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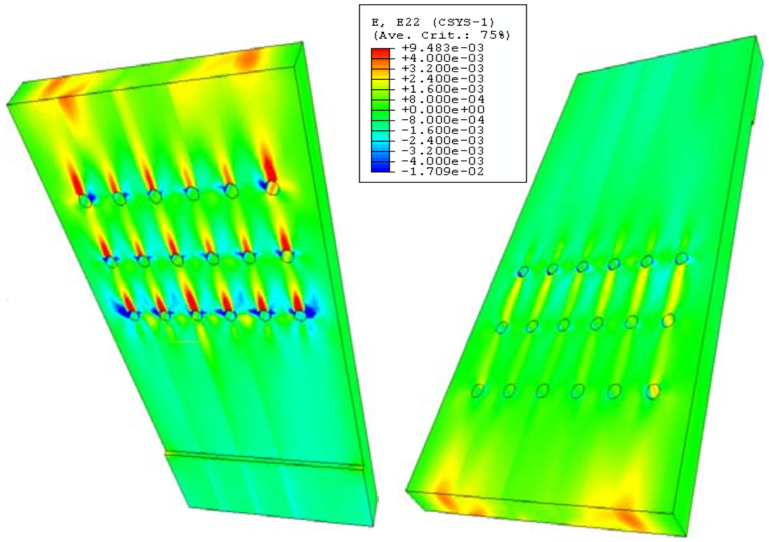

Florian Mirianon, Stefania Fortino & Tomi Toratti

A method to model wood by using ABAQUS finite element software

Part 2. Application to dowel type connections

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A method to model wood by using ABAQUS finite element software

Part 2. Application to dowel type connections

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Keywords timber, gluelam, moisture transfer, stress analysis, FEM, ABAQUS, creep, mechano-sorption, dowel, connections

Abstract

This report presents numerical analyses of dowel connections modeled in ABAQUS using a rheological model for wood taking into account loading time, moisture content of wood and the load case. Some experimental tests under constant moisture content have been modeled as well and the numerical results are in good agreement with the experiments. Variable relative humidity conditions have been applied to some connections. The results show that the variations of moisture content in wood can strongly increase the stresses in wood, especially in the direction perpendicular to the grain. The same connection has been modeled with and without reinforcement based on glued-in rods. It appears that the presence of glued-in rods affects the stresses around the holes and most of the tension stresses are converted into compression stresses. A one dowel connection has been modeled to study the influence of the friction coefficient between wood and steel on the crack appearance. The results have showed that the higher the friction coefficient is, the smaller the strains perpendicular to grain are.

Mirianon, Florian, Fortino, Stefania & Toratti, Tomi. A method to model wood by using ABAQUS finite element software. Part 2. Application to dowel type connections [Puun mallintaminen käyttäen ABAQUS-elementtimenetelmäohjelmistoa. Osa 2. Sovellus puurakenteen liitosten toimintaan]. Espoo 2008. VTT Publications 690. 55 s. + liitt. 3 s.

Avainsanat timber, gluelam, moisture transfer, stress analysis, FEM, ABAQUS, creep, mechano-sorption, dowel, connections

Tiivistelmä

Työssä mallitettiin puurakenteiden liitoksia erilaisissa kosteusolosuhteissa. Analyysi tehtiin ABAQUS-elementtimenetelmäohjelmistolla. Puun materiaali-malli esitellään aikaisemmassa julkaisussa, ja sitä on käytetty tässä sovellettuna liitosten toiminnan arviointiin. Kosteudella on merkittävä vaikutus puun jännityksiin liittimien ympäristössä. Poikittaisella liimatankovahvistuksella jännityksiä voidaan tosin pienentää. Myös liittimen ja puun välisellä kitkalla on huomattava vaikutus liitoksen mekaaniseen toimintaan.

Preface

The present report documents research performed in 2 projects: The initial steps for the development of the analysis were carried out in the Woodfem project, which is a national project funded by Tekes and VTT and the main work was carried out in the Improved moisture project (Improved glued wood composites – modeling and mitigation of moisture-induced stresses), which is a European project within the Woodwisdom-net program and funded by Tekes, VTT and the Building with Wood group (for the Finnish sub-project).

The contributions and funding from the above mentioned parties is gratefully acknowledged.

The authors

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Appendix 1

1. Introduction

Timber is known to be an excellent building material: it is strong, light, available all over the world and low-cost compared to some other materials. The natural orientation of the wood fibres makes timber fit for beam and truss constructions (Hanhijärvi 1995).

For building purposes, timber elements are connected to each other by different kinds of connection. The most common connections are dowel joints, nail plates, nails and screws. In these connections, wood and steel are combined, which means that a natural material, which deforms with moisture is combined with a very stiff material. During moisture content changes in wood, the shrinkage causes relatively high deformations of the timber elements, but the stiffness of the steel components in the connections makes them extremely rigid and may cause high stresses around the connections. These induced moisture stresses in timber can cause cracks and in some extreme cases can cause the collapsing of the structure.

Some previous studies describe failures which have occurred in timber structures and investigations are carried out on the reasons of the failures. From reference (Frühwald et al. 2007), it appears that in the studied failure cases, 23% of them were due to joint failures, and 57% of them were dowel type connections.

The aim of this study is to understand interactions of moisture variations and estimate the levels of moisture induced stresses in these kinds of connections, and particularly in dowel type connections which are used in long span structures.

2. Background

2.1 Humidity environment: first step

Earlier literature gives plenty of information on moisture content of wood and its effects on mechanical performance. Moisture transfer and moisture induced strains and stresses have been the subject of many studies in the last decades, especially under artificial laboratory relative humidity and temperature conditions. However, only a few studies relate moisture content of wood and its effect in natural climate conditions.

Ranta-Maunus explains the mechanics of the moisture content in wood caused by a naturally varying climate (Timber Engineering 2003). He first explains that in function of the location of a building, the kind of building and its use, wood is not exposed to the same relative humidity. The mean value as well as the variation of moisture content of wood thus depend of these factors.

Figure 1 presents the measured relative humidity in two different buildings in Finland during several years. This shows that in a closed and heated building, the average relative humidity can be much lower than in an open area. It can be noticed that the relative humidity is yearly cyclic and that the cycle is different for different building types.

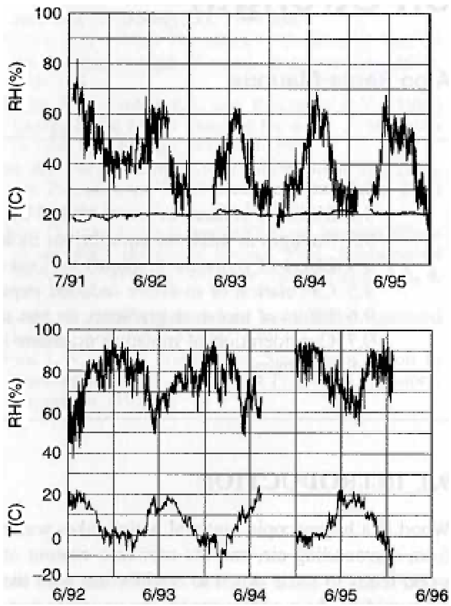


Figure 1. Changes in relative humidity and temperature (daily mid-day values) in a heated room in Espoo (above) and in a sheltered environment in Kirkkonummi (below) (Timber Engineering 2003).

Figure 2 presents the average moisture content of a glulam beam in a barn. It shows similar cycles as the relative humidity. The average moisture content varies between 14 and 20%. This has consequences on the strength of wood. Normally the strength is low when the moisture content is high. However, not only the average moisture content is important, in fact the gradient of moisture content induces stresses perpendicular to grain (see Figure 3), which can make the wood split.

Figure 3 shows that the moisture content varies in function of the distance from the surface: the closer from the surface it is, the more the influence of the surrounding relative humidity is high and fast.

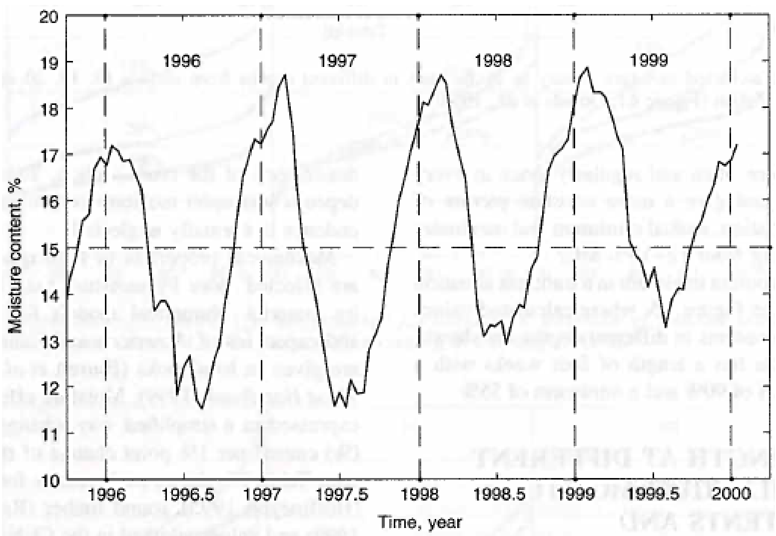


Figure 2. Mean moisture content in wood (glulam 90 x 100 x 600) versus time in a barn in Southern Sweden (Åsa) (Timber Engineering 2003).

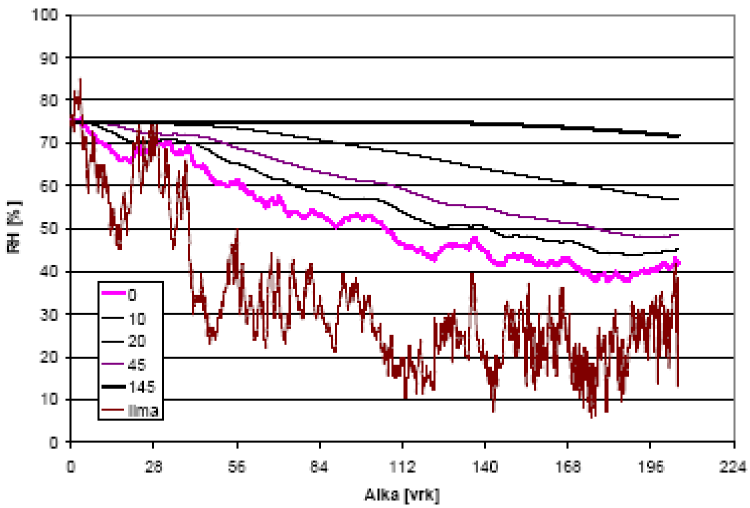


Figure 3. Calculated moisture history of a lacquered glulam beam under the relative humidity measured in the Sibelius hall during 224 days (in brown), results given in depths (0, 10, 20, 45 and 145 mm) from surface of 290 mm thick glulam (Koponen 2002).

2.2 Humidity environment: service climate conditions

The use of a building determines most of its climate conditions. It will condition its relative humidity, temperature and in some cases some aggressions by external components as chemicals, dust or mold.

The following factors can be used to classify the climate conditions in a building: heated, unheated, open, closed, insulated, not insulated, presence of ventilation system, presence of animals (agricultural), presence of water, presence of chemical vapors, etc. The indoor climate is strongly dependent on these factors.

Kevarinmäki et al. have studied the critical factors affecting the load-bearing capacity and the durability of structures in sports halls with long timber spans (Kevarinmäki et al. 2000). For this study, they have done a survey of Finnish ice sport halls and sports halls by interviews with their maintenance personnel, measurements on site, design studies and, in some cases, by calculations. The study has showed some design and manufacture errors. It also revealed that in the studied unheated ice sport halls, the average relative humidity is over RH90% for more than 5 months during a year (Figure 4). According to Kevarinmäki et al., this level of relative humidity clearly decreases the strength of wood and may lead to other moisture related deterioration such as mold and rot.

Koponen has studied the performance and long-term durability of timber structures under temperature and moisture loading (Koponen 2002). His aim was to control the humidity levels in construction of timber structures and wood products, in order to build high quality wood structures. The measurements of moisture in wood structures have been done by studying the Sibelius hall (Finland) under service conditions. The measurements of moisture in the “Forest Hall” of the Sibelius hall show that in a heated room, the relative humidity can be very low (Figure 5). In this case, during the winter time, the indoor average relative humidity is around RH15% (in blue Figure 5), while in the same time, the outdoor average relative humidity is around RH85% (in grey Figure 5).

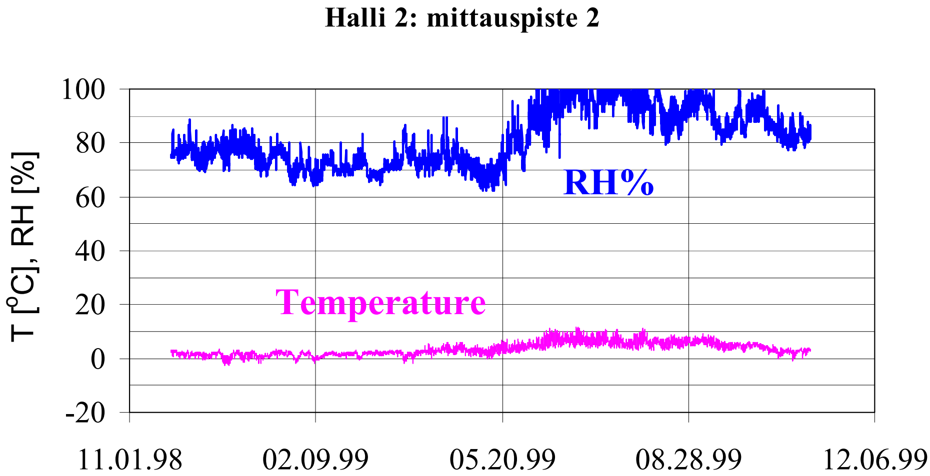


Figure 4. Relative humidity and temperature measured in the Myllypuron ice sport hall during one year (Kevarinmäki et al. 2000).

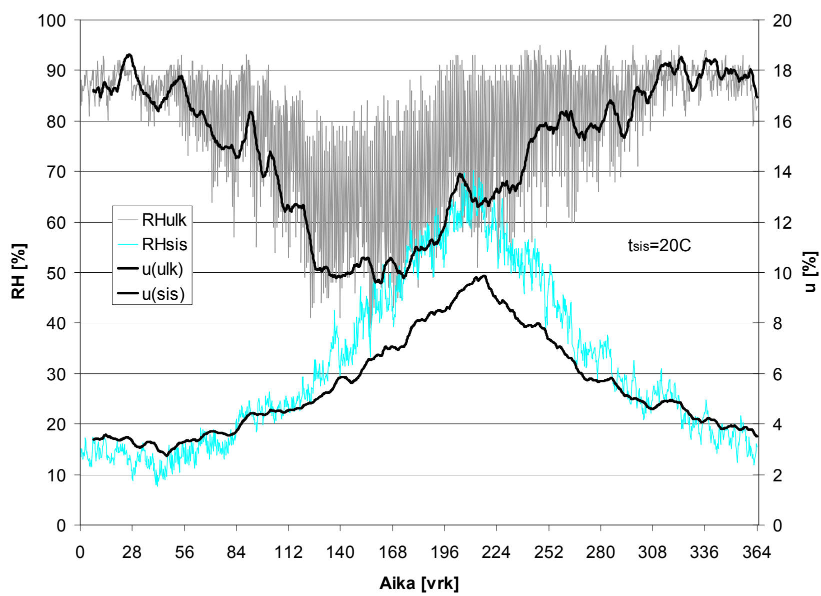


Figure 5. Relative humidity and corresponding moisture content measured in Sibelius hall (in blue) and in outdoor conditions in Jyvaskylä (in grey) during one year (Koponen 2002).

When wood is extremely dry as in the Sibelius hall, the risk of cracking on the wood surface is strongly increased, especially if in addition gradients of moisture content occur between the inner part and the outer part of the timber section. This gradient causes stresses perpendicular to grain as explained by Ranta-Maunus (Timber Engineering 2003).

Kivinen has studied the effects of climate conditions, relative humidity, temperature, carbon dioxide and ammonia emissions in nine dairy barns (Kivinen 2003). He has found that the ventilation systems have a strong influence on the conditions. As Kevarinmäki et al., he has noticed that the indoor relative humidity was between RH80% and RH100% for long periods, especially during the winter time. The high level of humidity seemed to enable mold growth on wall and ceiling surfaces, but the risk of wood decay was not obvious.

On the basis of the above studies, three main climate conditions can be considered as representative for most of the service cases:

- heated buildings: exhibition halls (in blue Figure 5)
- heated buildings or unheated building, presence of moisture: dairy barns, swimming pools, ice sport hall (in blue Figure 4)
- unheated buildings without insulation: barns, garages (in grey Figure 5).

Some more categories could be defined in function of the temperature, but since the temperature effects are considered to be very small compared to the moisture content effect (Fortino et al. 2008, Toratti 1992), it is not taken into account in this study.

2.3 Failures in connections

Frühwald et al. (2007) carried out a review of failures in all kinds of constructions with the aim to provide a good base to learn from failures and design safe timber structures. According to this study, the main failures that occur in timber structures are (the two first are the most common):

- Inadequate bracing of structural system
- Inadequate behavior of joints
- Effects of moisture exposure (imposed strains, shrinkage)
- Poor durability performance
- Inadequate performance of material and products
- Inadequate appreciation of loads.

The performance of joints in timber structures is in many cases problematic: 23% of the failures in timber structures occur in connections, 57% of them are dowel type connections. In most cases, the failures are due to shrinkage effect in wood or bad design of connections. The other failures are usually due to poor design of other parts or human errors during construction.

When timber trusses are used for long spans, the consequences of a joint failure can be high as for this exhibition hall in Jyväskylä (Figure 6). The roof collapsed just after a public happening, although at the time of failure this happening was over and nobody was injured. At this time, the amount of snow on the roof was only 25% of the design snow load. The investigation revealed that one of the joints failed because only 7 out of 33 dowels were in place.

Figure 6. Collapsing of an exhibition hall in Jyväskylä due to missing dowels in one of the joints (Jyväskylä 2003).

2.4 Failure mechanisms in connections

There are several failure modes typical for dowel type connections, some of them are due to wood failure, some due to dowel failure and some due to both (Eurocode 5 2002). In this study, only wood failures are taken into account (Figure 7).

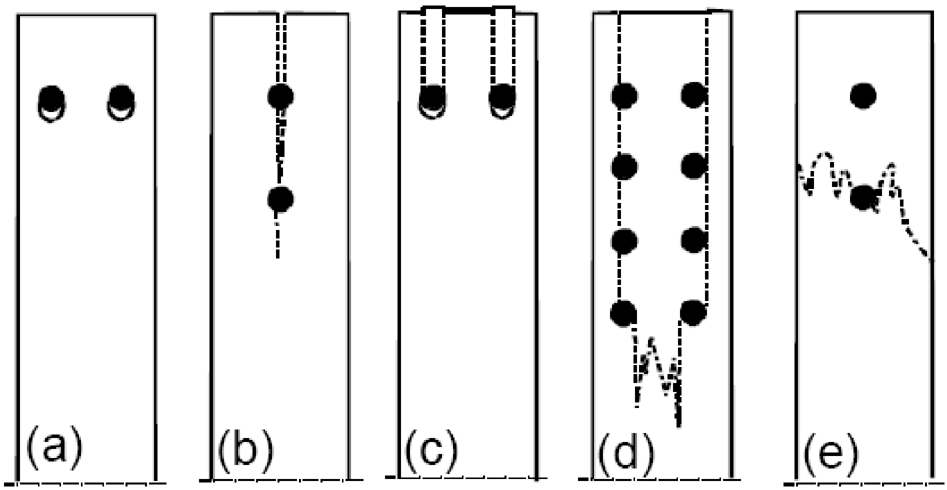


Figure 7. Failure modes for multiple dowel joints loaded in tension parallel to grain: (a) Embedding failure, (b) Splitting failure, (c) Row-shear-out failure, (d) Block-shear failure, (e) Tension failure (Eurocode 5 2002).

Some studies have demonstrated that several factors affect the connection capacity and the failure mode (Cointe & Rouger 2005, Hanhijärvi & Kevarinmäki 2008). The geometry is the first factor, such as the dowel diameter, the thickness of the connected elements, the distance between dowels and the distance between dowels and the edges of the connection are of importance (Cointe & Rouger 2005, Hanhijärvi & Kevarinmäki 2008, Eurocode 5 2002). The other factor which has some importance in the connection capacity is the moisture content of wood and the variation of moisture. This factor has been recently taken into account in the Eurocode 5 by adding a correction factor in the connection calculation in function of the moisture conditions of the connection. But moisture effects in connections are still not well understood and need to be further investigated. This is the aim of the present application.

3. Modeling of two dowel type connections

Two joints previously studied experimentally and numerically by Sjödin have been modeled in this report (Sjödin 2008). Sjödin has studied steel-timber dowel joints under tensile load in grain direction with the objective to determine how the short term capacity of these joints is affected by an initial drying exposure.

In the present research work, a tensile test done by Sjödin for both connections has been reproduced in constant moisture conditions using ABAQUS/Standard and the 3D rheological model developed in the first part of this study (Mirianon et al. 2008). The aim was to validate the modeling done with ABAQUS by comparing numerical results to experimental data. Then, some different relative humidity conditions have been applied to the simpler joint. The stresses have been studied in function of the moisture changes in order to understand the performance under varying relative humidity.

3.1 Description of the analyzed connections

3.1.1 Doweled connection type 1

Figure 8 shows the steel-to-timber joint modeled in this study (type 1).

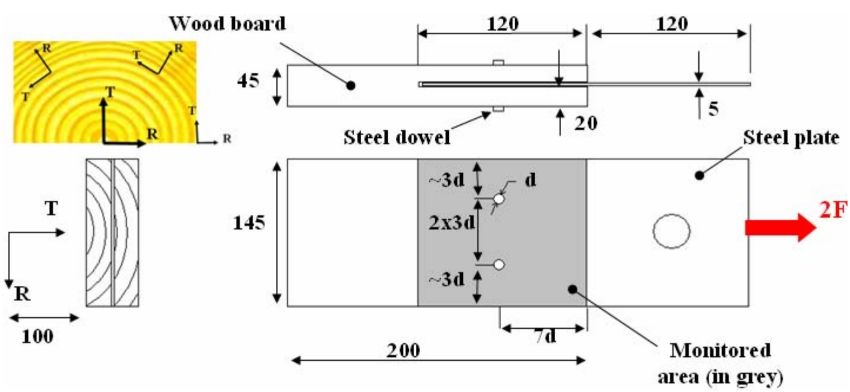


Figure 8. Scheme of the steel-to-timber connection type 1, dimensions in millimeters (d = 12 mm).

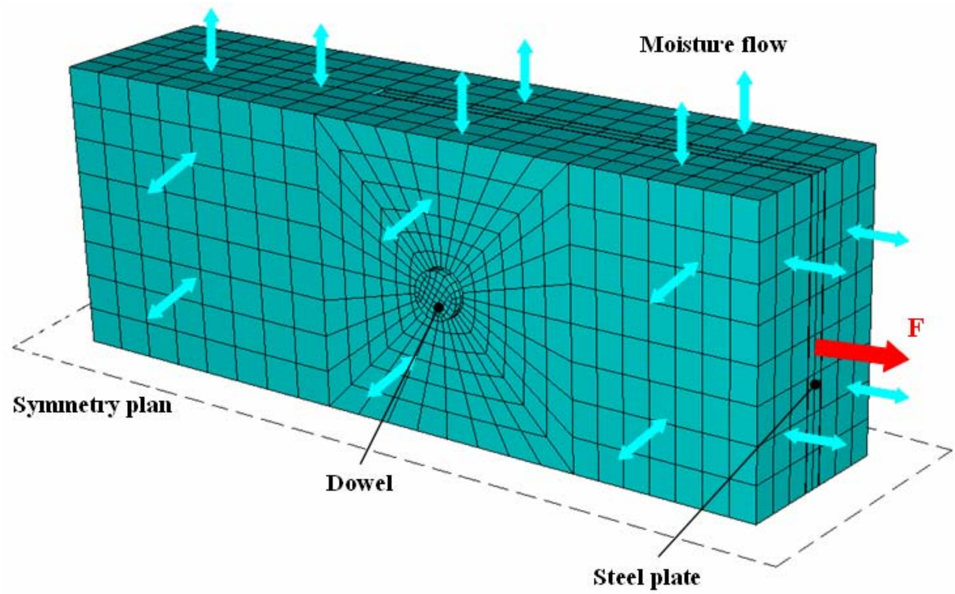


Figure 9. Numerical model of the steel-to-timber connection type 1 done with ABAQUS CAE.

This numerical model (Figure 9) uses a symmetry plan to limit the number of elements (3940 elements). The simulations use ABAQUS 6.5-3 and are run with ABAQUS/Standard. The hexagonal 3D elements C3D8T have been used to mesh the wood part and the hexagonal 3D elements C3D8 have been used to mesh the steel plate and the dowel. A 0.1 mm gap has been added between parts in the contact area in order to help the convergence of the calculation. The contacts have been modeled by a hard contact pair with a penalty method in the tangential direction using a 0.4 penalty factor. It uses a “small sliding” option and an “adjust slaves nodes in set” option. The rheological model of wood is implemented in a UMAT subroutine. The moisture flow is implemented in a DFLUX subroutine.

The distance of 100 mm between the pith and the closest edge of the connection is used because no information about the pith position is given in the description of the experimental specimens used by Sjödin.

3.1.2 Doweled connection type 2

Figure 10 shows the steel-to-timber joint modeled in this study (type 2).

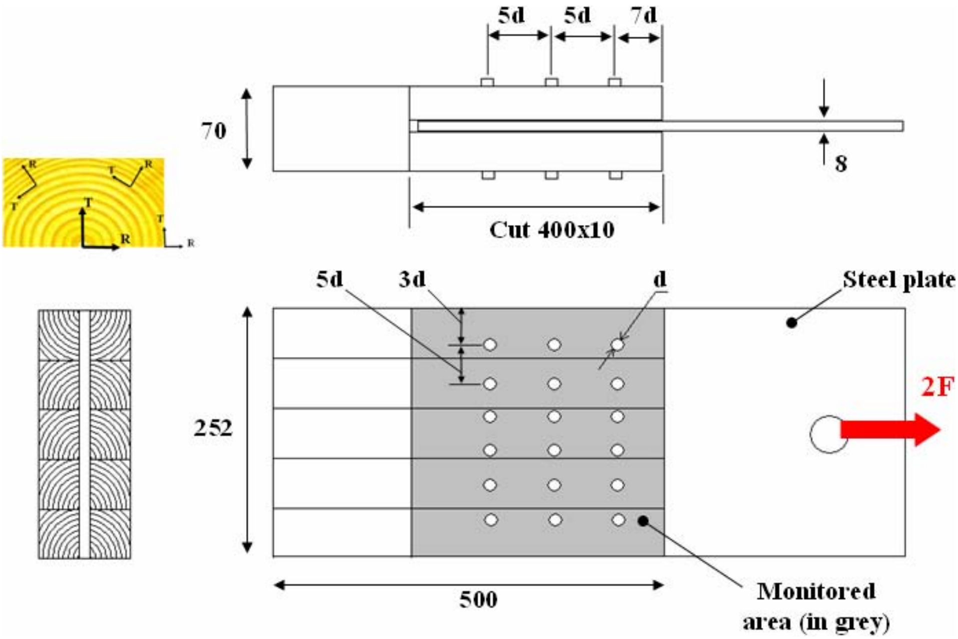


Figure 10. Scheme of the steel-to-timber connection type 2, glulam beam 252 x 70, dimensions in millimeters (d = 12 mm).

This numerical model (Figure 11) uses a symmetry plan to limit the number of elements (46 708 elements). The simulations use ABAQUS 6.5-3 and are run with ABAQUS/Standard. The hexagonal 3D elements C3D8T have been used to mesh the wood part and the hexagonal 3D elements C3D8 have been used to mesh the steel plate and dowel. A 0.1 mm gap has been added between parts in the contact area in order to help the convergence of the calculation. The contacts have been modeled by a hard contact pair with a penalty method in the tangential direction using a 0.4 penalty factor. It uses a “small sliding” option and an “adjust slaves nodes in set” option. The rheological model of wood is implemented in a UMAT subroutine. The moisture flow is implemented in a DFLUX subroutine.

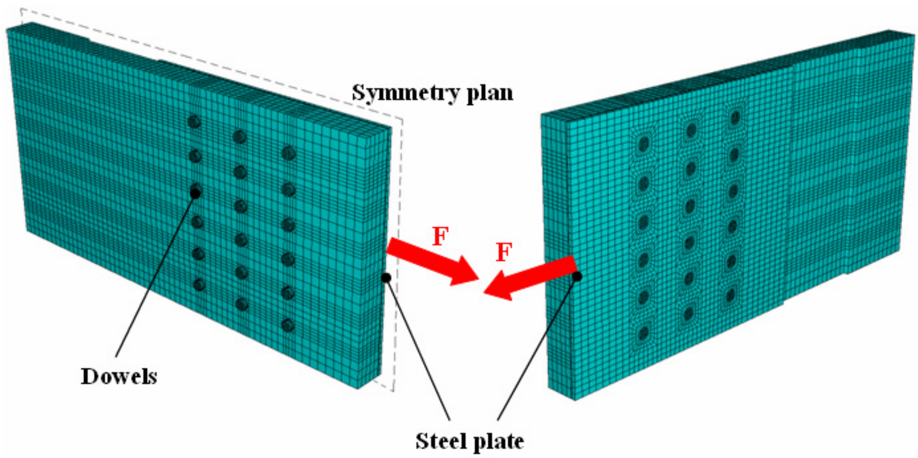


Figure 11. Numerical model of the steel-to-timber connection type 2 done with ABAQUS CAE.

4. Validation of the modeling: comparison with experimental results

4.1 Test 1: Connection type 1, short term analysis

This test reproduces the experimentation done by Sjödin (2008). The connection type 1 has been loaded by a tensile force of 28 kN applied in 1 minute (F = 14 kN). In this experiment, the load was just under the elastic limit of the connection. The moisture content of wood was 12% at the beginning of the calculation and remained constant. The parameters for *Norway spruce* have been used in the analysis (Appendix 1).

Figure 12 shows Sjödin's results as well as the results obtained from the present study. Sjödin used a 2D elastic analysis and found a good agreement with his experimental results. The experimental results have been obtained by using the ARAMIS-System: a camera measures optically the strains on the wood surface. The 3D numerical analysis has been done using the 3D model for wood developed in this study and the results are also in good agreement with the experimentation.

Figure 13 shows a 3D view of the loaded numerical model. It shows that the strains perpendicular to grain on the studied surface are lower than in the inner part of the connection. This is probably due to the bending of the dowel.

Note: the same connection has been modeled using shell elements and a "rigid body" option to model the dowel and the plate. It has been noticed that with this configuration, the stresses are around 10% higher than the ones measured with the presented model.

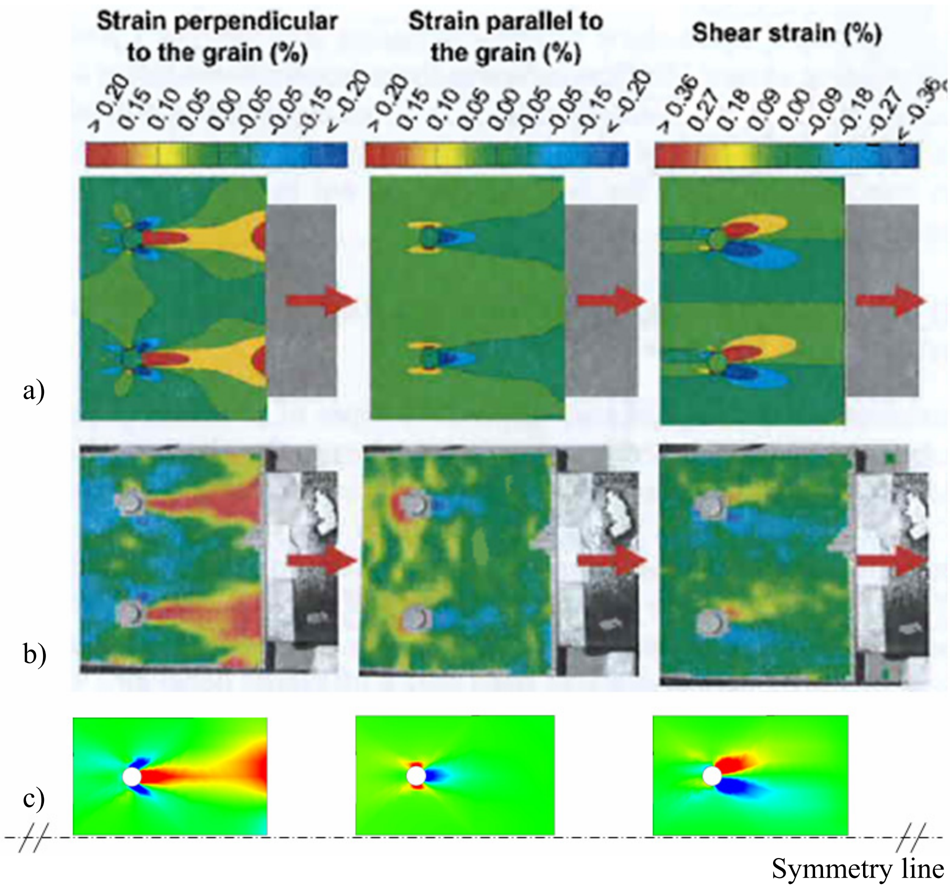


Figure 12. Strains for test 1: a) 2D Calculated results by Sjödin (2008), b) experimental results by Sjödin (2008), b) 3D Calculated results.

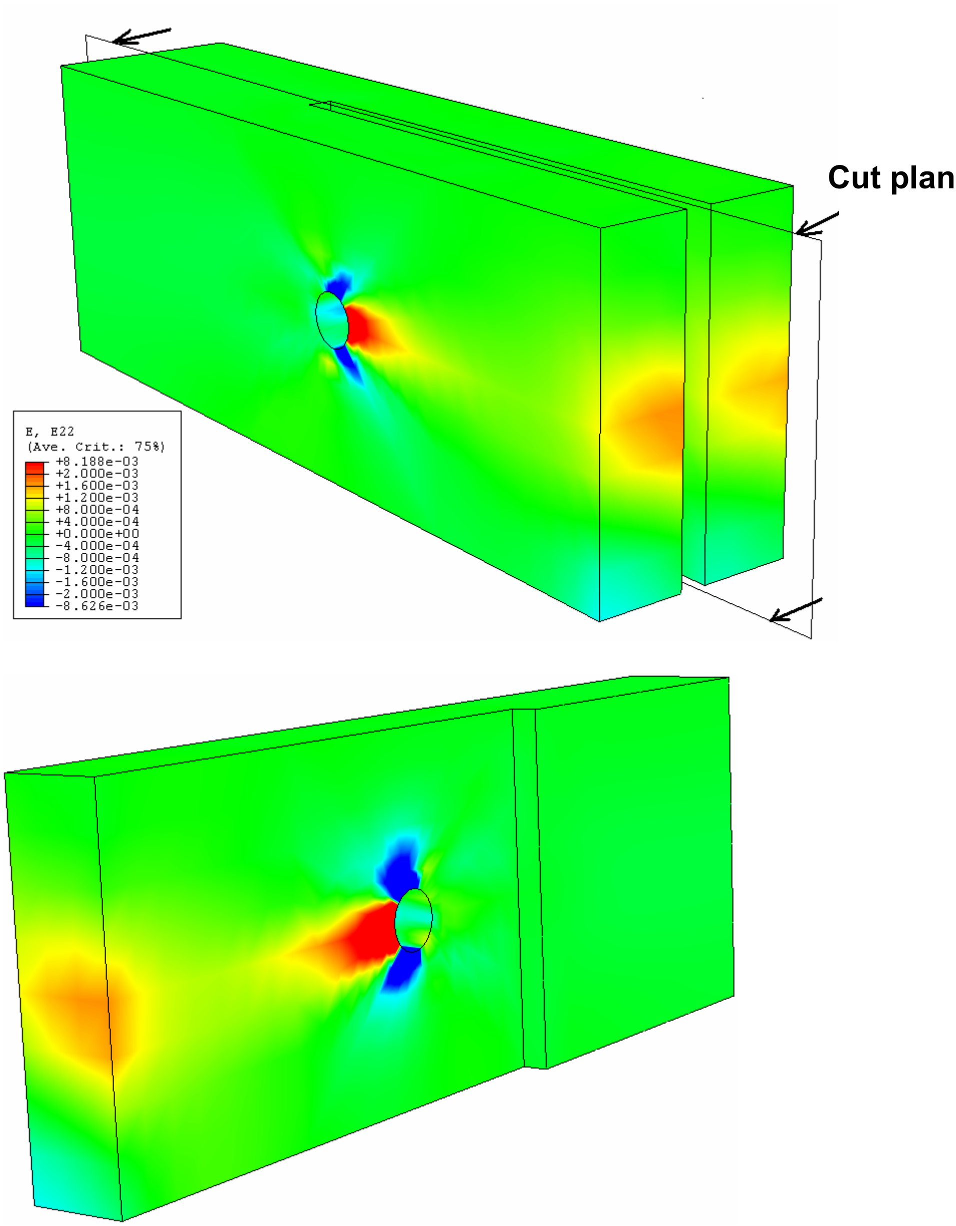


Figure 13. 3D views of the strains perpendicular to grain: full model (top), longitudinal cut (bottom).

4.2 Test 2: Connection type 2, short term analysis

This test reproduces the experimentation done by Sjödin (2008). The connection type 2 has been loaded by a tensile force of 270 kN applied in one minute (F = 135 kN). In this experiment, this load was also just under the elastic limit of the connection. The moisture content of wood was 12% at the beginning of the calculation and remained constant. The parameters for *Norway spruce* have been used in the analysis (Appendix 1).

Figure 14 shows Sjödin's results and the results obtained from the present study. Sjödin used a 2D elastic analysis and found a good agreement with his experimental results. The experimental results have been obtained by using the ARAMIS-System: a camera measures the strains on the wood surface. The 3D numerical analysis has been done using the 3D model for wood developed in this study and the results are also in good agreement with the experimentation.

Figure 15 shows a 3D view of the loaded numerical model. As for the connection type 1 (Figure 13), it shows that the strains perpendicular to grain on the studied surface are lower than in the inner part of the connection.

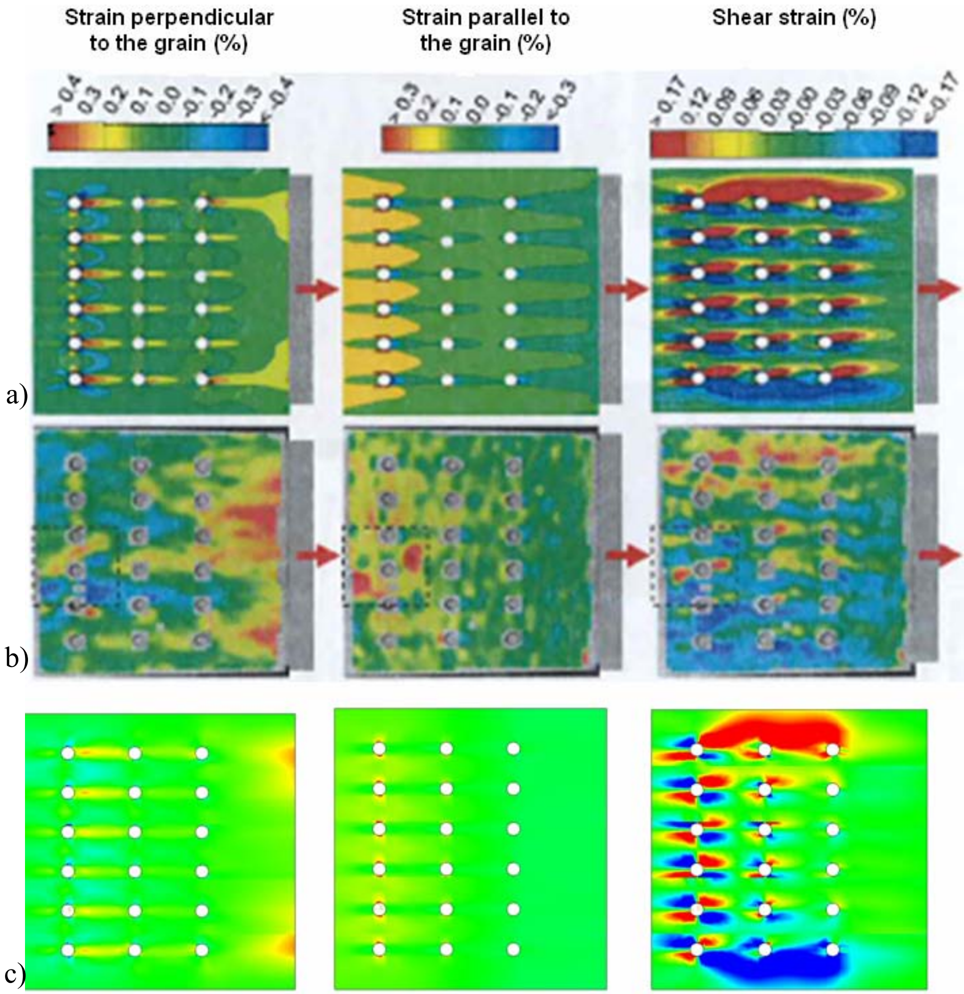


Figure 14. Strains for test 2: a) 2D Calculated results by Sjödin (2008), b) experimental results by Sjödin (2008), b) 3D Calculated results.

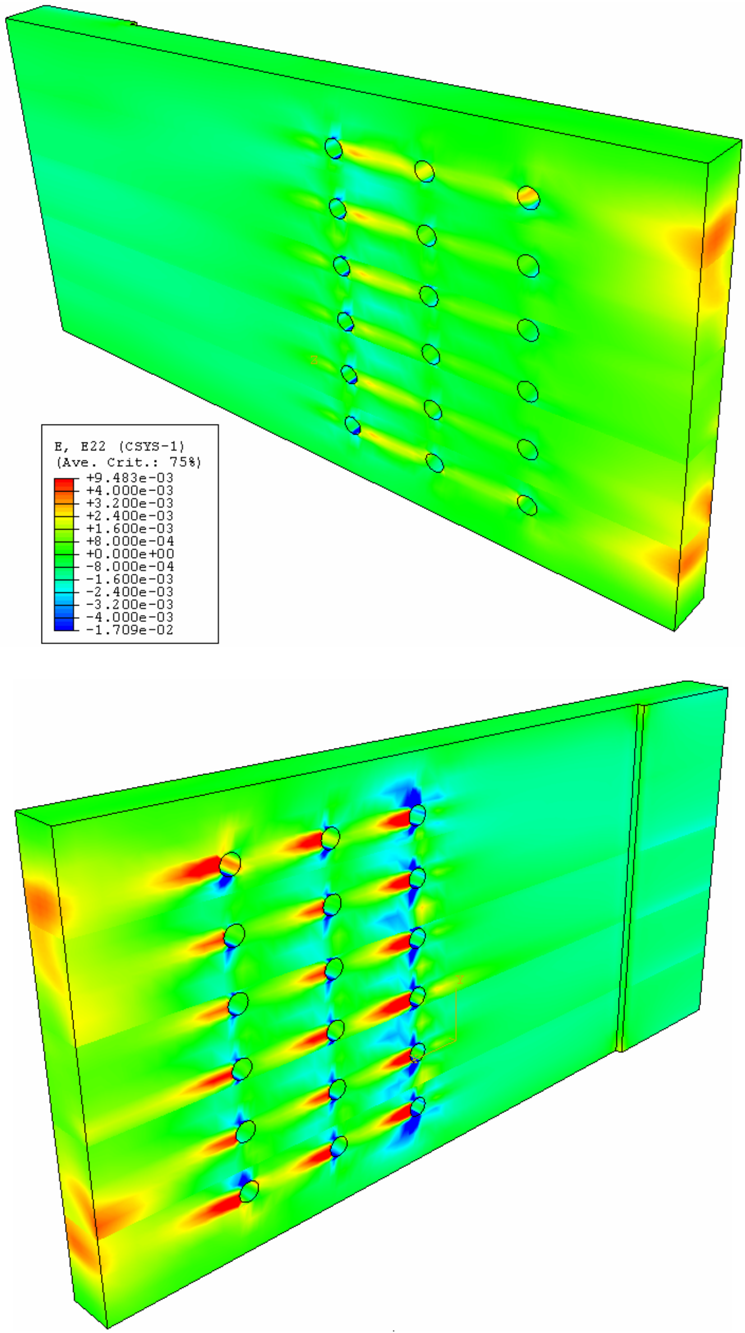


Figure 15. 3D views of the strains perpendicular to grain: outside view (top), inside view (bottom).

5. Effect of moisture changes on a dowel connection

The connection type 1 has been used here as a first approach to study the effect of moisture changes in connections.

5.1 Simple drying and wetting cases

Figure 16 shows the load cases applied to connection 1. The initial moisture content of wood was 12%. The connection has been loaded with a constant 7kN tensile load (F = 3.5kN) which corresponds to 25% of the experimental elastic limit of the connection. The connection has been exposed to a one month linearly changing relative humidity from RH65% to RH35% for the drying case, from RH65% to RH95% for the wetting case. The parameters for *Norway spruce* have been used in the analysis (Appendix 1).

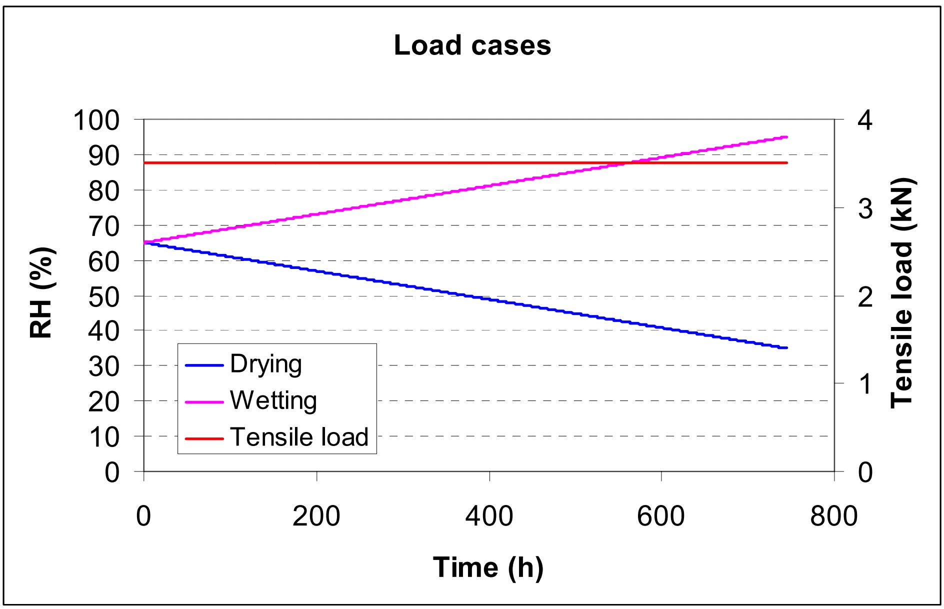


Figure 16. Simple load cases of drying (RH65%–RH35%) and wetting (RH65%–RH95%) under constant tensile load.

Figure 17 shows the stress state of the connection after one month. It shows that the moisture changes increase the stresses values and change their distribution in the connection.

Figure 18 shows the results obtained for the drying case, the wetting case and a constant moisture content case. The stresses are given in four points around the dowel hole in function of the time. The selected points are taken at around 7mm from the surface of wood to avoid the possible errors due to edge effects.

The dotted lines symbolise the characteristic values given for glulam beams (GL28c) in Eurocode 5 (see Table 1). They are presented here just for reference and show that these values can be reached in case of moisture changes.

Table 1. Characteristic values for glulam beams GL28c (Eurocode 5 2002).

Tension strength parallel to grain	16.5 MPa
Tension strength perpendicular to grain	0.4 MPa
Compression strength parallel to grain	24 MPa
Compression strength perpendicular to grain	2.7 MPa
Shear strength	2.7 MPa

In both the drying and the wetting cases, the stresses are strongly increased in magnitude by the moisture changes. Especially for the stresses perpendicular to grain, the characteristic values are far exceeded. The stresses parallel to grain are still below the characteristic value range. The characteristic shear strength (in the plan longitudinal-vertical) is reached in point 4.

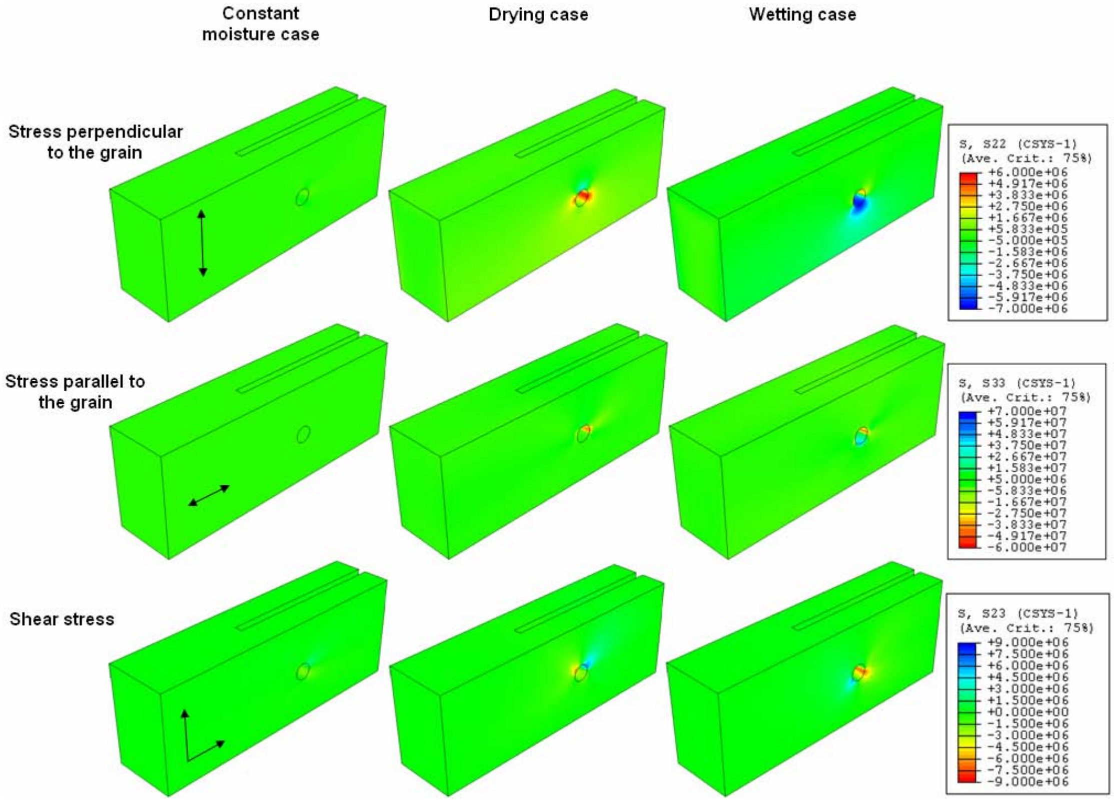
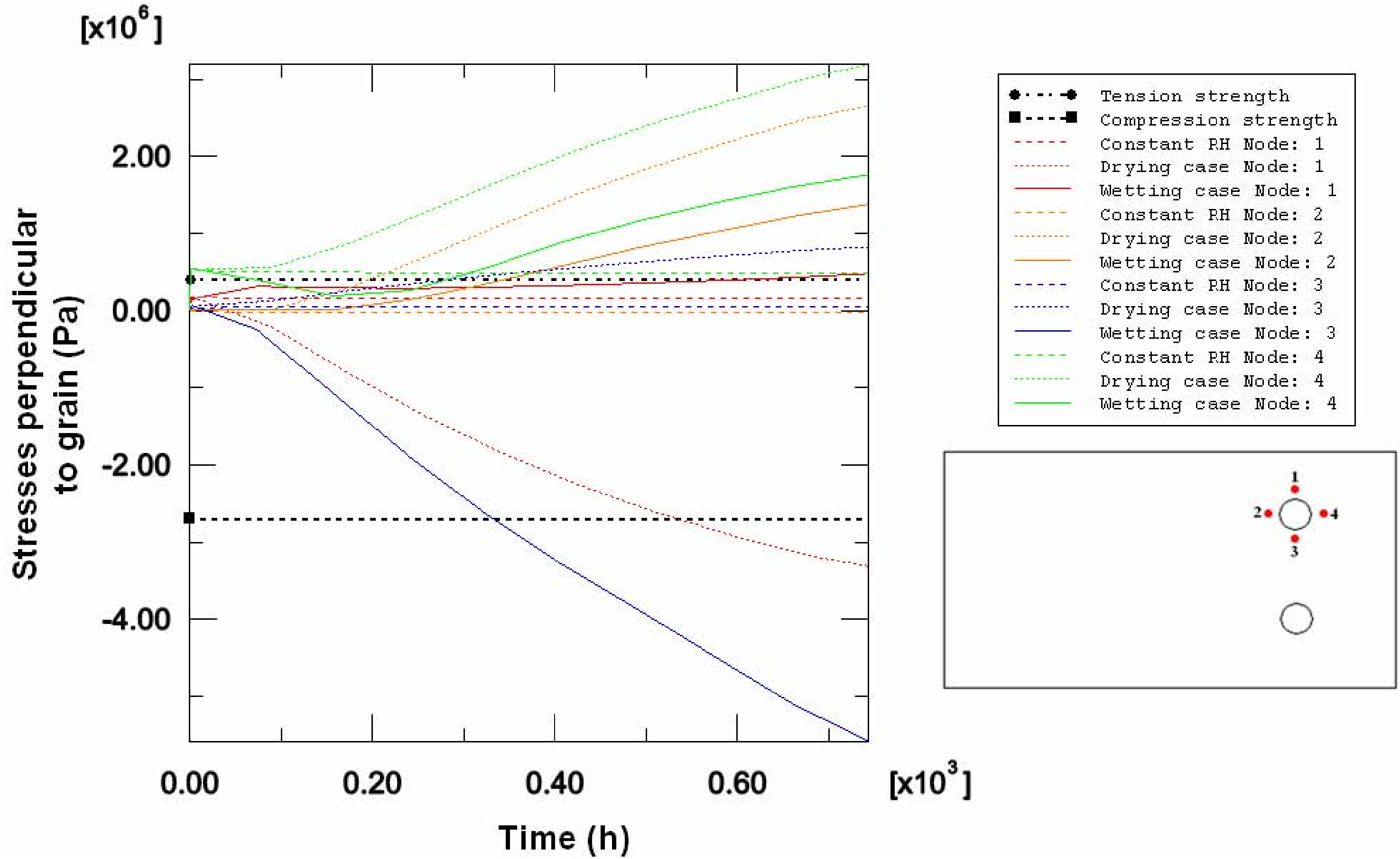
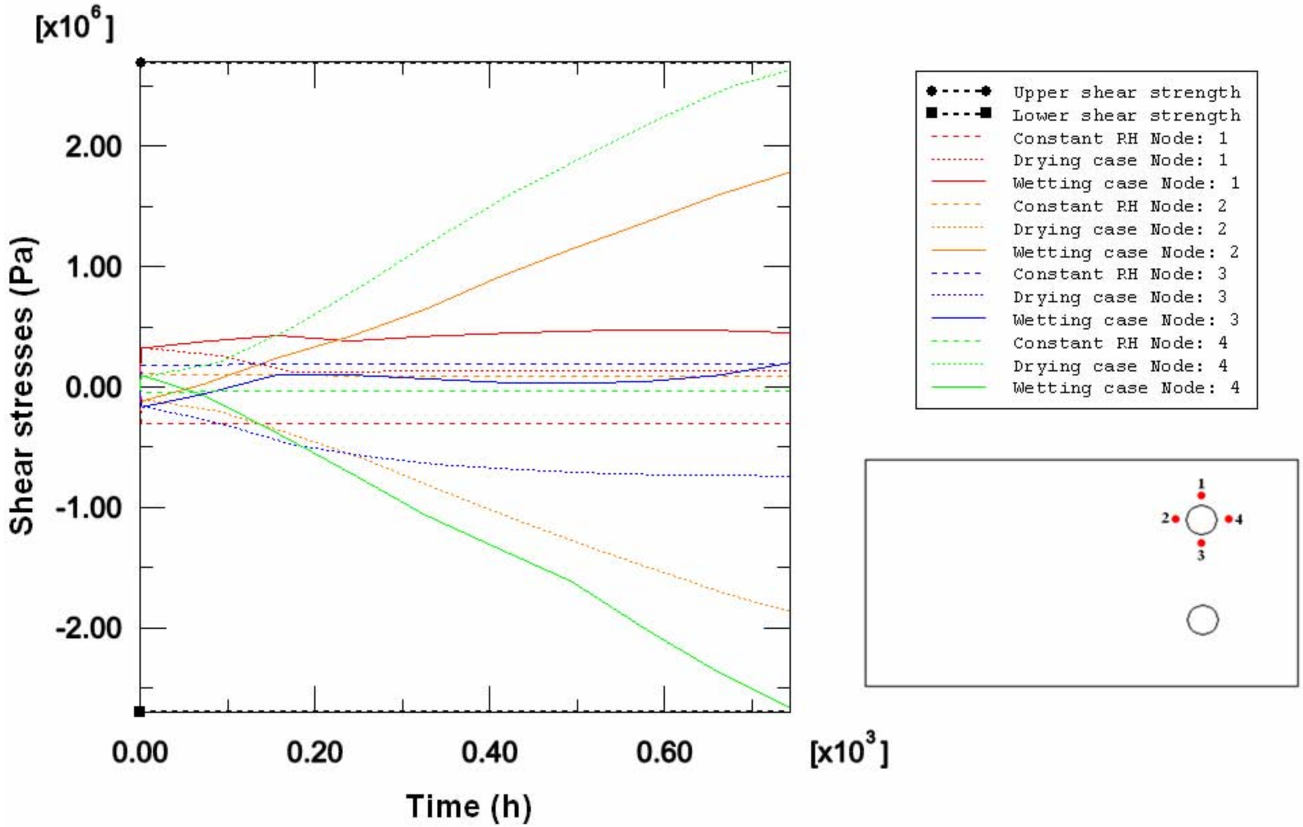


Figure 17. Stress state of the connection after one month in case of constant moisture content, drying and wetting with a tensile load (results in Pa).


[x10^6]
2.00
0.00
-2.00
-4.00
Stresses perpendicular to grain (Pa)
0.00
0.20
0.40
0.60
[x10^3]
Time (h)
Tension strength
Compression strength
Constant RH Node: 1
Drying case Node: 1
Wetting case Node: 1
Constant RH Node: 2
Drying case Node: 2
Wetting case Node: 2
Constant RH Node: 3
Drying case Node: 3
Wetting case Node: 3
Constant RH Node: 4
Drying case Node: 4
Wetting case Node: 4
1
2
3
4


[x10^6]
2.00
1.00
0.00
-1.00
-2.00
Shear stresses (Pa)
0.00
0.20
0.40
0.60
[x10^3]
Time (h)
Upper shear strength
Lower shear strength
Constant RH Node: 1
Drying case Node: 1
Wetting case Node: 1
Constant RH Node: 2
Drying case Node: 2
Wetting case Node: 2
Constant RH Node: 3
Drying case Node: 3
Wetting case Node: 3
Constant RH Node: 4
Drying case Node: 4
Wetting case Node: 4
1
2
4
3

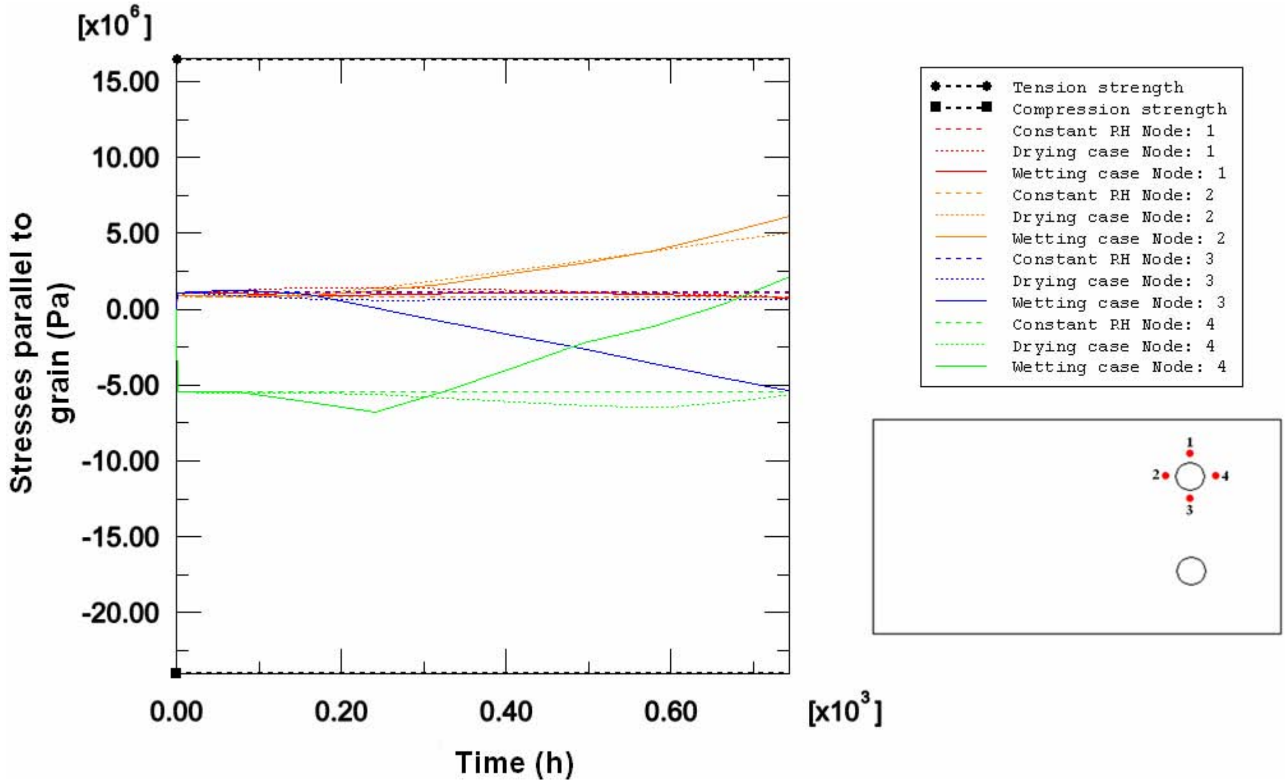


Figure 18. Calculated stresses in wood in four nodes around a hole.

5.2 Natural relative humidity conditions: indoor conditions

Figure 19 shows a natural load case applied to connection 1. The initial moisture content of wood was 12%. The connection has been loaded with a constant 7 kN tensile load (F = 3.5 kN) which corresponds to 25% of the experimental elastic limit of the connection. The connection has been exposed to conditions that have been measured during one year of relative humidity. This has been measured in the Sibelius hall (Finland) by Koponen (2002). The start of the test corresponds to the beginning of July. The parameters for *Norway spruce* have been used in the analysis (Appendix 1).

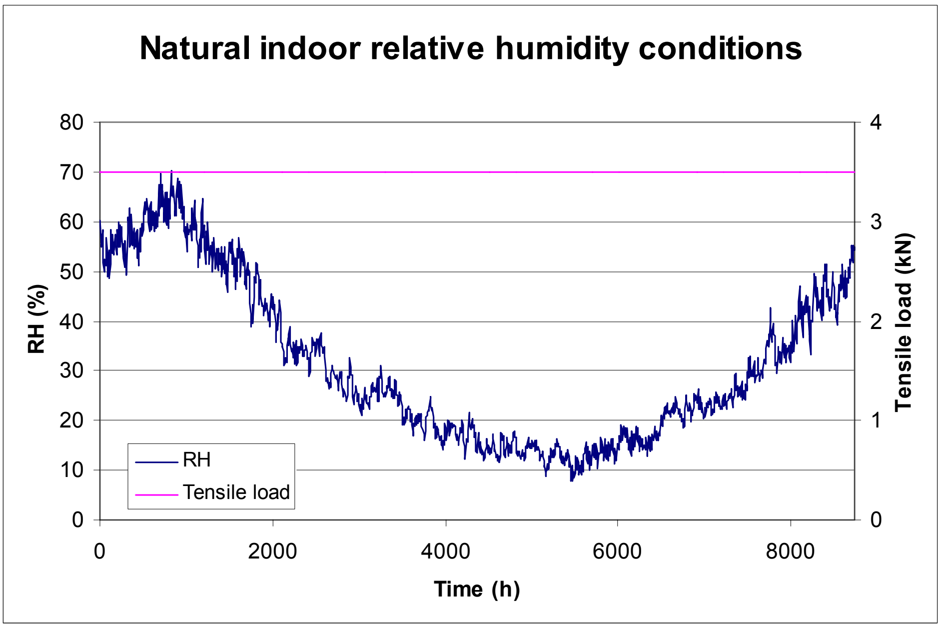


Figure 19. Applied natural indoor relative humidity conditions under constant tensile load.

Figure 20 shows the stress state of the connection at time 5550 hours, which corresponds to the middle of winter. It shows that the moisture changes increase the stress values and change their distribution in the connection.

Figure 21 shows the stresses in four points around the dowel hole in function of the time. The selected points are taken at around 7 mm from the surface of wood to avoid the possible errors due to edge effects. The strengths in Figure 21 are the characteristic values given for glulam beams (GL28c) in the Eurocode 5 (see Table 1). They are presented here just for reference.

The results show that the stresses are strongly influenced by the moisture changes. The stresses perpendicular to grain exceed the characteristic values during all the winter time, which corresponds to the time when the building is heated. This is the time of the year when the loading is also high due to snow loads. The stresses parallel to grain are still below the characteristic values range. The characteristic shear strength (in the plan longitudinal-vertical) is reached in point 2 and 4 during a part of the winter time. It is important to point out that these results depend on the used constitutive model (Mirianon et al. 2008).

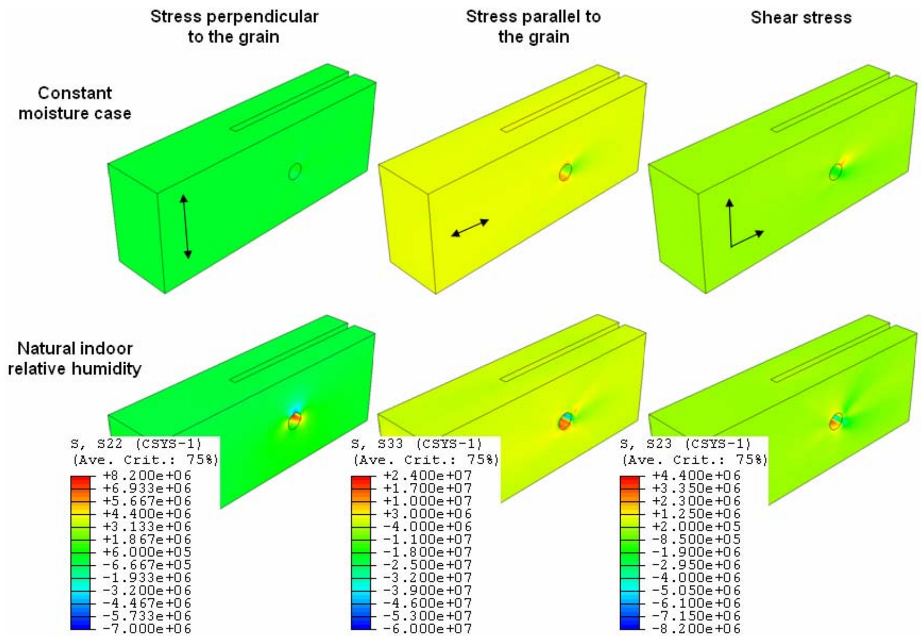
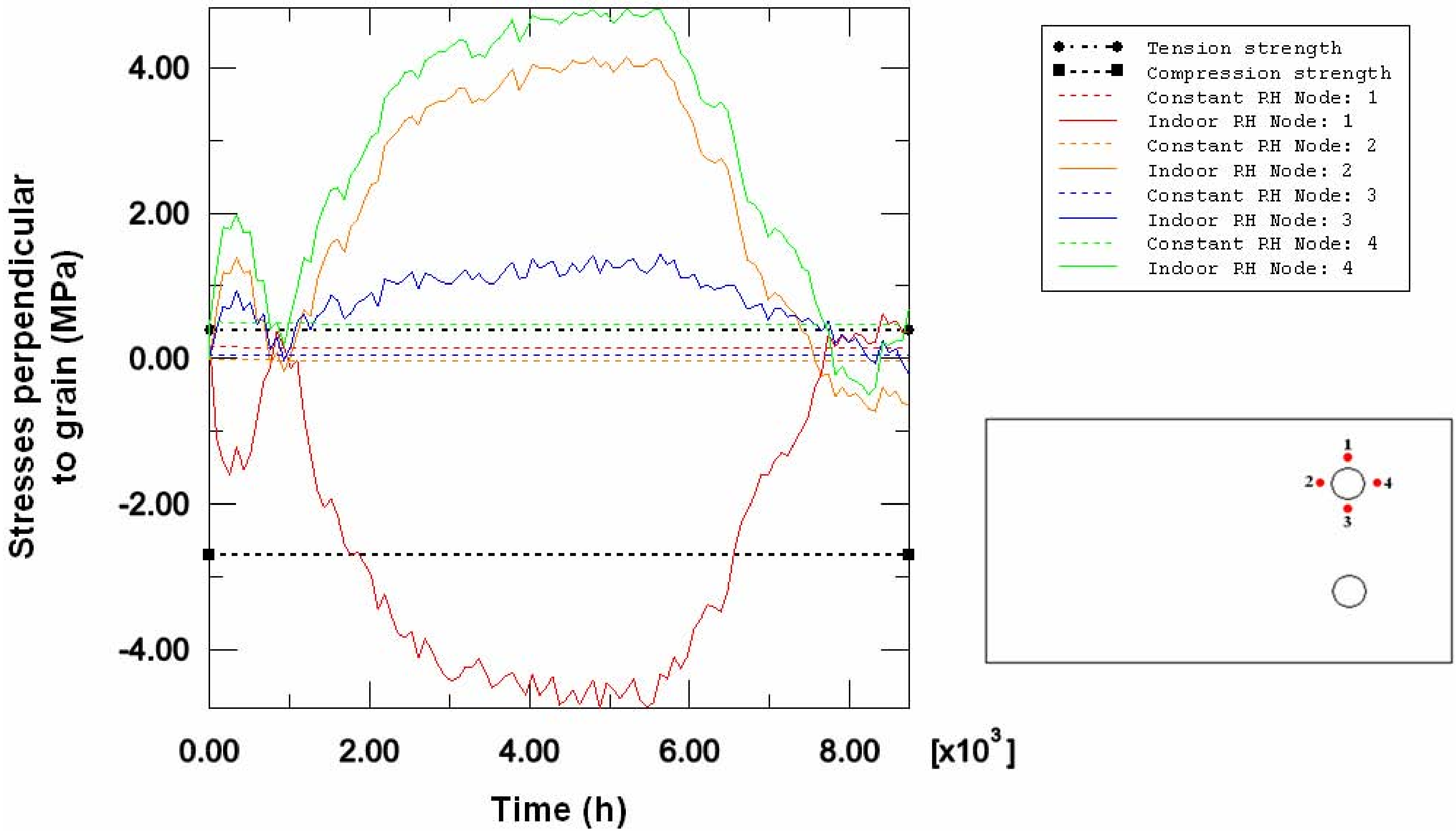
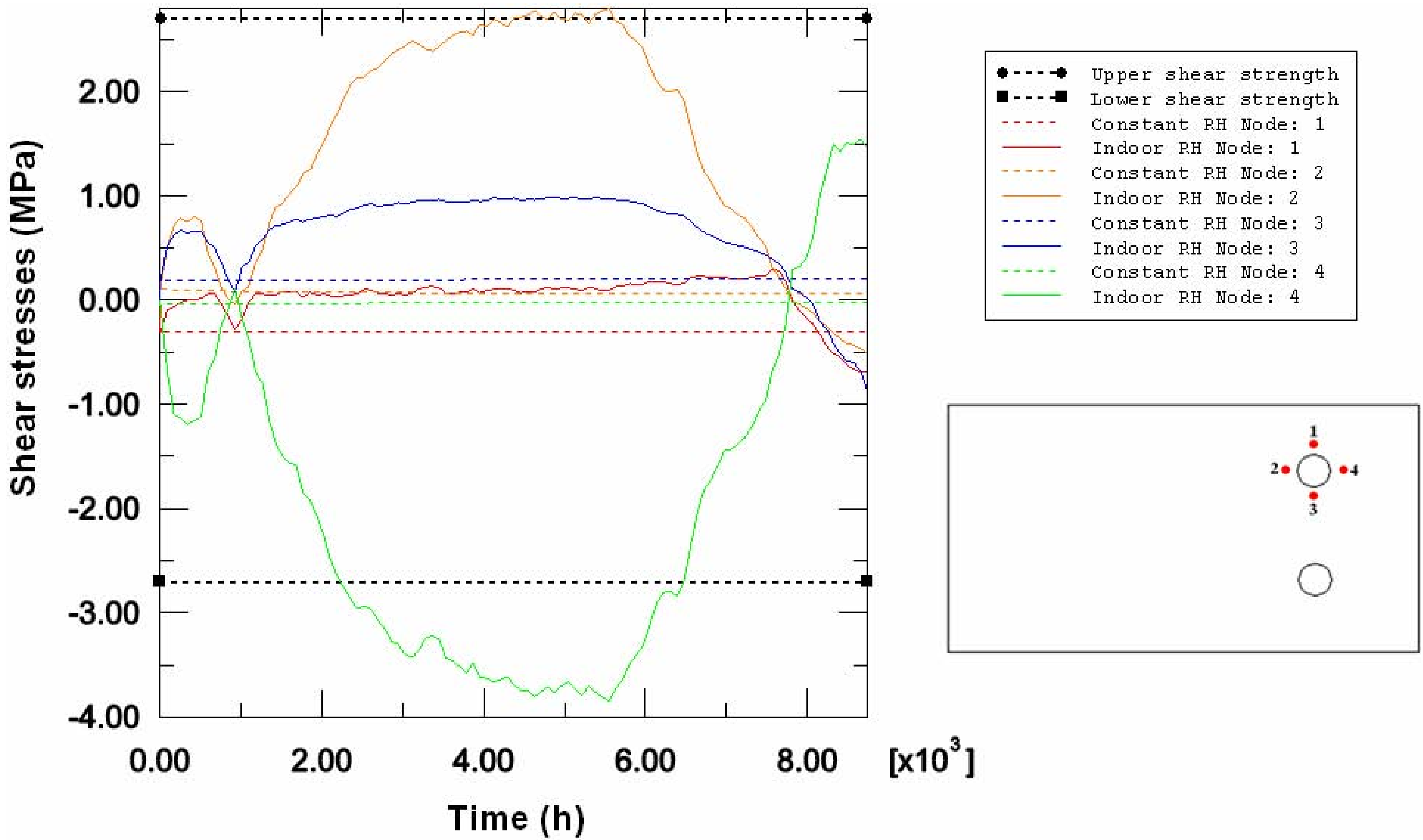


Figure 20. Stress state of the connection at time 5550 hours in case of constant moisture content and natural indoor relative humidity (results in Pa).



Stresses perpendicular to grain (MPa)
4.00
2.00
0.00
-2.00
-4.00
0.00
2.00
4.00
6.00
8.00
[x10^3]
Time (h)
Tension strength
Compression strength
Constant RH Node: 1
Indoor RH Node: 1
Constant RH Node: 2
Indoor RH Node: 2
Constant RH Node: 3
Indoor RH Node: 3
Constant RH Node: 4
Indoor RH Node: 4
1
2
3
4


Shear stresses (MPa)
2.00
1.00
0.00
-1.00
-2.00
-3.00
-4.00
0.00
2.00
4.00
6.00
8.00
[x10^3]
Time (h)
Upper shear strength
Lower shear strength
Constant RH Node: 1
Indoor RH Node: 1
Constant RH Node: 2
Indoor RH Node: 2
Constant RH Node: 3
Indoor RH Node: 3
Constant RH Node: 4
Indoor RH Node: 4
1
2
3
4

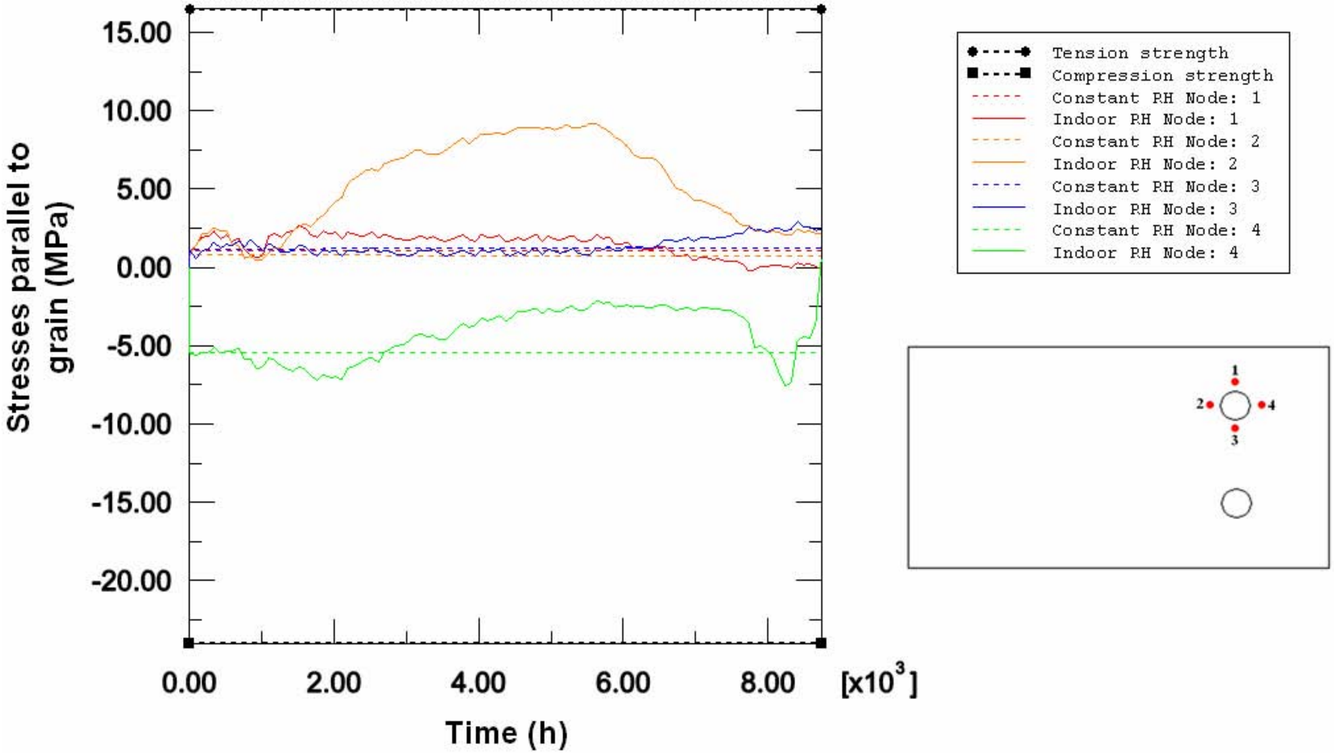


Figure 21. Calculated stresses in wood in four nodes around a hole, test done under natural indoor relative humidity.

5.3 Conclusions from the analysis

The calculations have shown that the stresses are strongly increased by the moisture changes. On the basis of the used constitutive model (Mirianon et al. 2008), the stresses perpendicular to grain in many cases exceed the characteristic values, especially during the winter time, when the building is heated. The shear stresses also exceed the characteristic values but not as significantly. The stresses parallel to grain are comparably less significant when compared to characteristic values, at least for this test.

The stress distributions presented here for a natural environment, in particular the stresses perpendicular to grain in points 2 and 4, could easily cause a splitting of the wood and this could lead to further failures.

6. Modeling of a dowel type connection with glued-in rods reinforcement

Glued-in rods and screws are sometimes used to reinforce connections in wood structures. They can prevent from crack propagation by taking a part of the stresses perpendicular to the grain. The aim of this analysis is to compare the stress distributions with and without glued-in rods.

6.1 Description of the analyzed connection

Figure 22 shows the steel-to-timber joint (connection type 3) with glued-in rods reinforcement which is modeled. The rods have a 6 mm diameter. The numerical model (Figure 23) uses a symmetry plan to limit the number of elements (7208 elements). The simulations use ABAQUS 6.5-3 and are run with ABAQUS/Standard. The hexagonal 3D elements C3D8T have been used to mesh the wood part and the hexagonal 3D elements C3D8 have been used to mesh the steel plate, the dowel and the rods. A 0.1 mm gap has been added between the dowel and the wood, between the dowel and the steel plate, and between the steel plate and the wood in order to help the convergence of the calculation. The contacts have been modeled by a hard contact pair with a penalty method in the tangential direction using a 0.4 penalty factor. It uses a “small sliding” option and an “adjust slaves nodes in set” option. The contact between rods and wood is modeled by a tie constraint. The rheological model of wood is implemented in a UMAT subroutine. The moisture flow is implemented in a DFLUX subroutine. The applied tension load is 3.5 kN. The parameters for *Norway spruce* have been used in the analysis (Appendix 1).

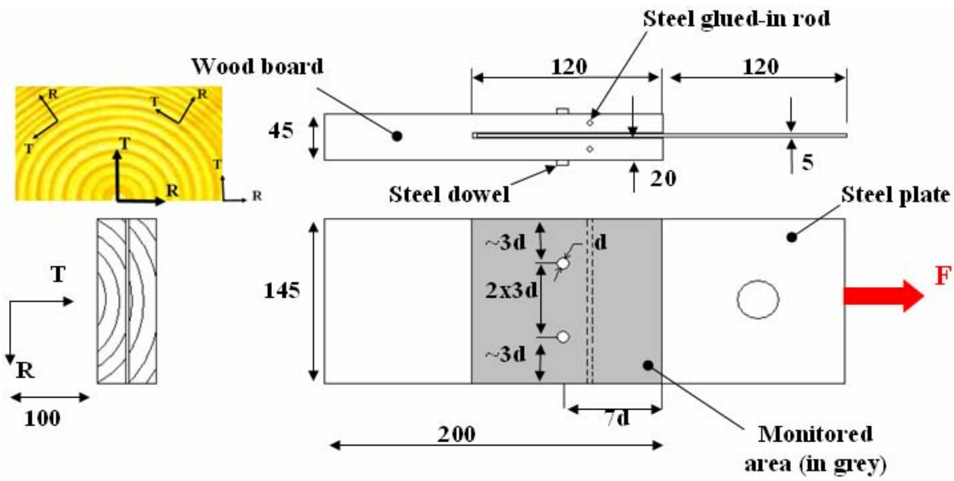


Figure 22. Scheme of the steel-to-timber connection type 1, dimensions in millimeters (d = 12 mm, F = 3.5 kN).

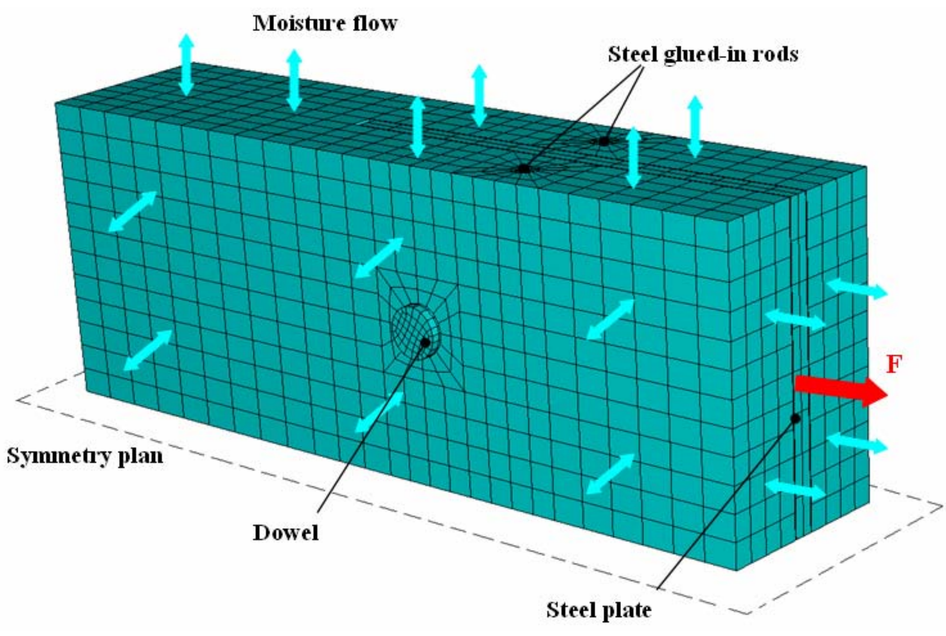


Figure 23. Numerical model of the steel-to-timber connection type 1 done with ABAQUS CAE.

6.2 One month drying and wetting analysis

The connection described above (Figures 22 and 23) has been exposed to drying and wetting conditions (see section 5.1). Figure 24 shows the stresses perpendicular to grain in both drying and wetting conditions with and without glued-in rods. The results show that the stresses perpendicular to grain are decreased when the connection is reinforced with glued-in rods, especially around the hole.

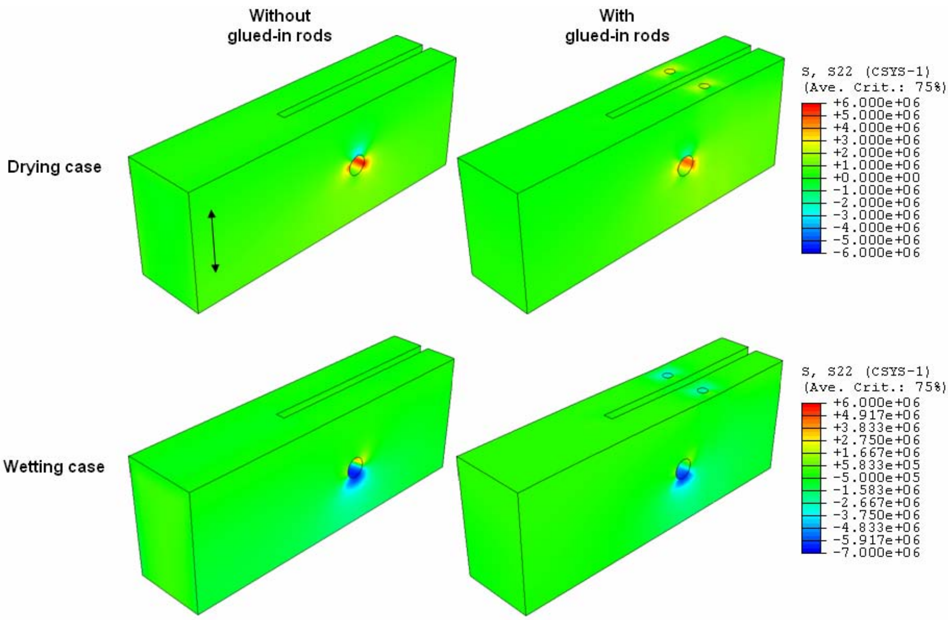


Figure 24. Stresses perpendicular to grain in a 2 dowels connection in drying and wetting conditions without and with glued-in rods (results in Pa).

6.3 Natural relative humidity conditions: outdoor conditions

Figure 25 shows the moisture load case applied to the connection 3. The initial moisture content of wood was 12%. The connection has been loaded with a constant 7 kN tensile load (F = 3.5 kN) which corresponds to 25% of the experimental elastic limit of the connection without glued-in rods. The connection has been exposed to a measured one year outdoor relative humidity cycle which has been determined by Koponen (2002). The beginning of the test corresponds to January.

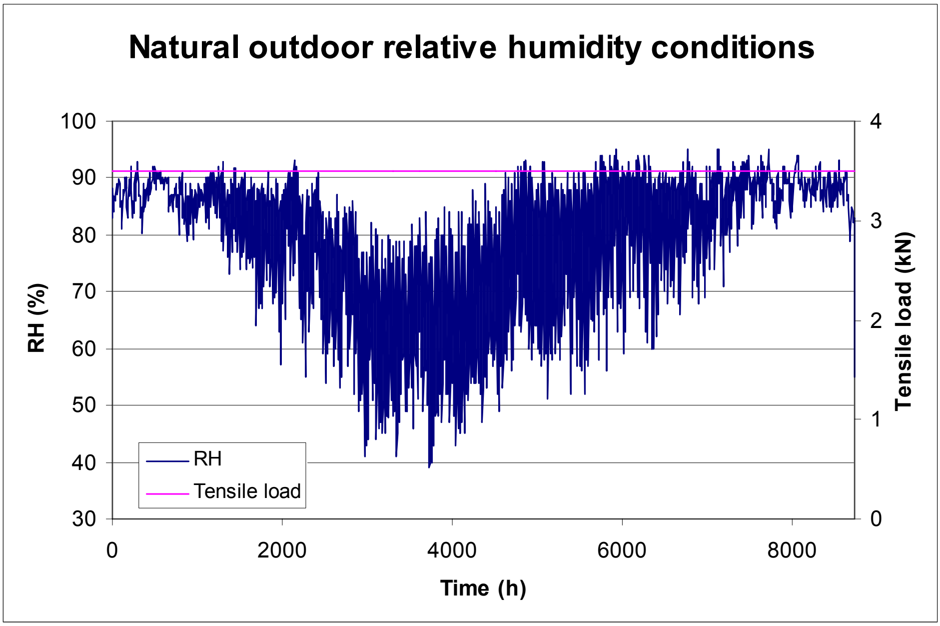


Figure 25. Applied natural outdoor relative humidity conditions under constant tensile load.

Figure 26 shows a 3D view of the stresses perpendicular to grain with and without glued-in rods at 2 different times of the calculation. Time 3230 hours is in summer time: the moisture content of wood decreases during this period of the year. Time 8000 hours is in winter time: the moisture content of wood increases during this period of the year.

The results show a difference in the stresses in the connection with and without glued-in rods. Nevertheless, it is not easy to say if the effect is beneficial based on these pictures.

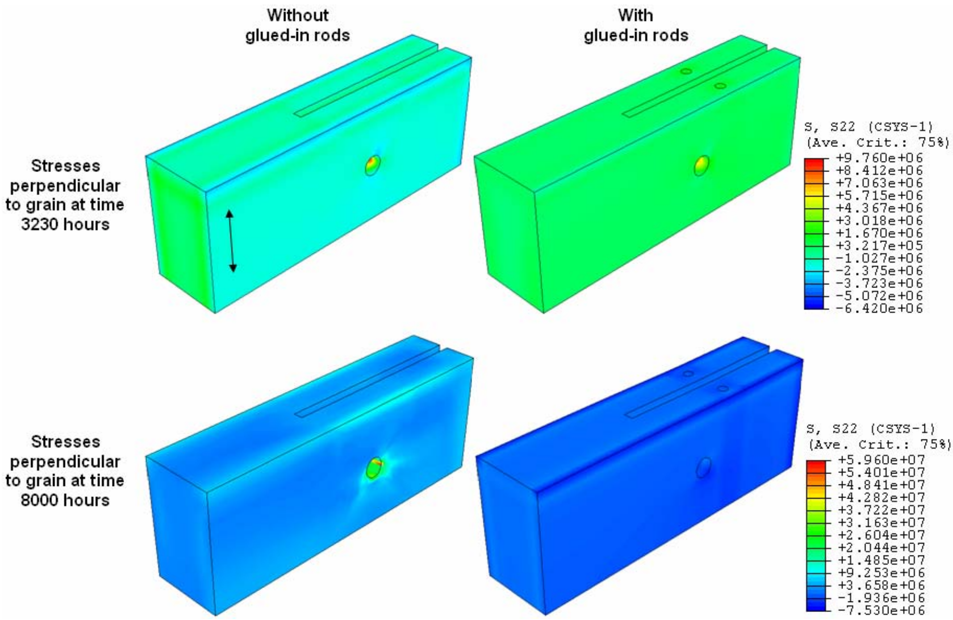
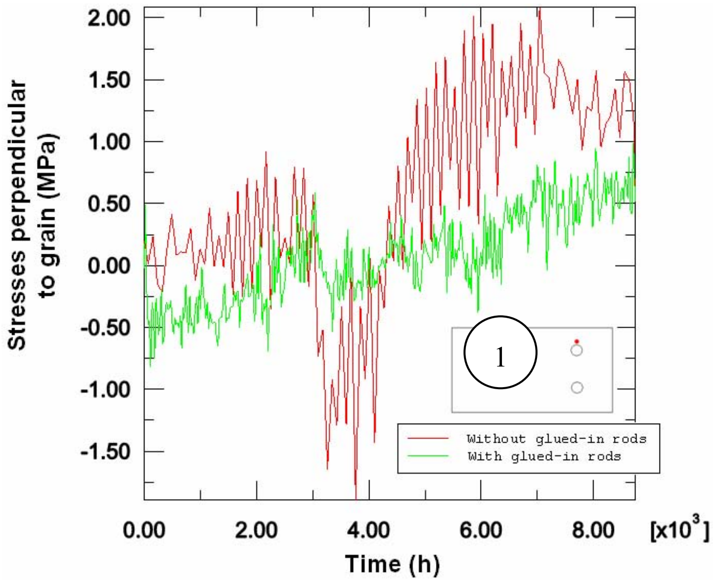
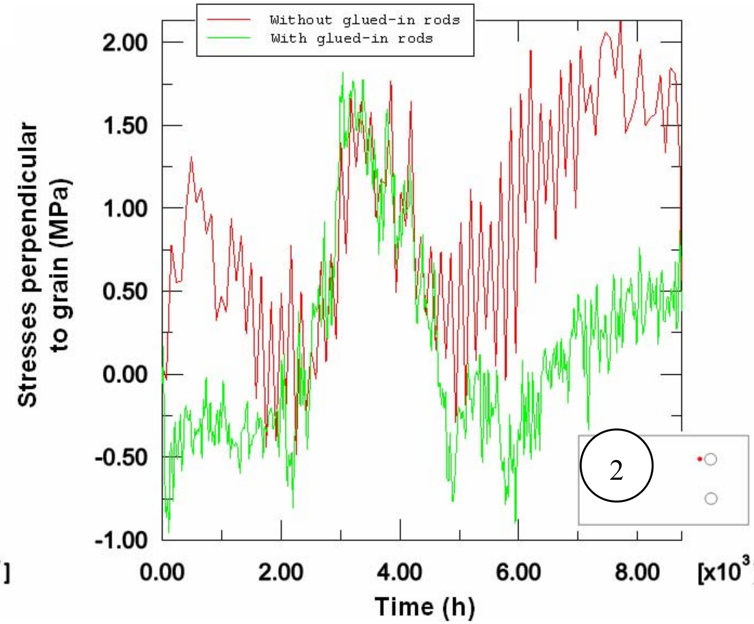


Figure 26. Stresses perpendicular to grain in a 2 dowels connection in outdoor conditions without and with glued-in rods at time 3230 h and 8000 h (results in Pa).

Figure 27 shows the stresses perpendicular to grain in 4 points around the hole in function of the time. The selected points are taken at around 7 mm from the surface of wood to avoid the possible errors due to edge effects.

It appears that, by using the constitutive model previously proposed (Mirianon et al. 2008), the stresses are changed around the hole in presence of glued-in rods, especially in points 1, 2 and 4. In point 3 the presence of the glued-in rods seems not to have any effect on the stresses. An interesting effect is that a big part of the tension stresses are converted to compression stresses. This is of importance because the strength in the direction perpendicular to the grain is much higher in compression than in tension.


Stresses perpendicular to grain (MPa)
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.50
0.00
2.00
4.00
6.00
8.00
[x10^3]
Time (h)
1
Without glued-in rods
With glued-in rods


Without glued-in rods
With glued-in rods
Stresses perpendicular to grain (MPa)
2.00
1.50
1.00
0.50
0.00
-0.50
-1.00
0.00
2.00
4.00
6.00
8.00
[x10^3]
Time (h)
2

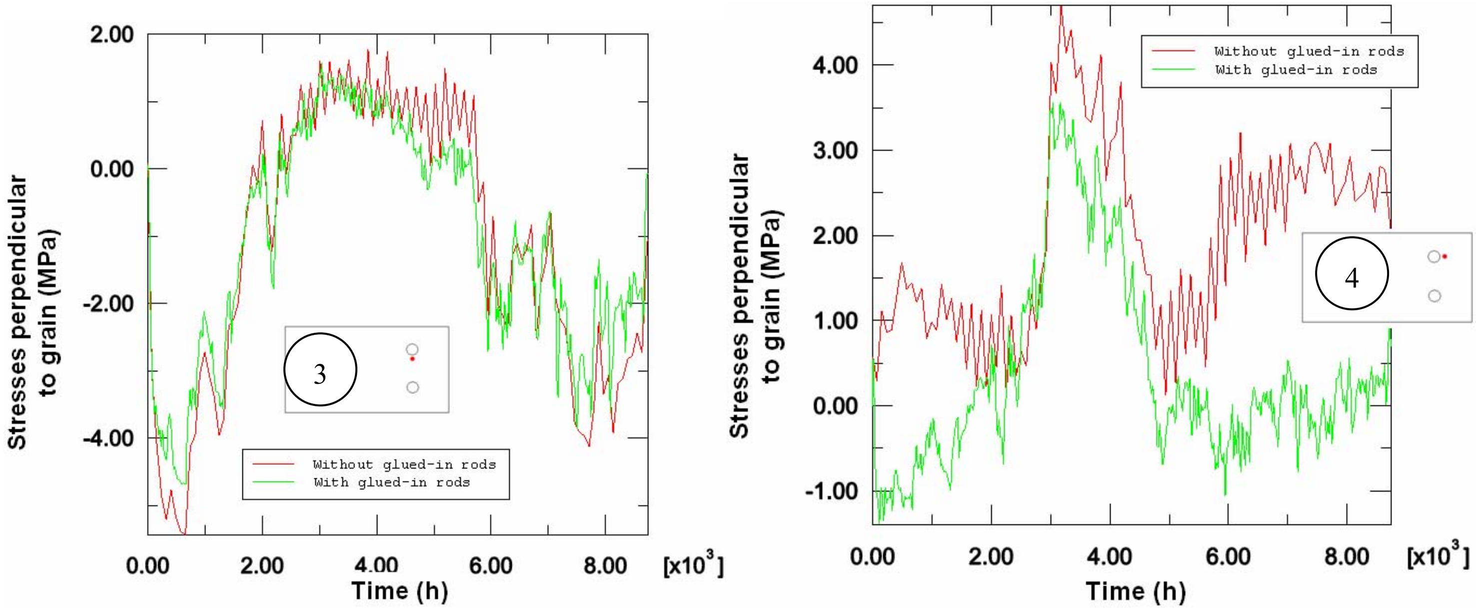


Figure 27. Calculated stresses perpendicular to the grain in wood in four nodes around a hole, connection without glued-in rods in red, connection with glued-in rods in green, test done under natural outdoor relative humidity.

7. Friction effect in a single dowel connection

Sjödin (2008) studied single dowel connections under tensile loads in grain direction with the objective to determine the effect of friction between the dowel and the surrounding wood on the load-bearing capacity of the joint. In the present study, the tensile test done by Sjödin has been reproduced in constant moisture conditions using ABAQUS/Standard and the 3D rheological model developed previously in this study.

7.1 Description of the analysed connection

Figure 28 shows single dowel joint modeled. The dowel has a 20 mm diameter. The simulations use ABAQUS 6.5-3 and are run with ABAQUS/Standard. The numerical model (Figure 29) uses 9880 elements. The hexagonal 3D elements C3D8T have been used to mesh the wood part and the hexagonal 3D elements C3D8 have been used to mesh the dowel. A 0.1 mm gap has been added between the dowel and the wood in order to help the convergence of the calculation. The contacts have been modeled by a hard contact pair with a penalty method in the tangential direction using a 0.1 and then a 0.4 penalty factor. A "small sliding" option and an "adjust slaves nodes in set" option are used. The tensile load is applied as a pressure on the dowel surface. The rheological model of wood is implemented in a UMAT subroutine. The elastic properties for *Scots Pine* selected by Sjödin have been used in the analysis (Table 2), the parameters related to the viscoelasticity and mechanosorption are given in Appendix 1.

Table 2. Elastic properties for Scots Pine *(Dinwoodie 1979, Sjödin 2008).*

Direction	Young's modulus (MPa)	Shear modulus (MPa)	Poisson's ratio (-)
Radial direction (R)	E_R = 1 100	G_{RT} = 66	v_{RT} = 0.558
Tangential direction (T)	E_T = 570	G_{RL} = 1 160	v_{RL} = 0.038
Grain direction (L)	E_L = 16 300	G_{TL} = 680	v_{TL} = 0.015

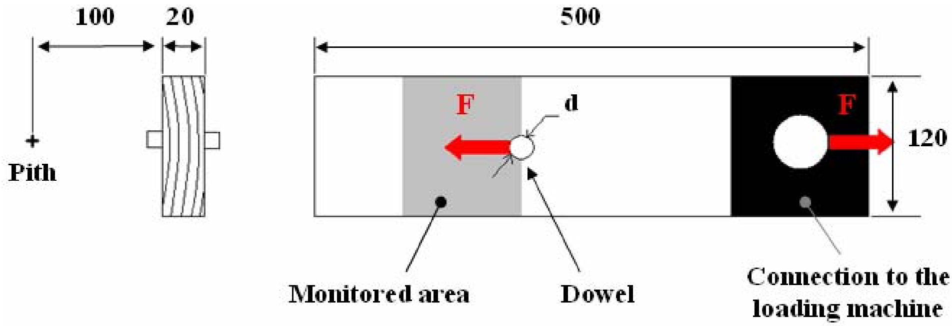


Figure 28. Scheme of the connection, dimensions in millimetres (d = 20 mm).

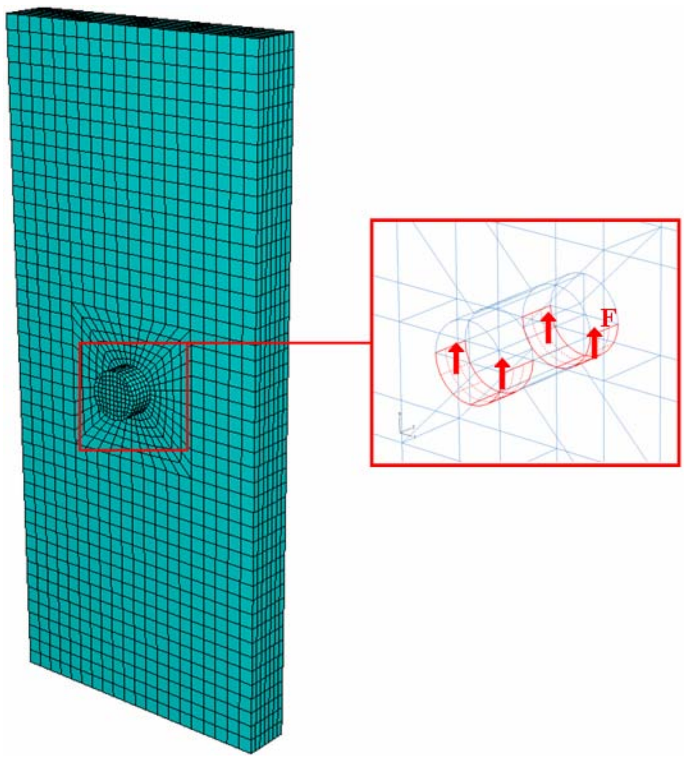


Figure 29. Numerical model of the connection done with ABAQUS CAE, the tension load is applied as a pressure on the dowel surface.

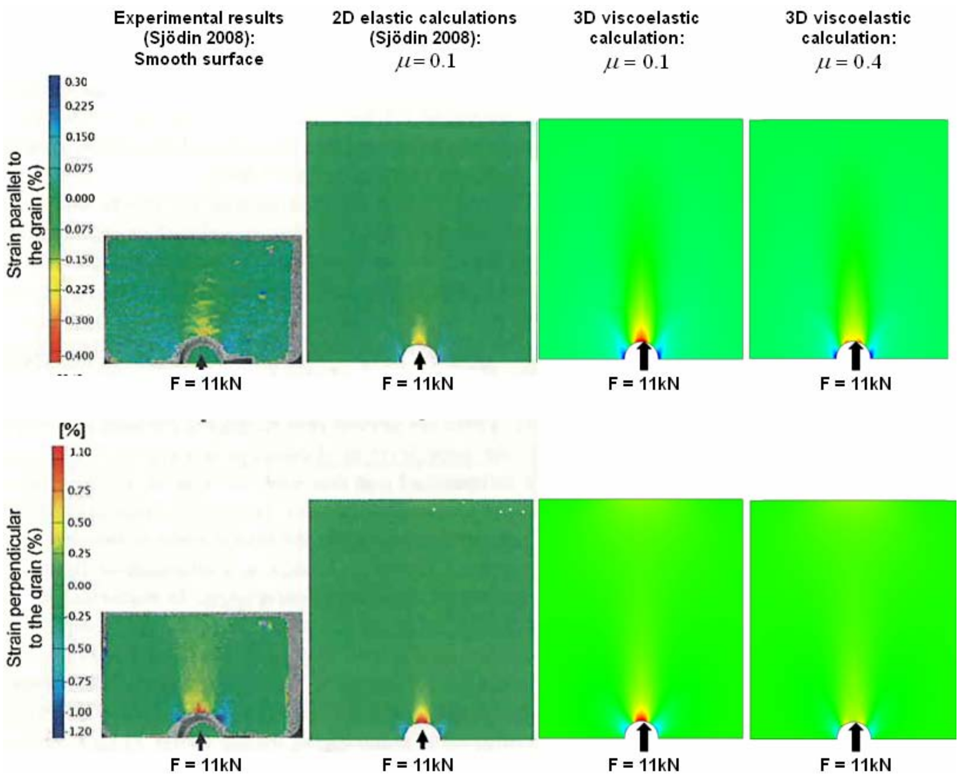


Figure 30. Comparison between experimental results obtained by Sjödin (2008) and numerical result, F = 11 kN, μ is the friction coefficient used for the calculations.

Figure 30 shows the strains found for a 11 kN tensile load. It first shows the results obtained by Sjödin (experimentally and by 2D calculation) and the results obtained by the 3D calculation conducted in the present study. The 3D calculations are in good agreement with the experimentation. A higher friction coefficient seems to have a positive effect by decreasing the strains.

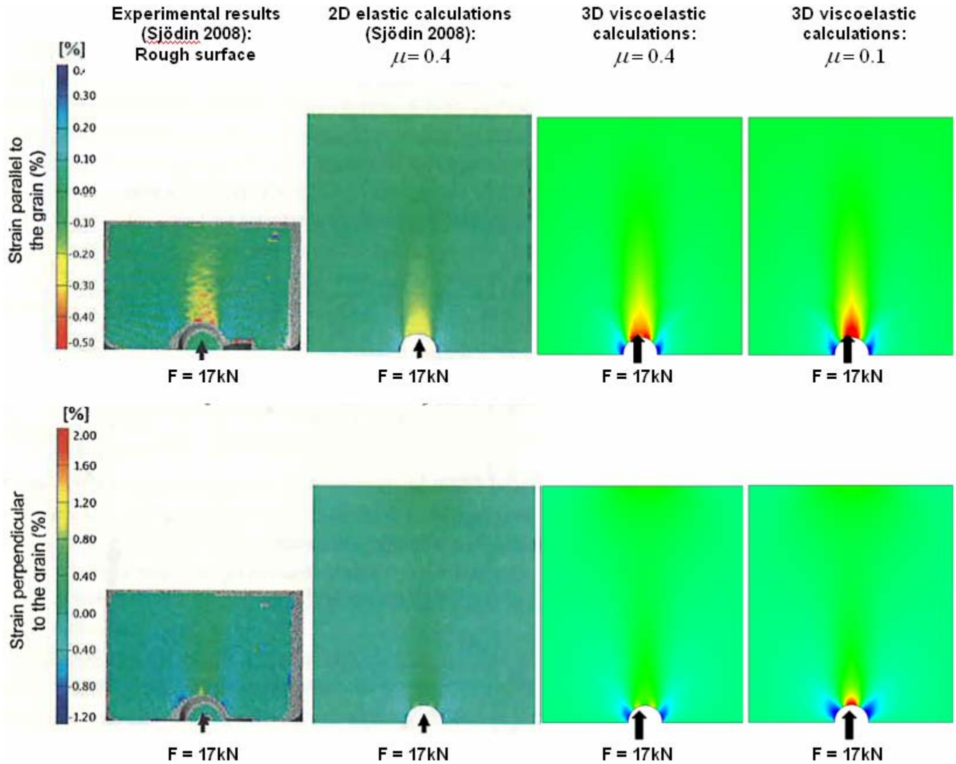


Figure 31. Comparison between experimental results obtained by Sjödin (2008) and numerical result, F = 17 kN, μ is the friction coefficient used for the calculations.

Figure 31 shows the strains found for a 17 kN tensile load. It first shows the results obtained by Sjödin (experimentally and by 2D calculation) and the results obtained by the 3D calculation. The 3D calculations are in good agreement with the experimentation. A higher friction coefficient seems to have a positive effect also in this case by decreasing the strains.

8. Conclusions

Earlier experience has shown that connections in general are often involved in the collapsing of wood structures. It appears that in some of these failure cases, the changes of moisture content in wood is the main reason of the connection's failure. In order to understand the effect of moisture in wood, some dowel connections have been modeled in ABAQUS using a rheological model for wood taking into account the time, the moisture content of wood and load case. Some experimental tests under constant moisture content have been modeled numerically and the numerical results seem to be in good agreement with the experiments. Variable relative humidity conditions have been applied for two dowels connections. The results have showed that the variations of moisture content in wood can strongly increase the stresses, especially in the direction perpendicular to the grain. The same connection has been modeled with glued-in rods. It appears that the presence of glued-in rods affects the stresses around the holes and most of the tension stresses are converted into compression stresses. A one dowel connection has been modeled to study the influence of the friction coefficient between wood and steel on the crack appearance. The results show that the higher the friction coefficient is, the smaller the strains perpendicular to grain are.

This study is a first step in the modeling of connection. The results presented depend on the proposed constitutive model and can only be used qualitatively at the current state-of-art. A further experimental and numerical investigation is needed in order to obtain quantitative results which could be used as a basis for better design for moisture related actions.

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Appendix 1

Table 1. Material properties used in the analysis.

Property number	Notation	Meaning	Value for spruce	Value for pine	Unit
1	$E_{r,ref}$	Elastic moduli at the reference configuration	600	900	MPa
2	$E_{t,ref}$		600	500	MPa
3	$E_{z,ref}$		12 000	12 000	MPa
4	ν_{rt}	Poisson's ratios	0.558	0.558	-
5	ν_{rz}		0.038	0.038	-
6	ν_{tz}		0.015	0.015	-
7	$G_{rt,ref}$	Shear moduli at the reference configuration	40	40	MPa
8	$G_{rz,ref}$		700	700	MPa
9	$G_{tz,ref}$		700	700	MPa
10	$\alpha_{u,r}$	Coefficient of moisture expansion	0.13	0.13	-
11	$\alpha_{u,t}$		0.27	0.27	-
12	$\alpha_{u,z}$		0.005	0.005	-
13	ρ_0	Density at initial moisture content	450	550	kg/m^3
14	T_0	Initial temperature	20	20	$^\circ C$
15	u_0	Initial moisture content	user	user	-
16	ρ_{ref}	Reference density	450	550	kg/m^3
17	T_{ref}	Reference temperature	20	20	$^\circ C$
18	u_{ref}	Reference moisture content	0.2	0.2	-
19	a_1	Parameter related to the density	0.0003	0.0003	m^3/kg
20	b_1	Parameter related to the temperature	-0.007	-0.007	1/$^\circ C$
21	c_1	Parameter related to the moisture content	-2.6	-2.6	-

22	τ_1^{ve}	Retardation of the viscoelastic element number 1	2.4	2.4	h
23	J_1^{ve}	Viscoelastic compliance of element 1 given as a factor of the elastic compliance	0.085	0.085	-
24	τ_2^{ve}		24	24	h
25	J_2^{ve}		0.035	0.035	-
26	τ_3^{ve}		240	240	h
27	J_3^{ve}		0.07	0.07	-
28	τ_4^{ve}		2400	2400	h
29	J_4^{ve}		0.2	0.2	-
30	τ_1^{ms}	Retardation of the mechanosorptive element number 1	0.01	0.01	-
31	$J_1^{ms,T}$	Compliance of the mechanosorptive element number 1 in tangential direction	0.0006	0.0006	1/MPa
32	$J_1^{ms,Z}$	Mechanosorptive compliance of element 1 in longitudinal direction given as a factor of the elastic compliance at reference configuration	0.035	0.035	-
33	τ_2^{ms}		0.1	0.1	-
34	$J_2^{ms,T}$		0.0006	0.0006	1/MPa
35	$J_2^{ms,Z}$		0.49	0.49	-
36	τ_3^{ms}		1	1	-
37	$J_3^{ms,T}$		0.005	0.005	1/MPa
38	$J_3^{ms,Z}$		0.175	0.175	-
39	m_v	Parameter for the irrecoverable part of mechanosorptive creep	0.066	0.066	1/MPa

Table 2. Diffusion values used in the analysis (derived from Hanhijärvi 1995 and Sjödin 2006).

Moisture content of wood [-]	Radial diffusion coefficient [m^2/h]	Tangential diffusion coefficient [m^2/h]	Longitudinal diffusion coefficient [m^2/h]
0	0.0003888	0.0003888	0.0009
0.05	0.0004751	0.0004751	0.00504
0.055	0.0004841	0.0004841	0.00535
0.07	0.0005137	0.0005137	0.00567
0.085	0.0005461	0.0005461	0.00585
0.09	0.0005572	0.0005572	0.00567
0.135	0.0006690	0.0006690	0.00454
0.18	0.0008026	0.0008026	0.00307
0.23	0.0009690	0.0009690	0.00210
0.28	0.0012029	0.0012029	0.00135

Series title, number and report code of publication

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Author(s)
Mirianon, Florian, Fortino, Stefania & Toratti, Tomi

Title

A method to model wood by using ABAQUS finite element software Part 2. Application to dowel type connections

Abstract

This report presents numerical analysis of dowel connections modeled in ABAQUS using a rheological model for wood taking into account loading time, moisture content of wood and the load case. Some experimental tests under constant moisture content have been modeled as well and the numerical results are in good agreement with the experiments. Variable relative humidity conditions have been applied to some connections. The results show that the variations of moisture content in wood can strongly increase the stresses in wood, especially in the direction perpendicular to the grain. The same connection has been modeled with reinforcement based on glued-in rods. It appears that the presence of glued-in rods affects the stresses around the holes and most of the tension stresses are converted into compression stresses. A one dowel connection has been modeled to study the influence of the friction coefficient between wood and steel on the crack appearance. The results have showed that the higher the friction coefficient is, the smaller the strains perpendicular to grain are.

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Project number
17546

Date	Language	Pages
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Commissioned by
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Keywords
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Julkaisun sarja, numero ja raporttikoodi

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Tekijä(t)

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Nimeke

Puun mallintaminen käyttäen ABAQUS-elementtimenetelmäohjelmistoa
Osa 2. Sovellus puurakenteen liitosten toimintaan

Tiivistelmä

Työssä mallitettiin puurakenteiden liitoksia erilaisissa kosteusolosuhteissa. Analyysi tehtiin ABAQUS-elementtimenetelmäohjelmistolla. Puun materiaalimalli esitellään aikaisemmassa julkaisussa, ja sitä on käytetty tässä sovellettuna liitosten toiminnan arviointiin. Kosteudella on merkittävä vaikutus puun jännityksiin liittimien ympäristössä. Poikittaisella liimatankovahvistuksella jännityksiä voidaan tosin pienentää. Myös liittimen ja puun välisellä kitkalla on huomattava vaikutus liitoksen mekaaniseen toimintaan.

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Julkaisuaika	Kieli	Sivuja
Syyskuu 2008	Englanti, suom. tiiv.	55 p. + app. 3 p.

Projektin nimi	Toimeksiantaja(t)
Improved glued wood composites – modeling and mitigation of moisture-induced stresses	Tekes, woodwisdom-net programme

Avainsanat	Julkaisija
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VTT PUBLICATIONS 690 A method to model wood by using ABAQUS finite element software. Part 2. Application...

The report presents some numerical analysis of dowel connections modeled in ABAQUS using a rheological model for wood which takes into account loading time, moisture content of wood and the load case. Moisture related actions on the connection seem to be highly significant. It seems that a natural variable humidity may induce splitting in wood. Perpendicular reinforcements hinder these effects.

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