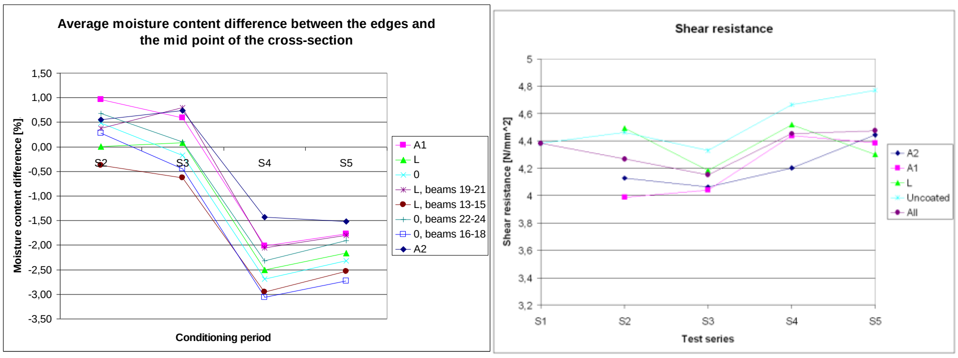

Figure 10. Evolution of moisture gradients in the beams (left) and mean shear strength in different conditioning phases (right).

The aim of the experiments was to find out if the variation of humidity affects the shear strength of large size glulam sections. It is known that moisture gradients are induced in dynamic humidity variations, and these produce internal stress distributions perpendicular to grain. The target here was to find out if these stress gradients have an effect on the shear strength of the beam. The test results show that there is no effect of the moisture gradients on the strength. Solely the actual mean moisture of the section seems to affect the strength. The coatings applied had minor effects on the induced moisture gradients. The results give no evidence to the recommended crack factor (kcr = 0,67) recently added to EN1995-1-1 design procedures for the reduction of shear resistance. The high initial moisture scatter between the material coming from one producer (out of four) did disturb the interpretation of test results.

Glulam beams tested in MPA

The purpose is to find experimental evidence on the effects of the environment moisture on the strength of glulam (shear strength, perpendicular to grain tension strength and crack propagation). This may be applied on the validation of the models from the previous WP's. This effect may also be applied in the structural design as a moisture load additional to the existing mechanical loads. The work of MPA focused on the realization of long-term test set-ups for bending tests of curved beams at changing climate conditions.

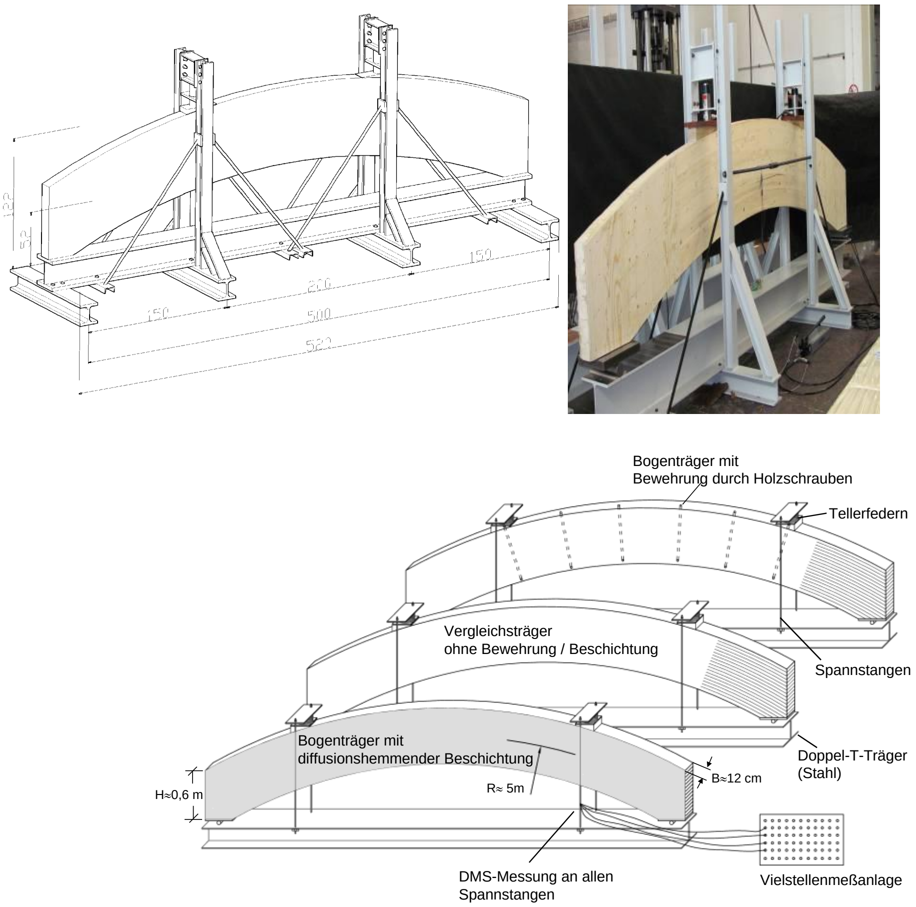

Figure 11. Long-term rigs for bending tests at cyclic climate conditions

The specimens, being curved beams of structural dimensions, have been designed and produced in co-operation with the industrial partners. A total number of 13 curved beams have been produced by two German glulam manufactures. The specimens were designed to have a failure due to tension stresses perpendicular to the grain. All the 3 coating (different suppliers) were ineffective in improving the glulam performance in variable conditions. Thicker coatings with higher particle amounts would be necessary. Climate changes act as additional loads perpendicular to the grain and reduce the time to failure of curved glulam beams drastically after 6 and 12 days up to 58% stress level, (acc. to EC5 kmod = 0,60 for permanent load, service class 2)

Available and widely used coatings are not usable as mitigation of moisture induced loads: hardly any influence on diffusion behaviour, no effect on times to failure

Reinforcement with self-tapping screws lead to significant increase of time to failure, although no significant influence of short-term strength. However, also with screws fulfilling the design equations given in DIN 1052, failure occurs after 3 months at SL=0.58

Experiments carried out in HIT, China

Outside the work program of this project, the China National Natural Foundation supplied funding for the testing of curved glulam beams under moisture variations and sustained load. The perpendicular to grain stresses induced by RH variations and load in curved beams were modelled with the FE models developed in this project. Short-term load capacity of three curved glulam beams made of China North-east larch were tested. Four curved beams subjected to sustained load and RH variations, of which two beams are under 30% of short-term ultimate load and the other two are under 60% of the ultimate load, have been being tested.

Numerical modelling showed that, most of the stress perpendicular to grain in curved glulam beams in service conditions is induced by moisture variations, and the stress can exceed the tensile strength of wood in the perpendicular direction. The three beams from short-term testing all failed identically due to tension perpendicular to grain. Under sustained load and varying RH, one of the four beams, which is under 60% of the ultimate load, failed due to tension perpendicular to grain. Both the numerical modelling and physical testing show that moisture-induced stress perpendicular to grain in the curved glulam beams can be the controlling factor of the load capacity, hence the necessity of controlling and mitigating the moisture-induced stresses.

1.3 Conclusions

The most important contributions to the state-of-the-art, derived from the results and discussion.

The present project has dealt with a wide range of mechanics from microstructural level to full scale level and from a multi-physical point of view when solving for mechanics, fracture, moisture and temperature transfer simultaneously. The project contains large efforts both in developing calculation methods and in testing. Some of the experimental work is still ongoing during 2011 (regarding the curved glulam beams in MPA) after the finishing of the project.

A consistent set of micromechanical approaches for the effective hygro-mechanical behaviour of wood was developed. A good agreement of experimental results and corresponding model predictions in a one-to-one comparison was observed throughout most of the investigated properties. This underlines the suitability of the developed micromechanical models to predict effective mechanical and transport properties in an orthotropic framework.

A material model for wood has been implemented to Abaqus FEM software. This is partly based on the micromechanical approaches explained above. This enables the calculation of stresses and strains in wood during variable humidity conditions and external mechanical loads. The modelling of moisture transfer and the novel testing of moisture distributions are utilised in the overall understanding of the performance of timber structures in variable climates. Full scale tests revealed that moisture induced stresses are mostly effected in curved glulam structures, where perpendicular stresses may also develop from mechanical loads. It seems that the variable humidity environment, which creates internal stresses, does not affect the shear resistance of glulam. Straight beams did not show any sign of strength loss. The test period was one year and it may be possible that this was a too short time to reveal such findings. The coatings applied at present perform poorly against RH variations. Better moisture resistance in coatings should be developed. The stacking of lamellas (pith position) does have some minor effect on the internal stresses. The best ways to manage moisture induced stresses would be to apply moisture resistant coatings and to produce glulam with material which is of a moisture content as close as possible to the equilibrium of the mean service conditions.

The number of publications and the number of PhD and MSc degrees obtained through this project is very high. This is due to the scientific level of the work carried out.

1.4a Capabilities generated by the project

Knowledge generated in the project / outcomes of the project, such as unpublished doctoral theses, patents and patent applications, computer programs, prototypes, new processes and practices; established new businesses; potential to create new business opportunities in the sector.

A total of six doctoral thesis were produced in this project. These relate to new numerical models and calculation methods and software subroutines to be used in the Abaqus software. The developed methods may be applied on new wood products (such as cross laminated timber or heat treated wood) to model their performance in different conditions.

1.4b Utilisation of results

Give a brief description of how the results of the research and development have been used and/or what is the exploitation plan or plans for transferring the results into practice.

The results will be used in the following:

- give a profound understanding of the effect of transverse anisotropy on the stress distribution in wood products and its influence on the performance characteristics

- provide numerical analysis tools for study of the effect of moisture variations on the performance of wood and wood products during the service life

- the results will be used as background material for development and possibly standardisation (in the long-term) of wood based composites

- the results will enhance safety and reliability of timber structures and accordingly improve the reputation of wood as a structural material. Additionally, new products will increase the competitiveness of timber construction and will lead to increased market share of wood materials in building sector.

1.5 Publications and communication

a) Scientific publications

For publications indicate a complete literature reference with all authors and for articles a complete name. Indicate the current stage of the publishing process when mentioning texts accepted for publication or in print. Abstracts are not reported. Indicate the five most important publications with an asterisk.

1. Articles in international scientific journals with peer review

Bader, T.K., Hofstetter, K., Hellmich, Ch., and Eberhardsteiner, J. (2010) Poromechanical upscaling of wood strength: from lignin to spruce. ZAMM 90: 750-767.

Bader, T.K., Hofstetter, K., Hellmich, Ch., and Eberhardsteiner, J. (2010) The poroelastic role of water in cell walls of the hierarchical composite 'softwood'. Acta Mechanica, DOI 10.1007/s00707-010-0368-8.

Eitelberger, J., and Hofstetter, K. (2010) Multiscale homogenization of wood transport properties – diffusion coefficients for steady state moisture transport. Wood Materials Science and Engineering 5: 97-103.

Eitelberger, J., Svensson, S., and Hofstetter, K. (2010) Theory of transport processes in wood below the fiber saturation point – physical background on the microscale and its macroscopic description. Holzforschung, in print.

Eitelberger, J., and Hofstetter, K. (2010) Prediction of transport properties of wood below the fiber saturation point - a multiscale homogenization approach and its experimental validation. Part I: Thermal conductivity. Composites Science and Technology, in print.

Eitelberger, J., and Hofstetter, K. (2010) Prediction of transport properties of wood below the fiber saturation point - a multiscale homogenization approach and its experimental validation. Part II: Steady state moisture diffusion. Composites Science and Technology, in print.

Fortino S., Mirianon F., Toratti T. A 3D moisture-stress FEM analysis for time-dependent problems in timber structures (2009). Mechanics of Time Dependent Material,. 13(4):333-356. DOI 10.1007/s11043-009-9103-z.

Zhou H.Z., Zhu E.C., Fortino S., and Toratti T. Modelling the hygrothermal stress in curved glulam beams (2010). Journal of Strain Analysis for Engineering Design. 45: 129-140.

Fortino S., Zagari G., Mendicino A.L., Dill-Langer G. FEM simulation of Mode I cohesive crack growth in glued laminated timber under short-term loading. Submitted to European Journal of Wood and Wood Products.

Fragiacomo M., Fortino S., Tononi D., Usardi I., Toratti T. Moisture induced stresses perpendicular to grain in timber members exposed to European climates. To be submitted to Engineering Structures (and presented at the COST E55 final conference).

Dvinskikh S. V., Henriksson M., Berglund L. A., Furó I. "A multinuclear magnetic resonance imaging (MRI) study of wood with adsorbed water - estimating bound water concentration and local wood density", Holzforschung, 65, 103-107 2011a.

Dvinskikh S., Henriksson M., Mendicino A. L., Fortino S., Toratti T. "NMR imaging study and multi-Fickian numerical simulation of moisture transfer in Norway spruce samples". Submitted to Engineering Structures 2011b.

Dvinskikh S. V., Furo I., Sandberg D., Söderström O. Moisture content profiles and uptake kinetics in wood cladding materials evaluated by a portable NMR spectrometer. Submitted to Wood Material Science and Engineering.

Hassel, B. I.; Berard P.; Moden C. S; Berglund, L. A. "The single cube apparatus for shear testing – Full-field strain data and finite element analysis of wood in transverse shear", Composites Science and Technology, 69, 877-882, 2009a.

Hassel, B.I.; Moden, C.S.; Berglund, L.A. "Functional gradient effects explain the low transverse shear modulus in spruce - Full-field strain data and a micromechanics model", Composites Science and Technology, 69, 2491-2496, 2009b.

2. Articles in international scientific compilation works and international scientific conference proceedings with peer review

Eitelberger, J., and Hofstetter, K. (2010) Modeling of transient moisture diffusion in wood below the fiber saturation point. In Proceedings of the 6th International Conference on Diffusion in Solids and Liquids (DSL-2010), Technical University of Malaysia, 2010, 6 pages.

Hofstetter, K., Bader, T.K., and Dorn, M. (2010) The benefit of micromechanical modeling in timber engineering. In Proceedings of the World Conference of Timber Engineering (WCTE) 2010, University of Trento, 2010, 6 pages.

Eitelberger, J., and Hofstetter, K. (2010) Modeling of moisture transport in wood below the fiber saturation point. In Proceedings of the 11th International IUFRO Wood Drying Conference, Lulea University of Technology, Skelleftea, 2010, pp. 131- 136.

Fortino S., Hanhijärvi A., Mirianon F., Toratti T. 3D coupled moisture-stress numerical analysis for timber structures. 5th European Congress on Computational Methods in Applied Sciences and Engineering (ECCOMAS 2008, Minisymposium "Mechanical modeling of wood and wood based materials), June 30-July 5, 2008, Venice, Italy. Keynote Lecture.

Fortino S. and Toratti T. A computational approach for the stress analysis of dowel-type connections under natural humidity conditions. CSE09 conference, Shanghai, China, June 2009.

Zagari G., Fortino S., Dill-Langer G. FEM simulation of crack growth in glulam by using a 3D orthotropic-viscoelastic model and cohesive elements. ESMC 2009 conference, Lisbona, Portugal, September 5-9, 2009.

Fortino S., Mendicino A.L., Toratti T. Stress analysis of timber structures by using a multi-Fickian moisture transfer model. ICSA2010 conference, Minisymposium "Timber construction" organized by the European program COST E55, Guimaraes, Portugal, July 21-23, 2010.

Fortino S. and Toratti T. A three-dimensional moisture-stress FEM analysis for timber structures. WCTE2010 conference, Riva del Garda, Italy, June 21-24 , 2010.

Mendicino A.L., Fortino S., Henning M., Dill-Langer G. A computational method for crack growth in glulam under variable humidity. WCTE2010 conference, Riva del Garda, Italy, June 21-24 , 2010.

Sundström T., Kevarinmäki A., Toratti T. Shear strength of glulam beams under varying humidity conditions. WCTE2010 conference, Riva del Garda, Italy, June 21-24 , 2010.

Furo, I. Wood MRI and NMR: molecules, interactions, and motion. Invited lecturer at the World Wide Magnetic Resonance 2010, Joint EUROMAR 2010 and 17th ISMAR Conference, Florence, Italy

Dvinskikh, Furó. High and low field NMR and MRI studies of wood moisture interaction. Nuclear Magnetic Resonance in Condensed Matter. 7th Meeting "NMR in Heterogeneous systems", St. Petersburg, Russia, 2010.

Dvinskikh, Furó. MRI studies of swelling, sedimenting, absorbing, and drying materials. Invited talk at 10th International Conference on Magnetic Resonance Microscopy, West Yellowstone, Montana, USA, 2009.

Dvinskikh, Henriksson, Berglund, Furo. Correlating water and macromolecules across growth rings in wood. A multinuclear magnetic resonance imaging study. Poster presentation at EUROMAR 2009, Sweden 2009.

3. Articles in national scientific journals with peer review

4. Articles in national scientific compilation works and national scientific conference proceedings with peer review

Gloimüller, S., and Hofstetter, K. (2010) Determination of the linear elastic stiffness and hygroexpansion of wood by a multilayered unit cell using poromechanics. In Proceedings of the PhD Symposium "Forschung + Praxis 2010", University of Stuttgart, 2010, 8 pages.

5. Scientific monographs

6. Other scientific publications, such as articles in scientific non-refereed journals and publications in university and institute series

Garcia C (2010) Numerical Simulations on the Strength Reducing Effect of Knots in Wooden Boards. Master Thesis, TU Vienna.

Mirianon F., Fortino S., Toratti T. A method to model wood by using ABAQUS finite element software, Part 1: constitutive model and implementation details. VTT publication nr. 687.

Mirianon F., Fortino S., Toratti T. A method to model wood by using ABAQUS finite element software, Part 2: application to dowel type connections. VTT publication nr. 687.

Tononi D., Usardi I., Fortino S., Fragiacomo M., Toratti T. Moisture transfer and moisture induced stresses in timber structures under environmental conditions in Europe. VTT publication, In preparation.

Sundström T., Kevarinmäki A., Fortino S., Toratti T. : Shear resistance of glulam beams under varying humiditry conditions. VTT publication, In preparation.

a) Other dissemination
Such as text books, manuals, user guidelines, newspaper articles, TV and radio programmes, meetings and contacts for users and results.
Dissemination of results to industrial partners and industrial partners dissemination within the company.

Project web page has been used of communication between participants from research and industry (total of 100 documents, www.buildingwithwood.eu)

1.6 National and international cooperation

Give a brief description of the cooperation/ networking (partnership between the project participants and how this has developed; industrial involvement; synergies of industrial and research expertise; Has the project collaborated with similar projects in the WW-Net countries or other regions, or established new links with/ between local or international organisations involved in the respective research field? Describe how these partnerships have supported the project.
National vs. transnational aspects in the project; added value for the project and its impacts which result from transnational cooperation.

The cooperation included joint detailed planning of the work programme, modelling, testing and analysis efforts as well as visiting scientists/post-graduate students. Transnational cooperation is needed because this is a challenging area of research and expertise is very limited in the national levels. The project has led also to new cooperation with China, Harbin institute of Technology.
The industrial implementations of the models developed in the project are under discussion at present. These may be readily applied to different wood products and for different load cases.