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Moisture induced deformations in prefabricated wooden building modules

May-Linn Sortland

Preface

First of all, I would like to thank my supervisor Thomas K. Thiis, who has provided me with a lot of assistance, guidance and support. This thesis could not have been conducted without all of his help. I would also like to address my deepest gratitude to Dimitrios Kraniotis, who I feel has gone above and beyond in terms of availability, interest and enthusiasm, and Kristine Nore for introducing me to the problem and for being a great co-supervisor.

Last, but not least, I would like to thank Øyvind Tørum and the rest of Støren Treindusti, for giving me a lot of insight to their work, and for providing me with the essential information needed to write this thesis.

An article based on the data from this thesis has been accepted for the World Conference of Timber Engineering and will be presented in Wien, August 2016.

Ås, May 18th, 2016
May-Linn Sortland

Abstract

Variation in micro climate induce shrinkage and swelling of wooden beams. The dimensional changes depend of the orientation of the annual growth rings and the moisture content of the beams. This causes laminated timber to experience different deformations than solid wood. A producer of element buildings with joists of laminated wood, have experienced deformations and sloping of the floor structure in several buildings, and believe that these might be caused by moisture.

This thesis combines in-situ measurements with simulations and a laboratory experiment, to make a survey of where in the buildings these problems are most likely to occur, and to estimate how much deformation the producer can expected in the areas where the differences in moisture content between the head joist and inner joist of the floor system is at its highest.

The results show that the largest deformations occur in a bedroom facing north, with low solar radiation and high moisture gradients between indoor and outdoor climate. In this room, a 13 % difference in moisture content is measured between the head joist and inner joist, one meter from the edge of the floor system. This results in an estimated height difference of almost 8 mm, and an average slope of 0.8%. These values are higher than the tolerances for finished surfaces, and the producer will improve their construction accordingly.

Simulations of the problem do not show exactly the same values as the measurements, but they are still helpful, since they confirm that the water content and deformations of the floor system is limited if the head joist is retracted 50 mm further in, in the construction.

Sammendrag

Variasjoner i mikroklima induserer krymping og svelling av trebjelker. Dimensjonsendringene avhenger av orienteringen på årringene og vanninnhold i bjelkene. Dette gjør at limtre vil oppleve andre deformasjoner enn heltre. En produsent av element bygg med bjelker av typen «K-bjelke», en limt bjelke bestående av flere tynne lameller, har opplevd deformasjoner og helling i gulvkonstruksjonen i flere av sine bygg, og mistenker at disse problemene kan være fuktrelaterte.

Denne oppgaven sammenligner situasjonsmålinger med simuleringer og et laboratorieforsøk, for å kunne lage en oversikt over hvor i byggene store deformasjoner mest sannsynlig vil oppstå, og for å estimere hvor store deformasjoner bygningsprodusenten kan forvente i det rommet med størst forskjell i vanninnhold mellom kantbjelken og bjelkelaget.

Resultatene viser at de største deformasjonene vil oppstå i et nordvendt soverom med lav solstråling og store fuktighetsgradienter mellom inne- og uteklima. I dette rommet er det målt en maksimal forskjell i vanninnhold mellom kantbjelken og bjelkene inne i bjelkelaget, en meter fra kanten, på 13 %. Dette har resultert i en estimert høydeforskjell på nesten 8 mm mellom bjelkene, og en gjennomsnittlig helling på 0.8 % Disse verdiene er høyere enn toleransene for ferdige overflater, og bygningsprodusenten vil forbedre sin konstruksjoner deretter.

Simuleringer av problemet viser ikke nøyaktig de samme verdiene som målingene, men de er fremdeles nyttige, siden de bekrefter at vanninnholdet og deformasjonene i gulvsystemet vil bli begrenset dersom kantbjelken blir trukket 50 mm inn i konstruksjonen.

Contents

1. Introduction

1.1 Background

Dimensional instabilities has resulted in problems for a Norwegian producer of prefabricated element buildings. Deformations occur in the head joists of the floor system, likely caused by moisture and swellings. The head joist changes dimensions relative to the surrounding climate, and the whole floor system bends and slopes inward. This has led to problems when installing balconies and wall elements of the second floor.

The producer has observed that climate on site plays an important role, and the worst cases registered have been in the north of Norway, in areas where the temperature is low and the climate is humid. The orientation of the building, indoor climate, and season may also influence on the problem.

Together with the Norwegian Institute of Wood Technology, a case study from a two-story, semi-detached, module building in Trondheim, situated at 63 degrees North, in Norway is performed. The building construction is made of prefabricated elements, produced in an indoor climatically controlled industrial hall. The assembling of the building started in November 2015.

All the joists in the floor and roof system of the building are made of laminated timber of Nordic spruce, with dimensions 48x300mm. The type of joists used are called K-beams, and are specifically designed for roof and floor constructions that need a high degree of stability in dimension. [19] When assembling the construction, the floor element is placed between the two wall elements, the wind barrier is fastened and a cardboard sealing and cladding is installed on the outside of the head joist. See figure 1.

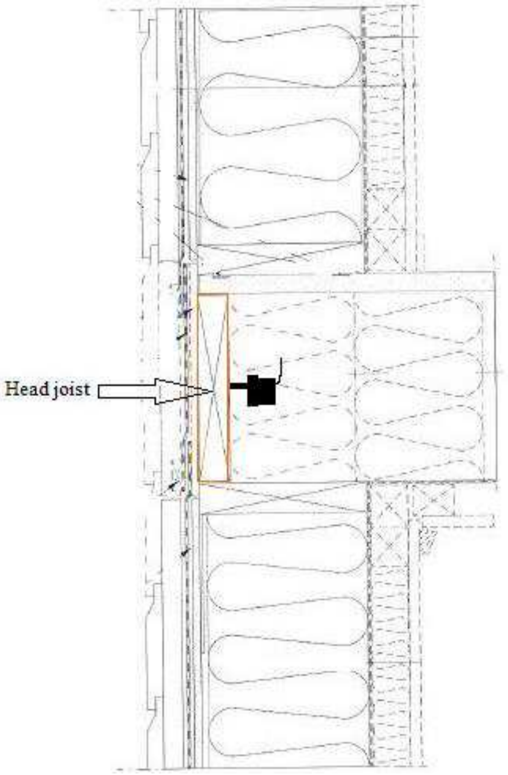

Figure 1*: Cross section of the element detail of the wall elements of the first and second floor, and the floor element between these. The positioning of the head joist is marked*

The head joist is close to the cladding, and will experience large variations in temperature, and in some periods temperatures below freezing point. This means that the micro scale climate and the orientation of the building will influence the thermal and moisture conditions of the head joist. If untreated, these problems may also cause mould-, rot- and health problems for the residents, as well as structural defects in the joists.

1.2 Problem

The objective of this thesis is to determine if the dimensional deformations experienced by the producer of the buildings can be explained by the moisture content of the joists in the floor system. Another part of the problem is to figure out the approximate deformations expected, and to see if in-situ measurements can verify numerical simulations of the same problem. Lastly, an analysis on different ways to improve the construction to avoid further problem will be made.

2. Theory

2.1 Material

2.1.1 Wood technology

Changes in moisture content result in swelling and shrinkage of wooden materials. In the range from zero to 30% moisture content, a perfect sample of spruce swells and shrinks approximately linearly. [1] Swelling is a result of water pressing the wood cell wall fibrils apart. Shrinkage is the opposite, and water from the cell wall is released. See figure 2. When the water content is higher than approximately 30%, the cell wall is saturated, and the cell lumen starts to fill up. This excessive water is known as free water and will not affect shrinkage and swelling. [1] See figure 3.

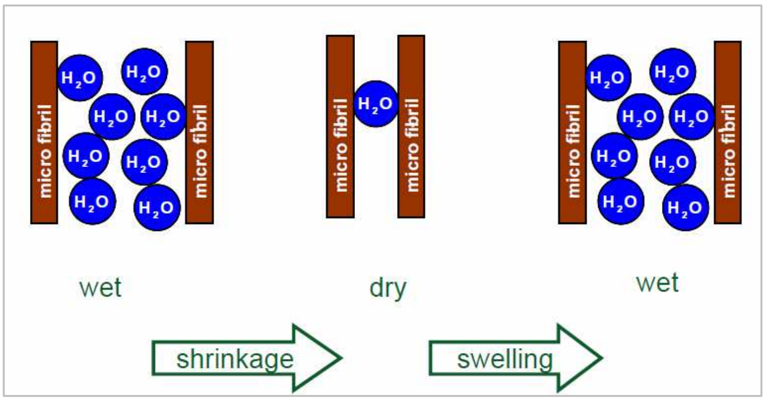

***Figure 2**: The changes inside the wood cells during shrinkage and swelling*

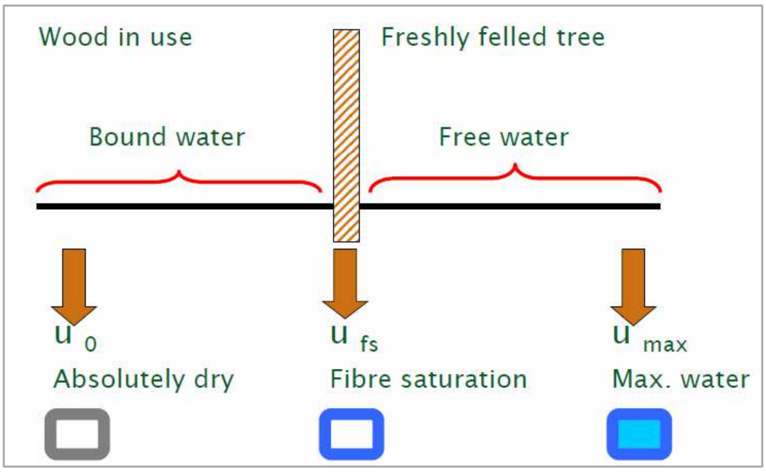

***Figure 3**: Explanation of the difference between absolutely dry, fibre saturation and maximum water content in the cells*

The dimensional deformations vary between the three main directions of the wood. The deformations in radial direction is roughly half of the tangential deformations for spruce and pine. In longitudinal direction, we find very low values compared to the cross section. However, the beams are often of long lengths, and the total longitudinal deformation can be substantial. The cross section of a typical solid wood beam and the main directions of the wood can be seen in figure 4. For a perfect sample of spruce, the total shrinkage from green to dry is approximately 7.8 % in tangential direction, 3.6 % in radial direction and 0.3 % in longitudinal direction. [2] See figure 5. These values are based on small, flawless samples of wood, and can only represent the ground values. Other factors will also effect the swelling and shrinkage. Wood species, water content and the size and orientation of the growth rings are the most influential. Coating, wood modification, density, anatomical structure and the earlywood/latewood portion will also have an effect on the deformations. [2]

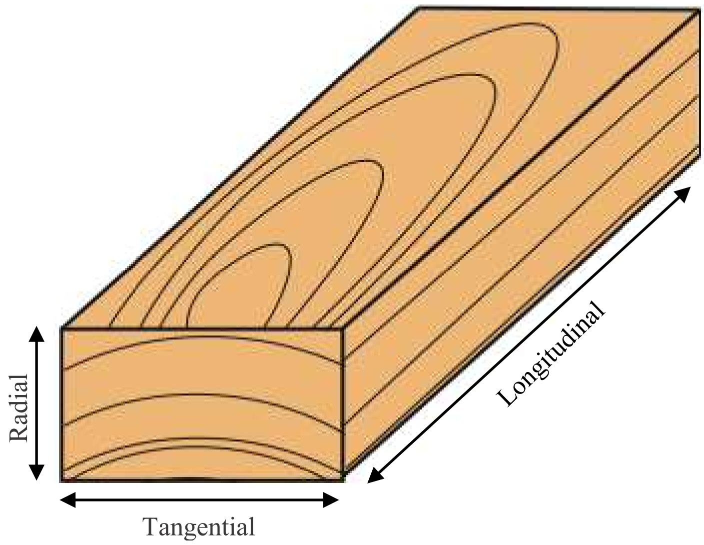

***Figure 4**: A typical wooden beam with the three main directions of the wood*

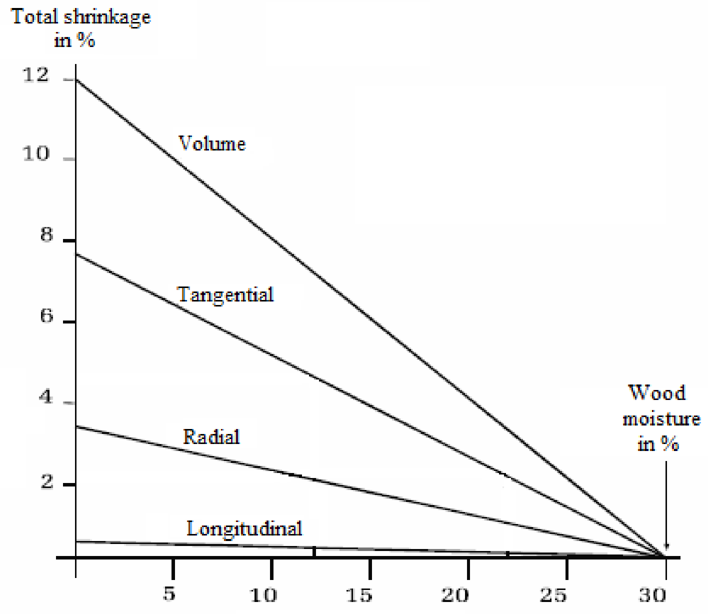

***Figure 5**: The total shrinkages in a perfect sample of spruce*

The maximum swelling coefficient α, is related to absolute dry conditions, and can be calculated be the following equation

$$\alpha_{\text{max}} = \frac{\alpha\ max - \alpha min}{\alpha\ \text{min}}\ \text{x}\ 100[\%] \tag{1}$$

Air with high relative humidity causes wood to swell, while dry air induce shrinkage. Warm air has a higher ability to store moisture than cold air, causing a decreased temperature to result in a higher moisture level in of air. [3] See figure 6.

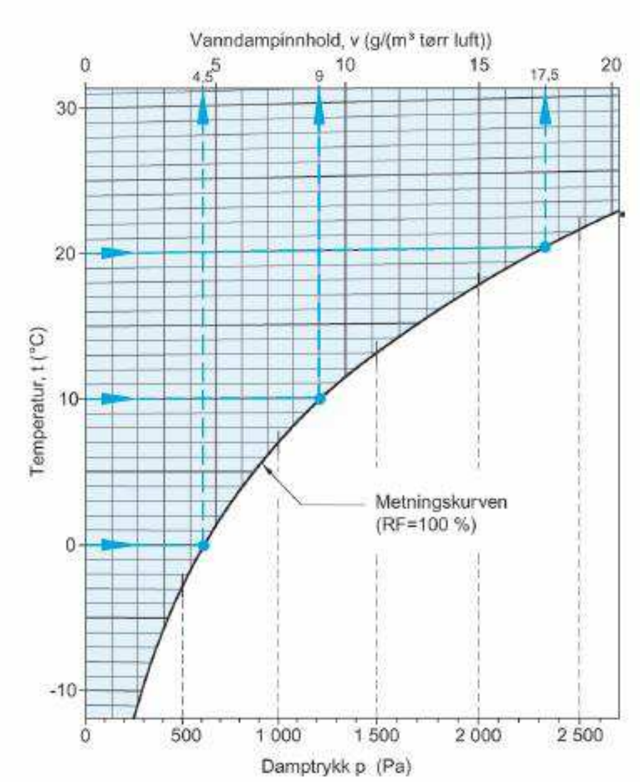

***Figure 6**: Diagram showing the relation between temperature, relative humidity, amount of damp in the air and the damp pressure*

Laminated timber will experience different deformations than solid timber, even if the wood species is the same. The main reason is the change in orientation of the growth rings, but differences in density caused by the anisotropy of the wood may also occur and influence the deformation. In extreme cases, the perpendicular and tangential directions are shifted compared to solid wood. This will lead to different dimensional deformations in a building with joists of laminated timber than in a similar building with joists of solid wood.

Carling [4], claims that an average 0.2 % increase in the dimensions of the cross-section of regular types of laminated timber can be expected if the water content is increased by one percent. Only 0.01 % increase is expected in the longitudinal direction of the timber, under the same circumstances.

Since wood is a hygroscopic material, it will, over time, adapt to the surrounding climate. The moisture level it adjusts to is known as its equilibrium humidity. This value varies between different wood species and is affected by many different wood properties. The equilibrium humidity will decrease with increased temperatures. [1] See figure 7.

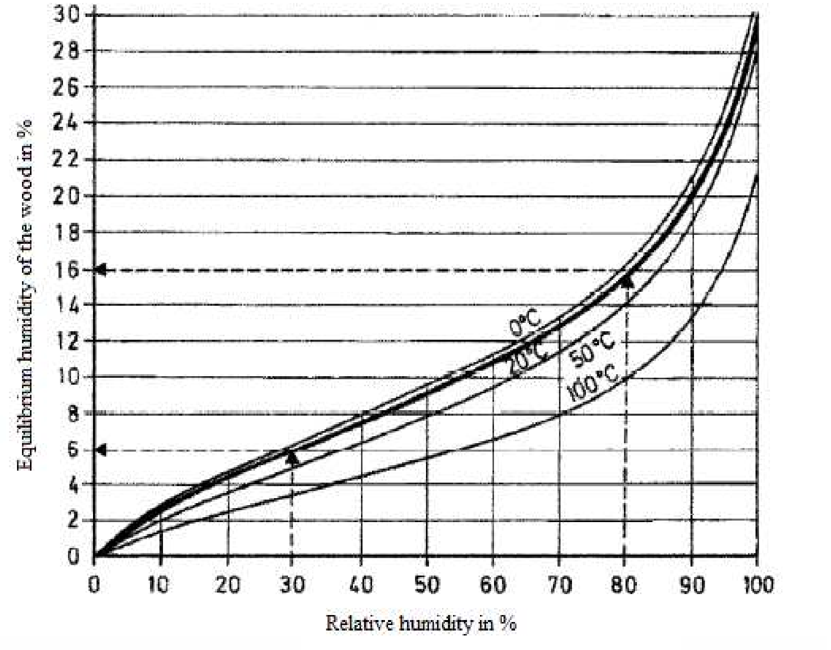

Figure 7: *Equilibrium humidity under different temperature and relative humidities*

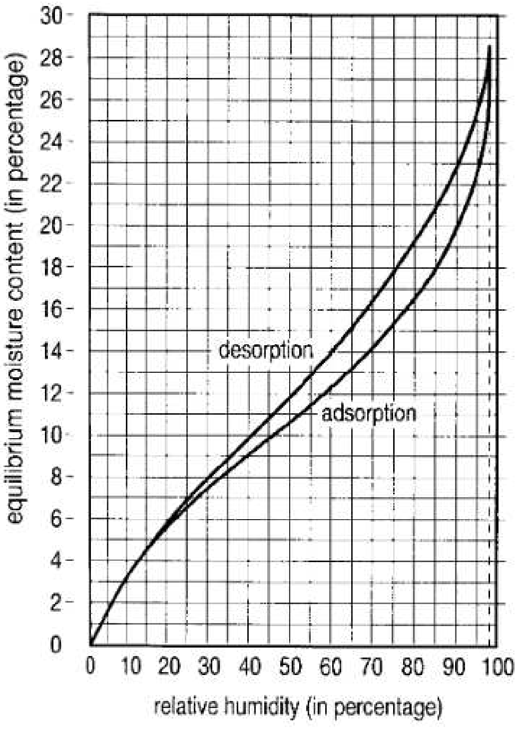

Figure 8: *Hysteresis between absorption and desorption*

If two pieces of wood, one dry and one wet, is exposed to the same climate, they will adapt to different equilibrium humidities. This effect is called hysteresis, and makes the wood moisture under wetting higher than the moisture content would be under drying, even if the climate conditions were the same. [2] See figure 8. Variations in relative humidity causes the equilibrium moisture values to follow a transition curve between the two curves for absorption and desorption. If a sample of wood is varying between climates, hysteresis will make the difference in wood moisture between the levels of relative humidity smaller. The effect decreases with higher temperatures.

2.1.2 Tolerances

There are several tolerances regarding deformations, moisture and assembling of constructions. The Planning and Building Act and the Norwegian Standards mainly present these.

According to the Norwegian Standards, the sloping tolerances of finished surfaces is maximum 7,5 mm on lengths over 5 meters, 1,5 ‰ for lengths between 2 – 5 meters, and 3 mm if the length is shorter than 2 meters. [5] These values represent the total height difference between two points, and the sloping deviation between these points can be calculated as shown in figure 9.

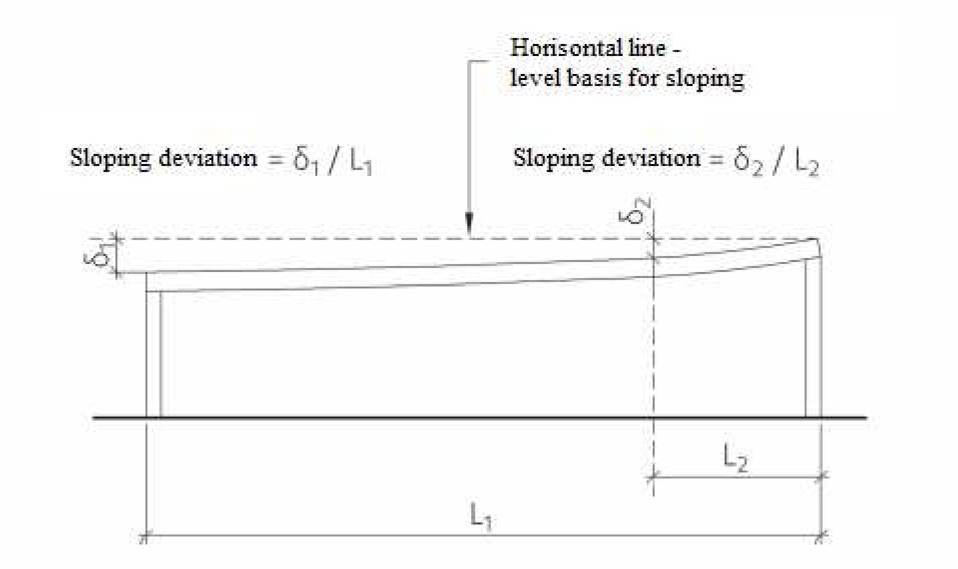

Figure 9: *Measurements of sloping deviation in relation to the level basis*

Deformations are usually caused by moisture. This is one of the reason why it is important to have control of the moisture in the wood and the dehydrating period, as well as to come up with preventive measures to avoid further hydration. Moisture in the building might also result in indoor air quality problems and building damages.

All building suppliers have to document the moisture of the wood on delivery, and make sure this value is under an acceptable level. According to the Norwegian standards, all wooden materials delivered on site, covered against precipitation, should have a moisture content lower than 20%, equivalent to 85-90% relative humidity. This is to avoid that the moisture exceeds the critical moisture level after assembling. Critical moisture value is defined as the highest moisture content level a material can have without experiencing moisture related damages. The Norwegian Standards present some guiding values for these critical moisture levels. In walls, this value is 20% and in beams used in floor constructions, it is 12%. [6]

Under assembling, before the constructions are closed and insulation is installed, the wooden elements needs to be dehydrated. If the construction is too damp-proof on the cold side, it will not dry out, and the moisture stays inside the timber. This makes it important to use wind barriers with as low water vapour resistance as possible. The recommended ground values for wind barriers today is $S_d \leq 0{,}5m$, but $S_d \leq 0{,}2m$ is desirable. [7] The wind barrier should also have an ability to store condensation, to avoid accumulation of moisture on the inside of the vapour barrier. Another important stage of the building process is to assemble the vapour barrier immediately after the insulation. This is to prevent the moisture to move further out in the construction. [8]

2.1.3 Stresses

Several researchers have studied the hygroscopic behavior of the wood and the stresses occurring inside the materials. Dinwoodie [9], describes how the hygroscopicity of the wood causes absorption and desorption of moisture, to maintain equilibrium of the moisture state with the surrounding air. This will lead to moisture gradients in the wood, and stresses will be induced. Stresses perpendicular to grain direction my cause splitting of the wood, as explained by Ranta-Maunus. [10]

The stresses that arise inside the wood structures after external exposures, is termed as the ‘humidity loads’ and are affected by different factors, like precipitation, sun radiation, indoor heating and indoor activities. The humidity load influence on the moisture content of the wood, which again will affect on several physical, mechanical and rheological properties, like durability, shrinkage and swelling, modulus of elasticity and several strength properties. [11]

The moisture gradient has a significant effect on the stress state of the wood. Moisture diffusion in wood is a rather slow process in comparison to heat flow. Gradients of moisture in the wood sections are created when the humidity load is variable or different from initial equilibrium. These gradients may be high, particularly when air humidity changes are fast. [12]

Mårtensson [13], describes deformations in the sill and beam supports to be typical deformations perpendicular to grain, and claims these are the dominant deformations in, for example, multi-story wood framed buildings. Usually, these kinds of deformations are mainly explained by the load stresses. Deformations and stress distributions in the cross section, caused by natural variations in the climate, are less understood.

Moisture-induced stresses are different in cross-laminates and other types of laminated timber, then in solid wood. Eigenstresses, caused by hygroscopicity, orthotropy and volume changes result in shape distortions and reduced serviceability and drying stresses. These stresses occur in the layers between the wood panels as the humidity changes. [14]

Carling [4], explains how the water content can be unevenly distributed in the cross section, for example in beams located in the insulation layer, where the moisture gradients between the warm inside air and the cold outside air is specifically high. This will lead to different deformations of the outside of the beam than on the inside, and the beam will start to bend. These problems are most critic in the wintertime, when the indoor climate is at its driest and warmest, and the outdoor climate at its wettest and coldest. If the moisture related deformations in the cross-section is restricted, either by other building components or by heavy loads, the strength capacity may be exceeded, and cracks will occur in the wood.

2.2 In-situ measurements

To carry out the measurements on the building in Trondheim, the OmniSense moisture monitoring system is used. This system is great for logging internal wall installations. The sensors register temperature and relative humidity through an air sensor and moisture content of wood through two mounting screws [15]. See figure 10a.

***Figure 10a**: OmniSense sensor*

***Figure 10b**: OmniSense gateway*

The sensors send the registered data to a gateway, as shown in figure 10b, which is in contact with the internet through a SIM card, and allows the users to download the data from the OmniSense webpage. The sensors are easy to install and has a battery life of 15-45 years, depending of the logging interval. The gateway should be set up less than 100 meters from the sensors, in order to receive all data. [15]

Readings of the moisture content is accurate to a few percent in wood. Wood species and temperature must be taken into account, and a calibration formula for the water content is needed. The water content measured by the OmniSense sensors presumes that the material is made of pine, and the water content is adjusted, in order to be valid for spruce, by the following equation

$$WC_{spruce} = 0.5570224 + (1.0743609 * WC_{measured}) + 0.0111586 * ((WC_{measured} - 16.5) * (\mathrm{M2} - 16.5)) \quad (2)$$

2.3 Simulations

WUFI-2D, a two-dimensional, hydrothermal, State of the art Heat and Moisture (HAM) simulation tool is used to perform the simulations of the problem. The program was developed at the Fraunhofer Institute for Building Physics in Holzkirchen, Germany. Based on the finite element method, WUFI-2D analyses heat and moisture transfer of building envelope constructions, by developing a closed differential equation system, which calculates the moisture behavior of multi-layered building components under natural climatic boundary conditions. It is based on a derivation of a coupled equation system and a numerical solution technique. [16]

The program introduces two potentials for moisture flow: the liquid transport flux, which depends on relative humidity, and the vapour diffusion flux, which depends on vapour pressure. The airflow is not considered in the assessment of moisture behavior. [17]

Energy transfer is calculated by the following equation

$$\frac{dH}{d\vartheta} * \frac{\delta\vartheta}{\delta t} = \nabla * \Big(\lambda\nabla\vartheta) + h_v\nabla * \left(\delta_p\nabla(\varphi p_{sat})\right)\Big) \tag{3}$$

Moisture transfer is calculated by the following equation

$$\frac{dw}{d\varphi} * \frac{\delta\varphi}{\delta t} = \nabla * \left(D_\varphi\nabla\varphi + \delta_p\nabla(\varphi p_{sat})\right) \tag{4}$$

Where

$\frac{dH}{d\vartheta}$	[J/m^{3}K]	heat storage capacity of the moist building material
$\frac{dw}{d\varphi}$	[kg/m^3]	moisture storage capacity of the building material
λ	[W/mK]	thermal conductivity of the moist building material
D_φ	[kg/ms]	liquid conduction coefficient of the building material
δ_p	[kg/msPa]	water vapour permability of the building material
h_v	[J/kg]	evaporation enthalpy of the water
p_{sat}	[Pa]	water vapour saturation pressure
ϑ	[°C]	temperature
φ	[-]	relative humidity

3. Method and materials

Measurements from the case studies are used to verify numerical simulations of heat and moisture in the floor system. The moisture induced dimensional variation of the joists has been determined in controlled climates in laboratory experiments.

3.1 Laboratory experiment

To define the moisture induced dimensional variations, laboratory experiments are performed. A regression model of dimensional deformations under different water content levels is created from the measurement results. This model is used to determine the dimensional variations over time, with input of moisture content from the measurements in the case study and from the numerical simulations.

The experiment involves twelve samples of K-beams. See figure 11. The edges of the samples were sealed, to avoid moisture absorption in longitudinal direction. This will make the experiment more comparable to the measurements in Trondheim, since moisture absorption in longitudinal direction is not a relevant problem in the middle of long beams.

***Figure 11**: The twelve samples studied in the laboratory experiment*

The samples were distributed between four climate chambers with the climates described in table 1. These climates are based on observed climates around the joists in other buildings. After three weeks in the climate chamber, when the moisture content has stabilized, the weight of the samples and the dimensions of the cross sections was measured. The height of the samples was measured at three positions. See the black lines on figure 12a. The width of the top and bottom lamella, as well as lamella number two, five and eight from the top, on the right side of the samples, were measured, to find an average width of the joists. See figure 12b.

***Table 1**: The four climates of the climate chambers*

Climate	Samples	RH [%]	T [°C]
1	1 – 3	43	20
2	4 – 6	65	
3	7 – 9	86	
4	10 – 12	99	

***Figure 12a**: One of the samples, with lines indicating where the height measurements are performed*

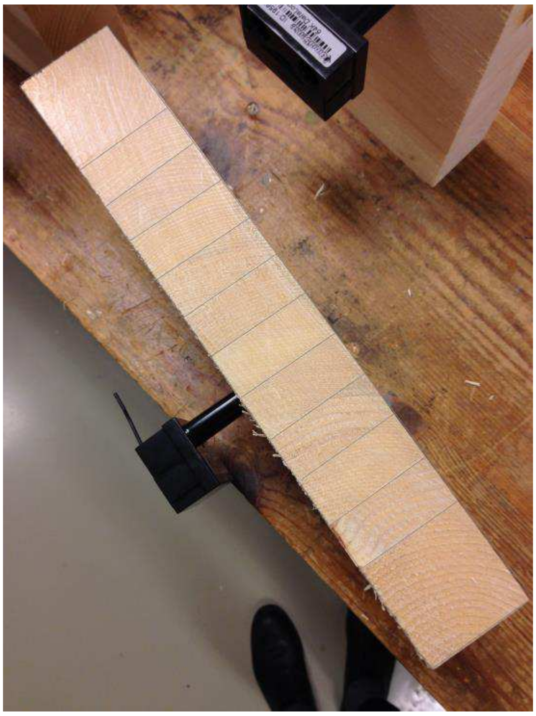

***Figure 12b**: The cross section of one of the samples, with lines indicating the separation of the lamellas*

To keep track of the water content, sensors were installed on each sample. The weight of the sensors and sealing is subtracted from the measured weight of the samples. Because the beams have several lamellas, with different grain directions, there is no fixed radial or tangential direction. This makes this experiment different from similar experiments with solid wood beams. In order to see the extreme values, four samples, one from each of the previous climates, were submerged in water and subsequently dried.

3.2 In-situ measurements

3.2.1 Climate and area

In-situ measurements are performed in a building in Sigrid Johansens Street 16B, located south-west of Trondheim city in Norway. See figure 16a. The site is 197 meters above sea level, and is climatically exposed. The site is based on a relatively flat plateau, and is only sheltered from wind and direct sunlight by other houses and a few trees. This means there is high wind stresses, and a lot of heat radiation from the sun during the summer months. See figure 16b. There is also a tramline going past the site on the southwestern end, which makes this area even more open and exposed.

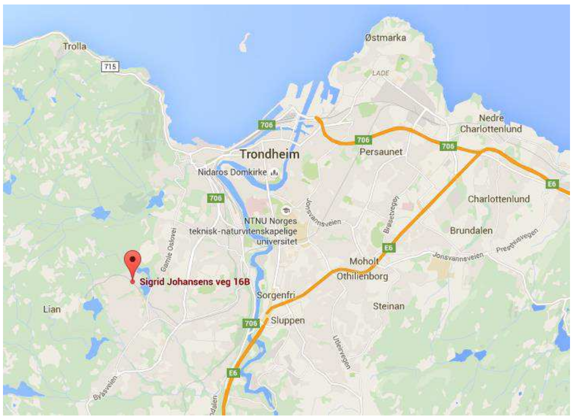

***Figure 13a**: Trondheim, with the location of the site*

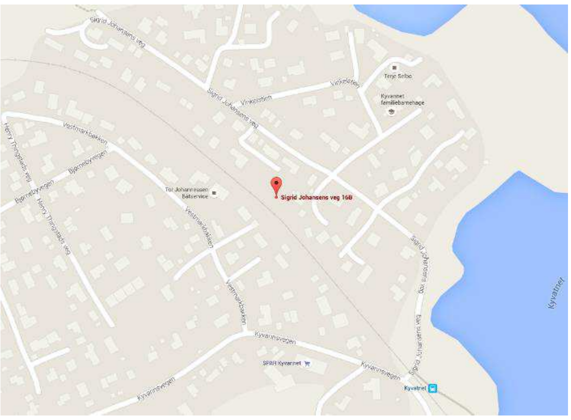

***Figure 13**b: Surroundings and other buildings*

3.2.2 The building

The building is a semi-detached house, over two floors. On the first floor, apartment B is approximately a mirrored version of apartment A. They both have the main entrance facing north, a central bathroom and laundry, three bedrooms, one towards north and two towards south, and a carport and two storage rooms, one insulated and one uninsulated. In apartment A, the storage rooms and carport are facing east, and in apartment B, they are facing west. See figure 14a. Equivalently as on the first floor, there is also a mirrored wall structure on the second floor. However, on this floor, the room distribution is different. In apartment A, the kitchen is in the northern part of the apartment, with facades towards north and east, and a living room towards south. In apartment B, the living room and kitchen have switched places. There is also a storage room on the second floor of each of the apartments. See figure 14b.

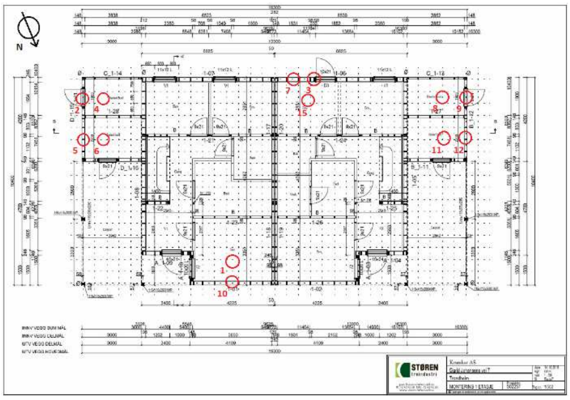

Figure 14a: *The first floor of the building, with sensors on the floor slab indicated with circles*

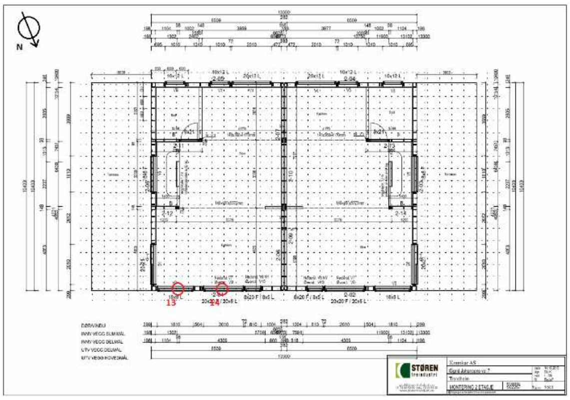

Figure 14b: *The second floor of the building, with the two sensors in the roof construction indicated with circles*

Fifteen sensors, measuring temperature and moisture content, is installed in the building. Thirteen of these sensors are in the floor construction between the first and the second floor, distributed between the head joists and the inner joists of the floor system, approximately one meter from the edge. The remaining two sensors are placed in the roof construction. See figure 14a and 14b. With these sensors, the difference in water content between the head joist of the roof construction and the head joist of the floor slab can be reviewed. A total of seven rooms were instrumented, with a mixture of heated and unheated rooms.

To verify that the measurements are correct, and because leaks were observed between the head joist, the cross-lying joist and the subjacent wall element, in the southern facing bedroom, two sensors were installed in the head joist of this room. See figure 15.

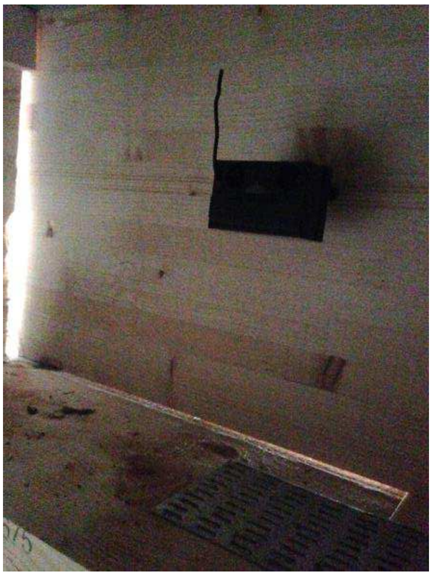

Figure 15: *The placement of one of the sensors in the southern facing bedroom, where leaks between the joists are observed*

3.2.3 Element detail

Floor and wall elements are delivered to the site as separate parts, and the delivered floor elements consist of head joists, tier of joists and a chipboard. The wall elements are more advanced, with a timber frame, insulation, wind barrier, cardboard sealing and cladding. Floor and wall elements are put together on site, by placing the floor element between the two wall elements. The wind barrier is fastened and an extra part of cardboard and cladding is installed. The insulation in the floor, a vapor barrier and internal cladding is installed after the assembling of the elements, and are indicated by the stippled lines in figure 16.

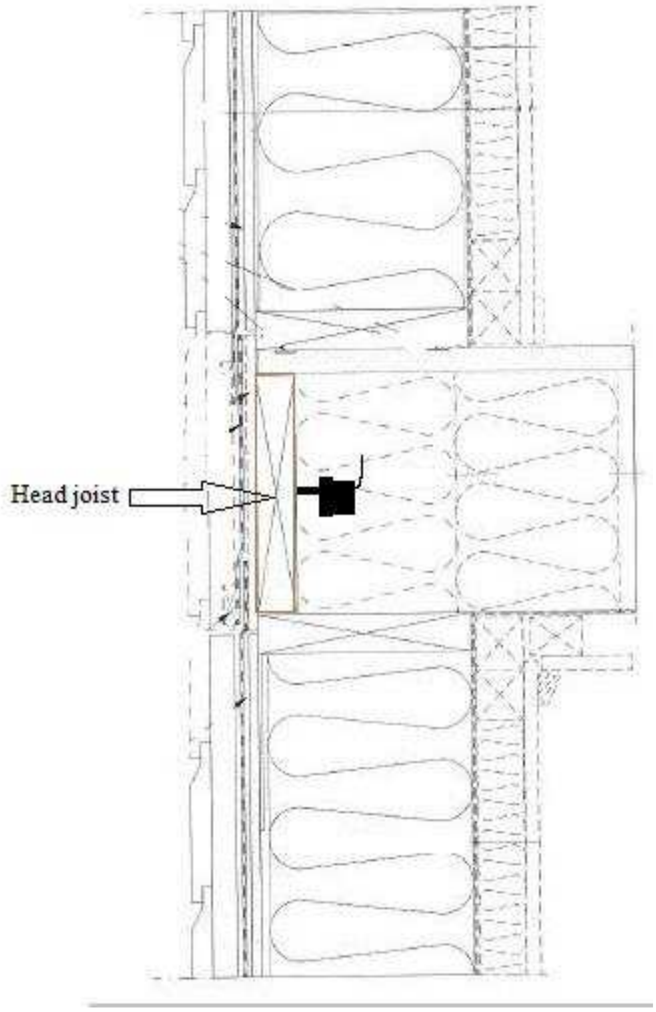

Figure 16: *Element detail given by the building producer, showing the building layers of the floor and wall elements, as well as the placement of the sensor on the head joist*

All the joists in the floor system are made of glued laminated timber of spruce. The cross section consists of two 47 mm thick outer lamellas and ten 2.06 mm thick inner lamellas, glued together by moisture resistant Emulsion Polymer Isocynate (EPI) adhesive glue. The outer lamellas are normally 6000 mm long. The inner lamellas are shorter, between 240-900 mm, and are finger jointed to a length of 6000 mm. This type of beam is developed by the Norwegian company Kjeldstad, and is called a “K-beam”. [18] The beams can be produced in several different dimensions. Figure 17 show a typical cross-section for the beams used in the head joists, with the accurate dimensions.

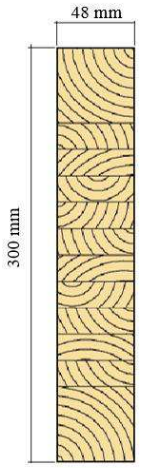

Figure 17: The cross-section of a K-beam with dimensions 48*300

The K-beams have several advantages over solid wood beams: More of the tree trunks is used, resulting in a higher utilizing of the timber, it is easy to make the desired dimensions, and the beams get good strength and stability qualities. [19] Another important aspect, which is the most important regarding this problem, is that the orientation of the growth rings change. This affects the swelling and shrinkage of the beam. Usually, the tangential direction of the growth rings would be in the beams height direction, but in this case if becomes, more or less, in the beams width direction. This makes the deformations in the height direction of the K-beams smaller that it would be on regular solid wood beams. Another, more negative, discovery is that the K-beam absorbs water more quickly than solid wood. At short moisture intervals, this can have a big impact on the swellings and moisture content, and large moisture gradients can be induced in the cross-section.

3.3 Simulations

Two cases are simulated. The reference case is similar to the detail given by the producer, seen in figure 16. The setup for this geometry is displayed in figure 18a. The other simulation is similar to the reference case, but contains an extra 50 mm thick insulation layer on the outside of the head joist. See figure 18b. This case is simulated in order to see if this detail will lead to better results regarding moisture and temperature.

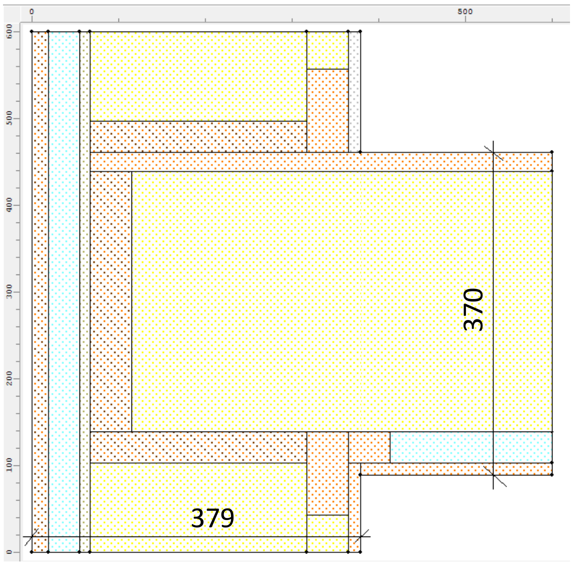

***Figure 18a**: Geometry if the reference case*

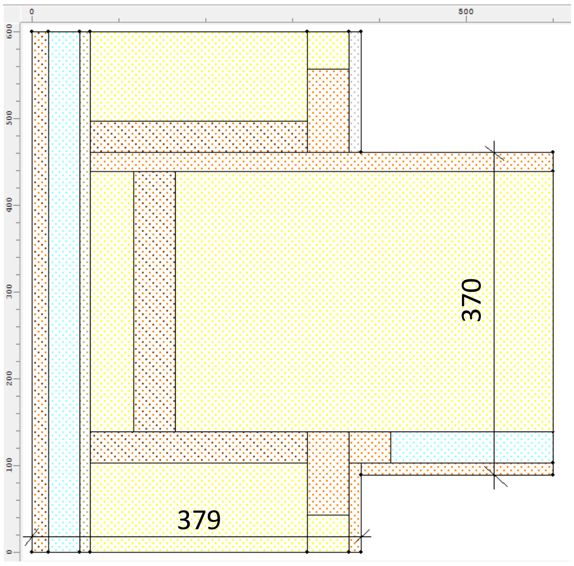

***Figure 18b**: Geometry of the second case, with the head joist retracted 50 mm*

The numerical grid is refined in the areas where large gradients of temperature and moisture is expected. A description of the materials used can be seen in table 2. The simulations start when the building is taken in to use. Initial conditions of the materials at this time, is obtained from the in-situ measurements of the building.

***Table 2**: Material data included in the simulations*

		Bulk density [kg/m^3]	**Thermal Cond.** [W/mK]	**δ - Value** [-]	
				x	**y**
Wall elementI	Exterior cladding	430	0.13	50.0	83.3
	Air layer, 36mm	1.3	0.21	0.415	
	Wind barrier	130	2.3	20.0	
	Cardboard	235	0.049	20.0	
	Insulation	60	1.3	0.037	
	Vapour barrier	130	2.3	1000000	
	Interior cladding	510	0.13	50.0	
Floor element	Subfloor	550	0.14	50.0	
	Head joist	430	0.13	83.3	50.0
	Tier of joists	430	0.13	4.3	50.0
	Insulation	60	1.3	0.037	
	Air layer, 36mm	1.3	0.21	0.415	
	Ceiling	510	0.13	50.0	

The simulated cases are oriented towards north, and are based on the assumption of a normal indoor climate, defined in EN 15026. [20] With these assumptions, high moisture gradients between indoor and outdoor temperature and low solar radiation is expected. Temperature and moisture in both the head joist and inner joists is simulated.

For the outer surface, weather data obtained from two weather stations in Trondheim is used. These include hourly values of temperature, relative air humidity, air pressure, rain, wind direction and wind speed, collected from a weather station on Voll, 5.57 km from the site, and solar radiation from Gløshaugen, 3.85 km from the site.

The simulations start on January 5, at 12:00. This represents the time when the residents moved in to the building, and the indoor and outdoor temperatures started to separate in the in-situ measurements. The initial conditions for the building components at this time is also collected from the in-situ measurements. These values are presented in table 3.

Table 3*: Initial values for the head joist and the inner joist*

	Temperature	**Moisture content**	**Relative humidity**
Head joist	2.3	50.9	11.49
Inner joist	3.7	46.8	11.22

The simulations give hourly values of moisture content, temperature and relative humidity. The simulated relative humidity refers to the relative humidity of the air inside the pores of the material. This makes it difficult to compare this value to the relative humidity of the surrounding air, and the values will most likely be lower and more stable, since they are based on the moisture content of the material, and not the moisture content of the air.

4. Results

4.1 Laboratory experiment

The changes in dimensions and weight of the different samples was considerable. A summary of the results is displayed in table 3. The focus will mainly be on the height deformations in relation to the water content, but the width deformations of the samples will also be shortly reviewed.

Table 4*: Data from the laboratory experiment*

	RH [%]	**WC** [%]	**Height** [mm]	**Width** [mm]	**Weight** [g]
Dry	~0	-	295.77	46.57	863.6
			296.36	46.86	851.9
			296.69	46.60	846.7
			296.75	46.63	837.0
After climate chambers	43	8.3	298.78	47.96	940.4
		8.6	299.01	47.96	948.8
		8.8	299.29	47.89	937.6
	65	9.4	299.44	48.13	966.9
		9.7	300.55	48.19	960.9
		10.2	300.26	48.29	951.5
	86	12.2	301.73	48.73	1011.9
		12.4	301.29	48.49	963.0
		12.6	301.75	48.19	991.3
	99	18.0	305.43	48.99	1038.2
		18.1	305.31	49.19	1054.4
		18.3	305.38	49.44	1013.7
Wet	100	-	306.11	49.88	1264.4
			307.46	50.13	1300.2
			309.57	50.06	1297.4
			310.82	50.47	1311.3

The height measurements from the laboratory experiment after three weeks of exposure in the climate chambers is displayed in figure 19. The water content during drying and submersion was not monitored, excluding these measurements from the creating of the graph. With these results, a linear regression model is made. See equation 5. This model has a coefficient of determination (R^2) of 0,989.

$$Height = 0.6519 * WC + 293.55 \qquad [mm] \tag{5}$$

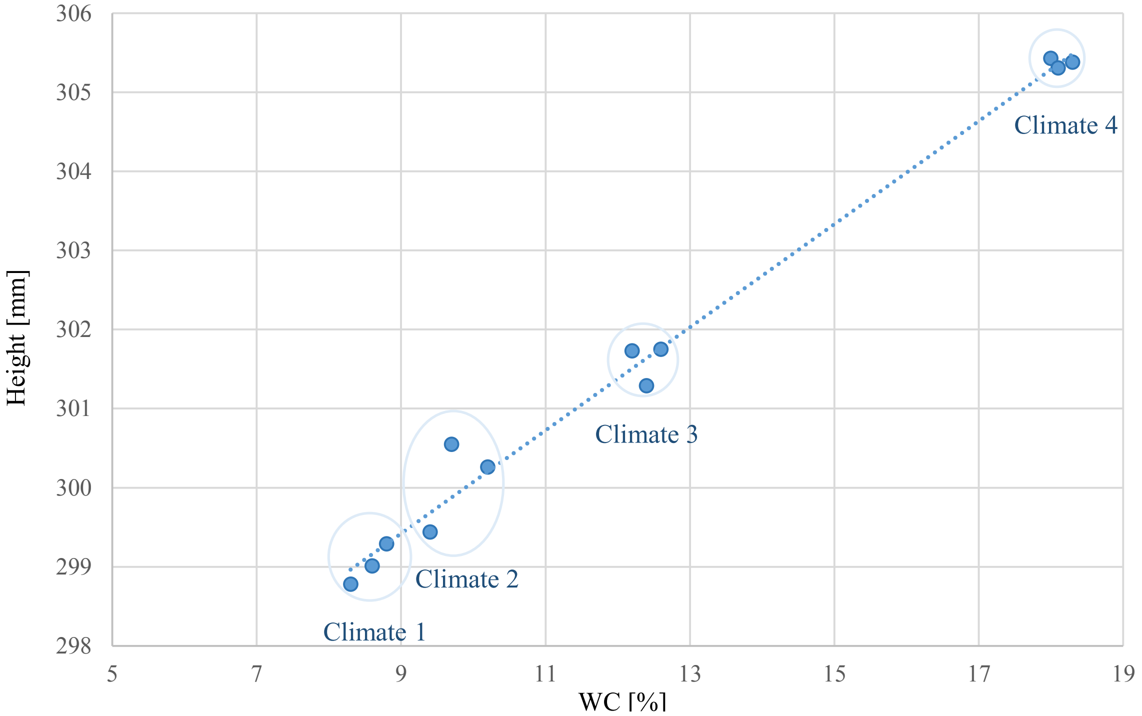

Figure 19: *Measurement points of height versus moisture content and the regression model created between these points*

The deformations and sloping of the floor system is mainly affected by the height dimensions of the joist, and the regression model in equation 5 will later be used to find the heights of the head joist and inner joist in the monitored building, and the constituting dimensional differences.

A similar linear regression model is also made from the width measurements and is displayed in figure 20. This model has a lower coefficient of determination (R^2) of 0.9015, and give the following equation.

$$Width = 0.1276 * WC + 46.895 \qquad [mm] \tag{6}$$

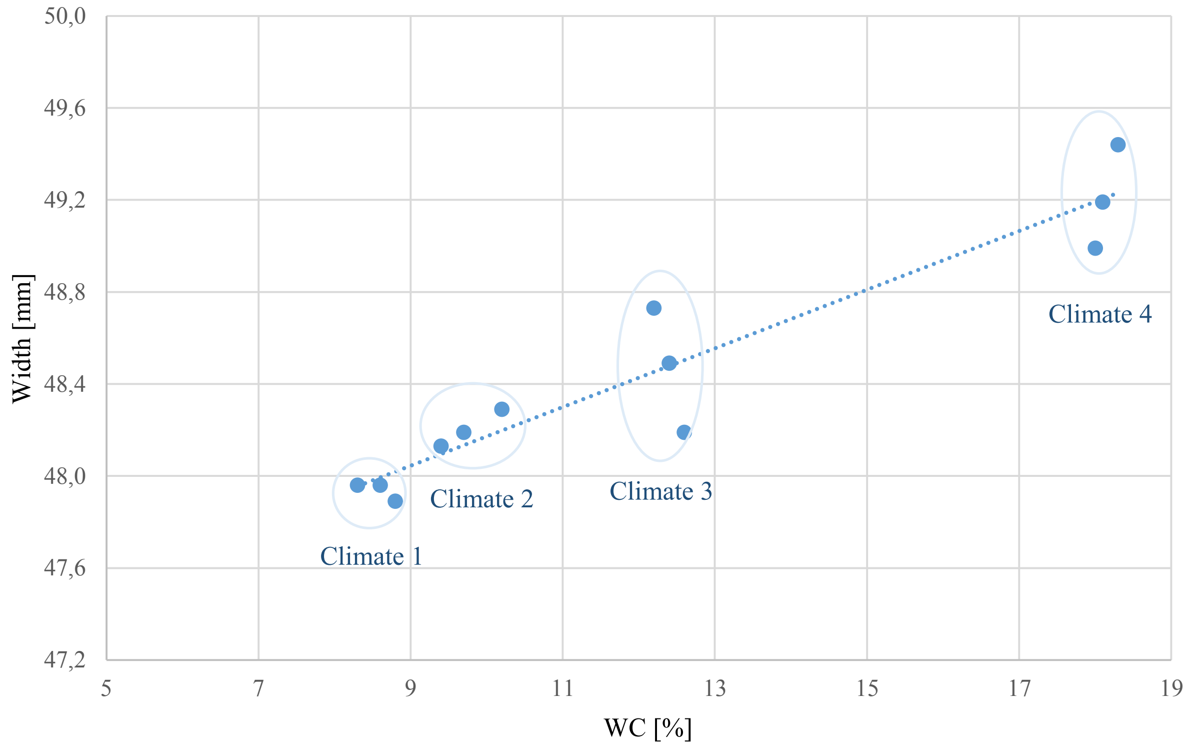

Figure 20: *Measurement points of width versus moisture content and the regression model created between these points*

These regression models can be used to calculate the maximum swelling of the K-beams, based on the assumption of linear swelling and shrinkage. Maximum swelling in the height and width dimensions are calculated by equation 7 and 8.

$$Maximum\ height\ swelling = \frac{Height_{green} - Height_{dry}}{Height_{dry}} * 100 \qquad [\%] \qquad (7)$$

$$Maximum\ width\ swelling = \frac{Width_{green} - Width_{dry}}{Width_{dry}} * 100 \qquad [\%] \qquad (8)$$

With a presumed water content of 30 % when green and 0 % when dry, the maximum dimensional swellings of the K-beams is calculated to be 6.66 % for the height dimension and 8.14 % in the width dimension. The calculations can be seen in appendix A.

4.2 Measurements

When analyzing the measurements, the room with the largest difference in water content between the head joist and the cross-lying joist is of most interest. Another aspect of the problem is to figure out why the results are different in this room then in the other rooms.

To find the room with the largest differences, similar rooms with different orientations are compared, followed by a comparison between heated and unheated rooms.

4.2.1 Orientation

Based on moisture load and indoor climate it is sensible to compare bedrooms, insulated storage rooms and uninsulated storage rooms with different orientations.

Significant changes in the water content occur in the head joists in the bedroom as the indoor climate changes, when residents move in to the building. See figure 21. Since the building is a semi-detached house, the date of moving in is not exactly the same for both of the apartments, and the increase in water content starts a few days earlier in the northern facing bedroom than in the southern facing bedroom. Two sensors were installed in the head joist of the southern facing bedroom. Only measurements from one of these sensors are included in the analyses, because of problems with the other sensor, resulting in inaccurate measurements.

In some occasions, the water content of the head joists in the southern facing bedroom is higher than in the northern facing bedroom. This only lasts for a few days, and after a period of fluctuating water content values in the southern bedroom, the values stabilize, and the water content starts to decrease. In the northern facing bedroom, the values continues to stay high, and a significant difference between the head joist and the inner joist occurs, making this the worst case of the two bedrooms.

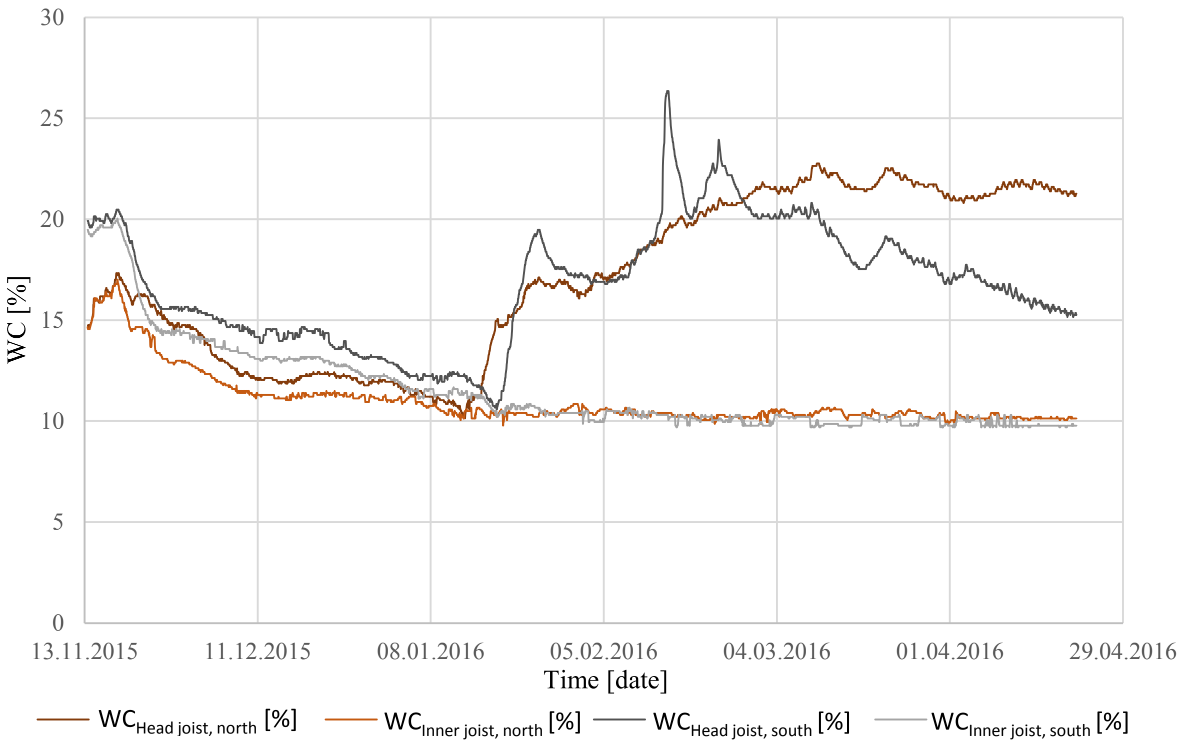

Figure 21*: Moisture content in the head joist and inner joist of the bedrooms towards north and south*

In insulated and uninsulated storage rooms, the water content increases in both the head joists and the inner joists, as the building is taken into use. See figure 22 and 23. This separates these measurements from the measurements in the bedrooms, where the water content of the inner joists were not affected by the changes in indoor climate.

The insulated storage rooms experience a larger difference in water content between the head joists and cross-lying joists, than the uninsulated storage rooms. The orientation of the room has less influence, with just a few percent higher difference in the western facing storage room than in the eastern facing storage room. Analyzes of the relative humidity confirm that the insulated storage room towards west will experience a higher moisture load than the other rooms and can be reckoned as the worst case of the four storage rooms.

In the uninsulated storage rooms towards east, the difference in water content is almost non-exiting, which expectantly makes this the rooms with the least deformational differences. Low activity in the room and no use of indoor heating, which makes the temperature approximately equal to the outdoor temperature, is the main reason, but low solar radiation and wind stresses may also be influential factors.

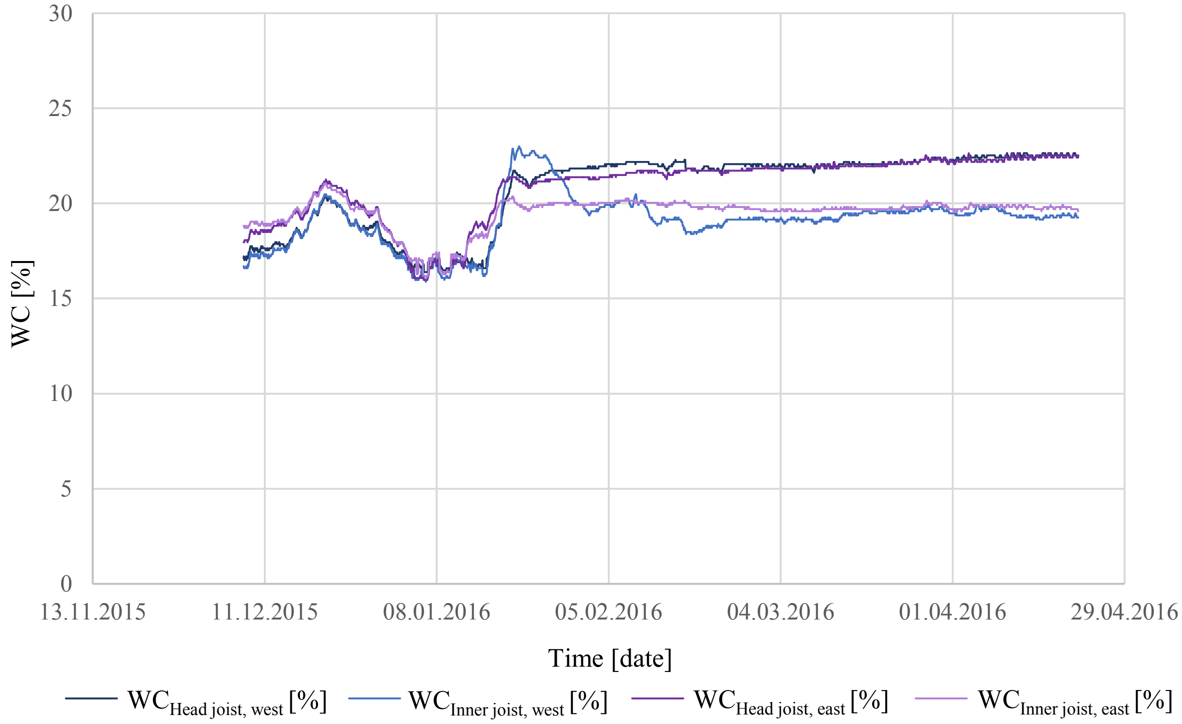

Figure 22: *Water content in the head joist and inner joist of the insulated storage rooms towards east and west*

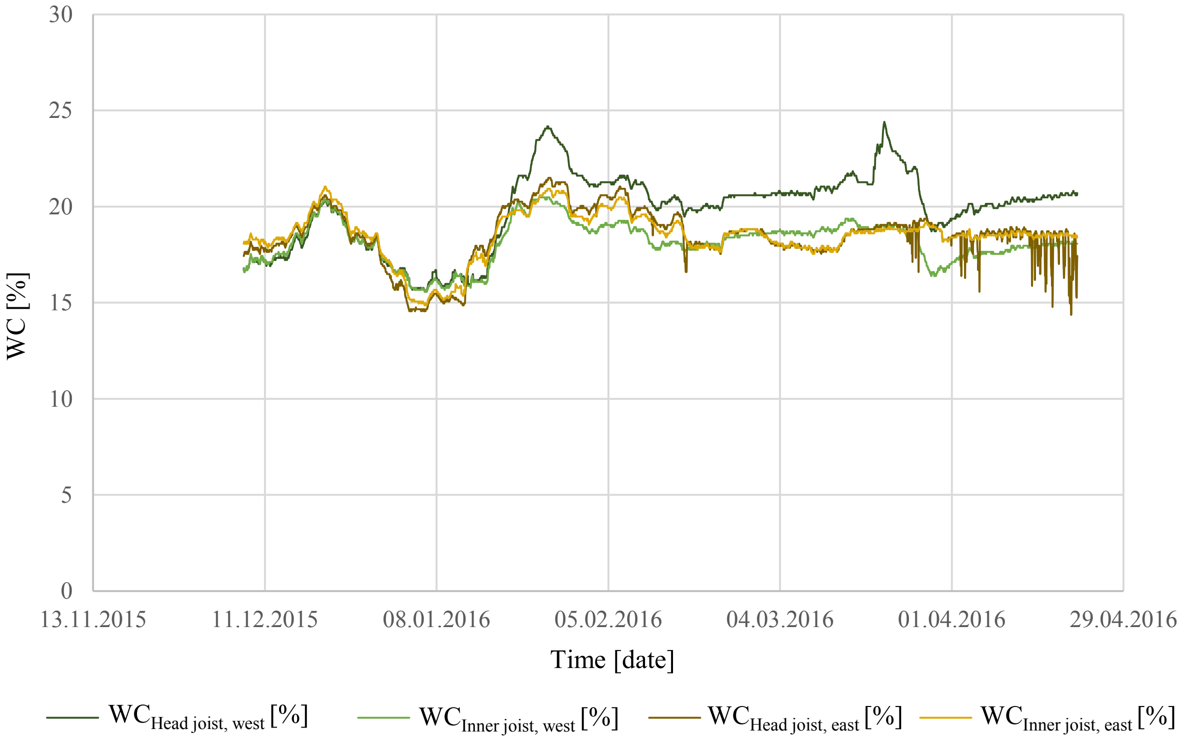

Figure 23: *Water content in the head joist and inner joist of the uninsulated storage rooms towards east and west*

4.2.2 Heated vs. unheated rooms

With the previous analyses of the bedrooms and storage rooms with different orientations, the northern facing bedroom of apartment A and the western facing insulated storage room of apartment B, is reckoned as the two worst cases of the six instrumented bedrooms and storage rooms. Together with the roof construction in the northern facing kitchen of apartment A, these will be compared. Based on the temperature measurements, the storage room is reckoned as a cold room.

Figure 24 shows the water content of the head joist and inner joist of the bedroom and storage room, as well as the head joist in the roof construction in the kitchen. Sensors were installed as the building parts were assembled on site, and the measurements start with different intervals. No measurements are performed on the joists inside the roof structure.

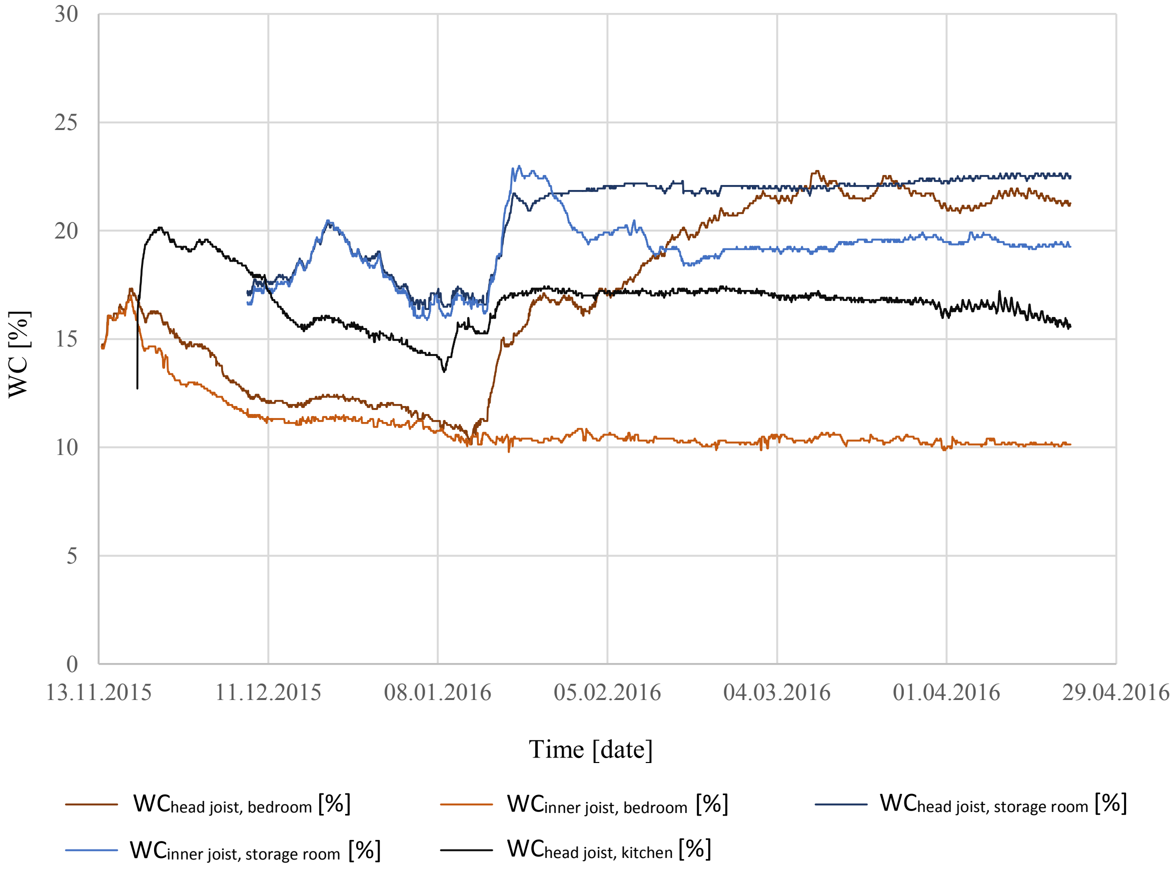

***Figure 24**: Water content of the joists in bedroom, insulated storage room and roof construction in kitchen over time*

Between assembling and the time when the building is taken into use, the water content decreases in all of the joists. When heating of the building occurs, the water content increases in all other joists than the inner joist of the floor system in the bedroom. This indicated that low water content of the inner joists might be a part of the problem, and an influencing factor on the deformations and sloping of the floor. The measurements from the head joist in the roof construction show a relatively low moisture content, indicating that the difference in water content between the head joist and the inner joist of this room is smaller than the equivalent difference in the bedroom.

The total difference in water content between the head joist and the joists inside the floor system is higher in the bedroom than in the storage room. This is a caused by the constant water content of the inner joists in the bedroom, and makes dimensional differences and sloping more likely to occur in this room than the other rooms monitored.

4.2.3 The worst case

The former analyses show that the largest differences in water content occur between the head joist and the inner joists of the bedroom towards north. This result corresponds well with previous observations made by the producer, from buildings where the same construction is used. The changes in water content over time is displayed in figure 25.

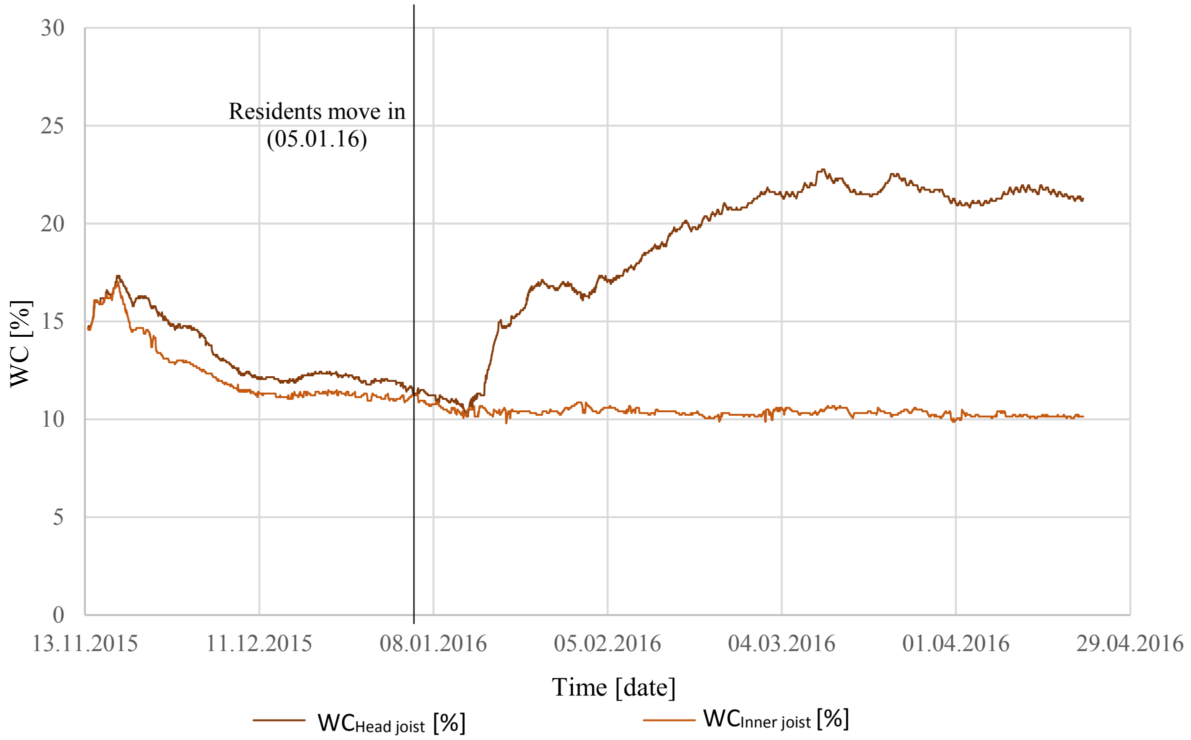

***Figure 25**: Water content in head joist and inner joist of the bedroom towards north*

The maximum difference in water content measured between the head joist and inner joist is approximately 13 %. This is a significant difference, and will most likely result in deformations and sloping of the floor system. The water content in the joist inside the floor system has stabilized at around

10 %, a normal value for this kind of wooden floor system during the winter season in Norway. In the head joist, the water content has been over 20 % for a long period, with maximum values of around 23 %. This is higher than normal values, and in addition to the deformational changes, it will most likely also results in problems regarding mould and rot, if the situation persists. This will again have a negative influence on the indoor air quality.

Until residents move in to the building, the temperature around the head joist and the joist inside the floor system is approximately the same. In the start of January the outdoor temperature experiences a sharp fall, and in eight days, the outdoor temperature drops from 8.1°C to -17.1°C. In the middle of this temperature drop, on January 5, residents move in to the apartment, and a periode of rapid indoor heating to achieve comfort temperature occurs. This makes the temperature around the joists increase significantly. See figure 26.

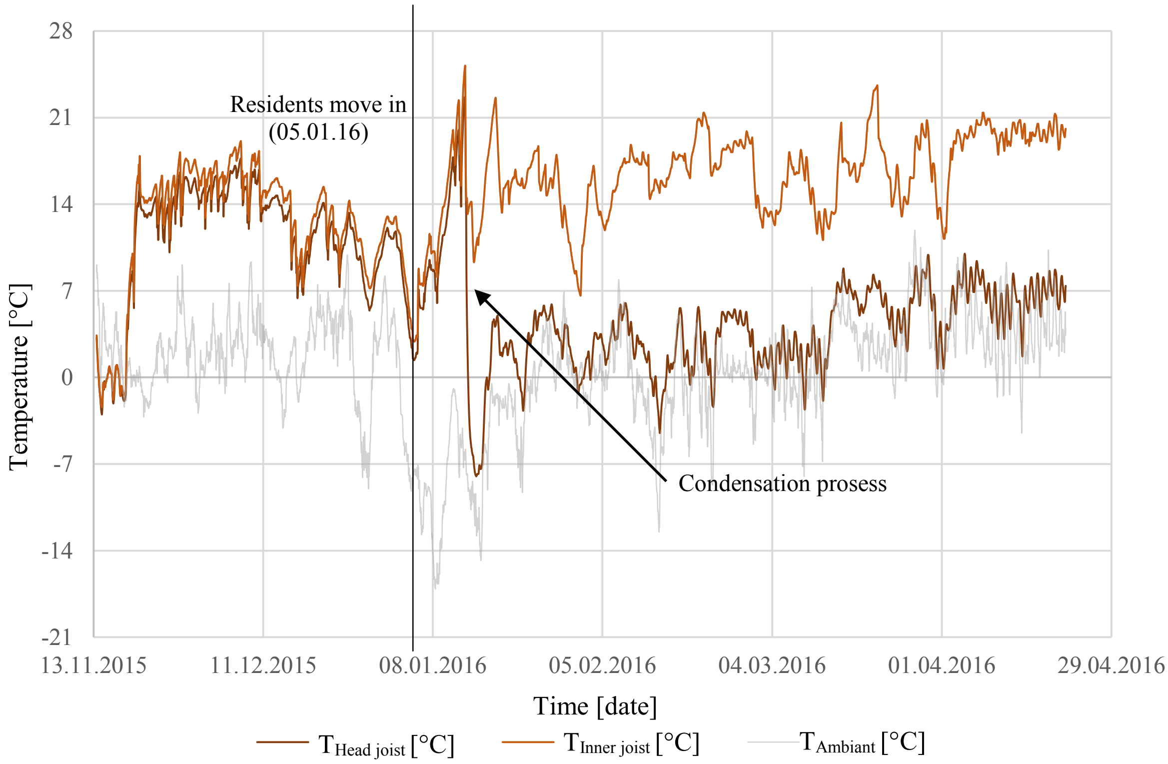

***Figure 26**: Temperature in bedroom joists compared to outdoor temperature*

At the end of the initial heating period, the air around the joists has achieved 23°C. The large difference in temperature that then occurs between the air around the head joist and the outdoor air causes a condensation process. This condensation process, takes heat from the surrounding building materials causing the surface temperature to drop. In just 48 hours, the temperature has decreased with more than 30°C. Since the temperature around the joists inside the floor system is close to the indoor temperature, the difference in temperature is smaller, and a condensation is avoided. After the temperature drop, the head joists adjusts to the outdoor climate. The joist inside the floor system is not affected by the outdoor climate, and the temperature continues to stay high.

Until residents move in, studies of the relative humidity shows that the climate around the joists is getting dryer with a final relative humidity around 30%. After the residents move in, simultaneously with as surface condensation occurs, the relative humidity in the edge joist increases dramatically, from 30 to 90 % in just a few days due to the temperature drop. This is explained by the fact that cold air has a lower ability to store moisture than warm air. As the temperature continuous to stay low, the relative humidity also continuous to stay high. See figure 27.

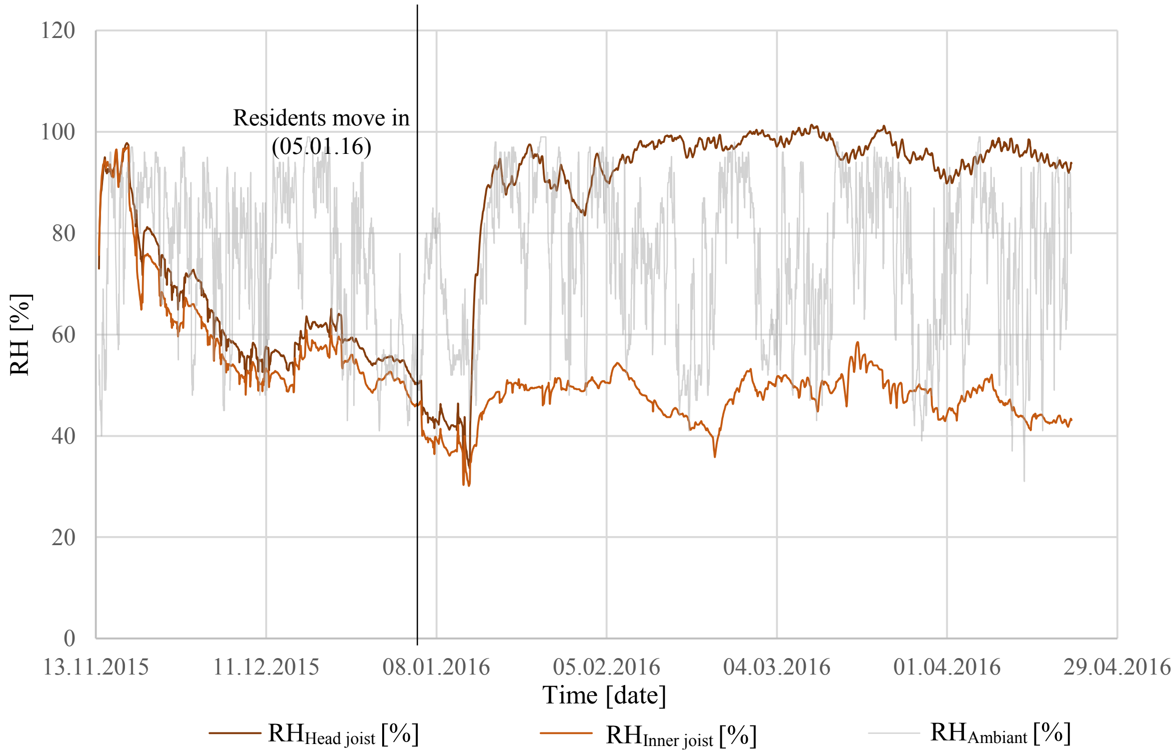

Figure 27: *Relative humidity in bedroom joists compared to outdoor humidity*

4.3 Simulations

Figure 28 shows the simulated moisture contents of the head joist with the reference geometry, the moisture content of the head joist when it is retracted, and the moisture content of the inner joist. The measurements from figure 25 is included for comparison.

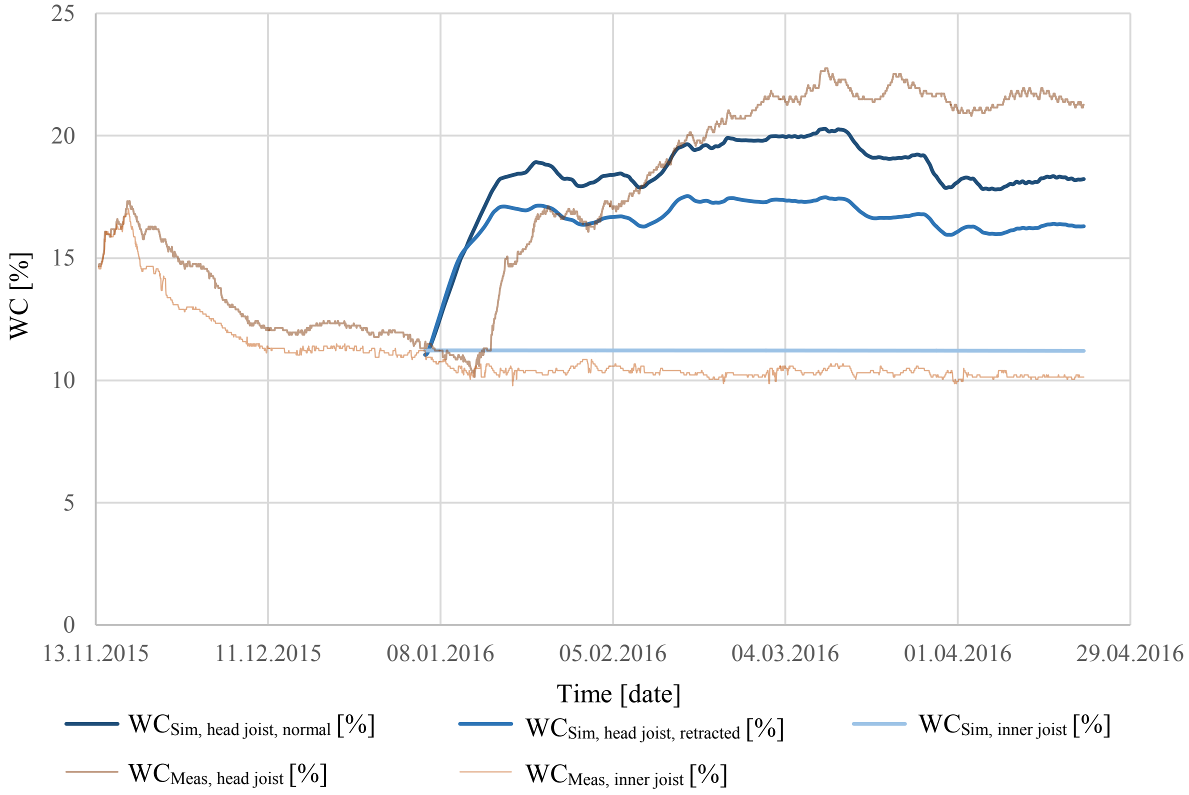

Figure 28*: Comparison of measured and simulated water content of the joists over time*

The simulation results show the same general pattern as the measurements, and a similar increase is observed until January 26. The water content in both the simulations and the measurements increase rapidly and gradually start to decrease. The measured water content continues to increase after a few days. This is also observed in the simulations, but this second increase is a lot smaller, and the water content soon stabilize and starts to decrease.

The difference between the measurement and the simulations might be caused by inaccurate data for the outdoor climate. Simulations of the water content of the inner joist show approximately no change in water content. This is as expected, since the simulations are based on a non-varying indoor climate, and do not include the changes in indoor climate as the building is taken in to use. This result in a smaller simulated difference in water content between the head joist and the inner joist compared to the in-situ measurements of the same case.

By adding 50 mm of insulation on the outside of the head joist, the average water content is reduced by more than 2 %. The difference between the head joist and the inner joist of the floor system is reduced accordingly.

If the simulations had been more accurate, they could have been used to simulate the expected deformations in buildings at other locations and at other times of the year. This would also had made it possible to simulate the long-term deformations of the buildings.

5. Discussion

5.1 Laboratory experiment

The water content of the samples was not monitored during drying and submersion. Moisture content values at these stages was calculated by the following equations, where x represents the moisture states after exposure to the climates previously explained in table 1.

$$WC_{wet/dry} = \frac{Weight_{water}}{Weight_{wet/dry}} * 100\%$$

$$Weight_{water} = Weight_{wet} - Weight_{0\,\%\,MC} \tag{9}$$

$$Weight_{0\,\%\,MC} = Weight_{x} * \frac{100 - WC_{x}}{100\,\%}$$

The calculations gave the following results, presented in table 5.

***Table 5**: Calculated moisture content of the dry and wet samples*

Sensor	Previous climate	Moisture content - dry	Moisture content - wet
2	1	1.34	32.61
4	2	-0.33	34.26
8	3	2.53	36.39
12	4	3.60	39.39

These results show obvious problems with the calculations, when studying both the water content of the dry samples, and the water content of the wet samples. The moisture content after two weeks in the drying chamber is expected to be abound 3-7 %, indication that the calculated values are too low. The calculated moisture content of the wet samples is too high, compared to the expected values.

The calculated moisture content is based on measurements of both weight and water content at a previous climate. Comparisons of the changes in moisture content and weight between two climates, prove that these factors do not increase equally when the wood is exposed to the climates for a short period. Changes in moisture content of the samples takes less time than changes in weight. When comparing the positioning of the sensors only registering moisture content of only the outer part of the samples, together with the fact that moisture absorption is a time-consuming process, these results are well understood.

A better way to find the approximate moisture content of the samples after submersion and drying is to use the regression model in equation 5 with input from the height measurements of the samples. This give the following results, shown in table 6.

Table 6: *Approximated moisture content of the wet and dry samples, by using the regression model*

Sensor	Previous climate	Moisture content - dry	Moisture content - wet
2	1	3.41	19.27
4	2	4.31	21.34
8	3	4.82	24.57
12	4	4.91	26.49

These results are a lot more reasonable than the calculated values in table 5, and indicate that the measured moisture contents of the samples after exposure to the climate chambers are good and that the regression model is valid.

The moisture contents could also have been calculated by the regression model made from the measurements of the width dimensions of the samples, seen in equation 6, but since this model has a lower coefficient of determination, these measurements would have been less accurate. A narrow cross section experiencing major impacts from small inaccuracies in the measurements is the main reason for the lowered coefficient of determination of this regression model.

The maximum swellings of the K-beam are compared to the maximum swellings of solid wood. The results are displayed in table 7. Maximum swelling values for solid wood are based on the assumptions that tangential direction equals height direction and radial direction equals width direction.

Table *7: Comparison between the maximum swelling in K-beams and solid wood beams*

	Height	Width
K-beam	6.7	8.1
Solid wood beam	7.8	3.6

This comparison confirms that the K-beams swell proportionately less in height dimension and more in width dimension compared to solid wood beams. This is as expected, based on previous theory of dimensional changes in wood in relation to the orientation of the annual growth rings.

Carling [4] has claimed that an average 0.2 % increase in the dimensions of the cross-section of regular types of laminated timber can be expected if the water content is increased by one percent. With input from the height dimension under 0 % moisture content of 293,55 mm, calculated by the regression model in equation 5, it is possible make a new equation showing expected height under different moisture contents, based on this statement. See equation 10.

$$Height\ (\Delta MC) = 293.55 * 1{,}002^{\Delta MC} \qquad \text{[mm]} \qquad (10)$$

With a maximum water content of 30 %, this equation present a maximum height dimension of 311.68 mm, resulting in a maximum swelling of 6.18 %. This value is compared to the maximum swelling in the height direction, displayed in table 7, and proves that this Carling's assumptions were good, and that this equation could have been used, if only values for the approximate height deformations of the K-beams were of interest.

Another important observation from the laboratory experiment is how the beams tend to bend under high moisture loads. Bending occur on all of the samples submerged in water, and the degree of deformation increases with the moisture content, with the largest deformations on sample 12, previously exposed to climate 4. See figure 29. All height measurements were originally performed on the same side of the samples, but when the deformations occurred, the measurement points on sample 8 had to be changed from the right side of the sample and to the left side, accordingly to the positions in figure 29, in order to capture the largest deformations. This may have resulted in inaccurate measurements for this sample.

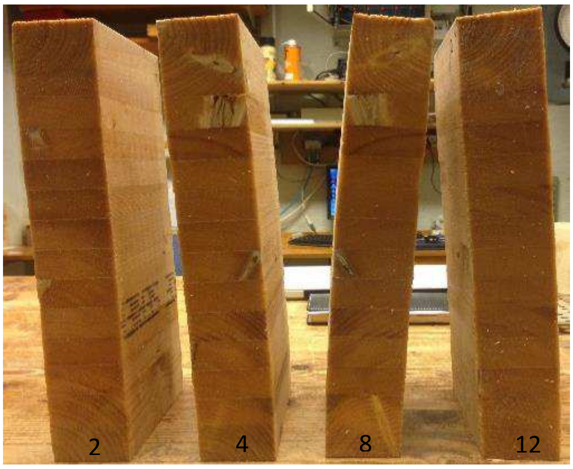

***Figure 29**: Sample 2, 4, 8 and 12, after submersion in water.*

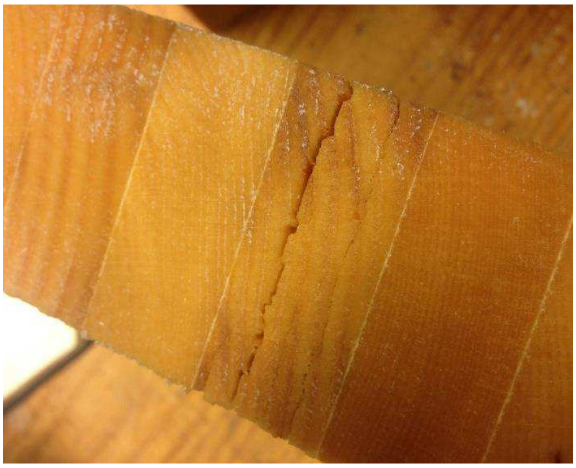

***Figure 30**: Splitting of the wood on the cross section of one of the samples after submersion in*

All the twelve samples in the experiment have approximately the same orientation of the annual growth rings, as explained in figure 31a. This is different from the expected cross section, based on information given by the producer of the beams, shown in figure 17, and explains why the bending occur. With all the lamellas oriented in the same direction, more deformation and a larger height dimension will occur on one of the sides than on the other. This problem could be avoided by changing the orientation of every other lamella, as shown in figure 31b.

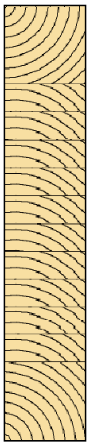

***Figure 31a**: Current cross section*

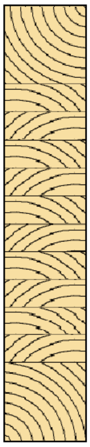

***Figure 31b**: Improved cross section*

The study was restricted to four climates. Exposure to additional climate chambers would have improved the accuracy of the experiment. Additionally, the samples should have been exposed to the same climate for a longer period, to ensure complete stabilization of the water content. Preferably, the experiment should have started with dry samples, and increased the humidity at all samples step-by-step, until the samples were fully saturated. When all samples had reached water saturation point, the process should have been reversed, and the samples dried. With this type of measurement, the hysteresis could have been included, by having measurement points both under submersion and drying.

The present procedure was chosen due to time limitations, and it is believed that the accuracy of the experiment is sufficient for the scope of the problem. The measurements of the dimensions could be more accurate to enhance the regression model, but the high coefficient of determination show that no large measurement errors has been made and the measurement equipment is good enough for this type of experiment. The high water content has resulted in cracks in the samples. See figure 30. This will not be emphasized in this paper, since it has little direct effect on the deformations of the beams, but the producers should still consider it, since it might have an impact on the structural properties of the beams.

5.2 Moisture-induced deformations in the monitored building

With the regression model in equation 5, the height of the joists is calculated. Combining the regression model with the water content gives the time dependent dimensions. This is performed with values from both the in-situ measurements and the simulations, and is displayed in figure 32.

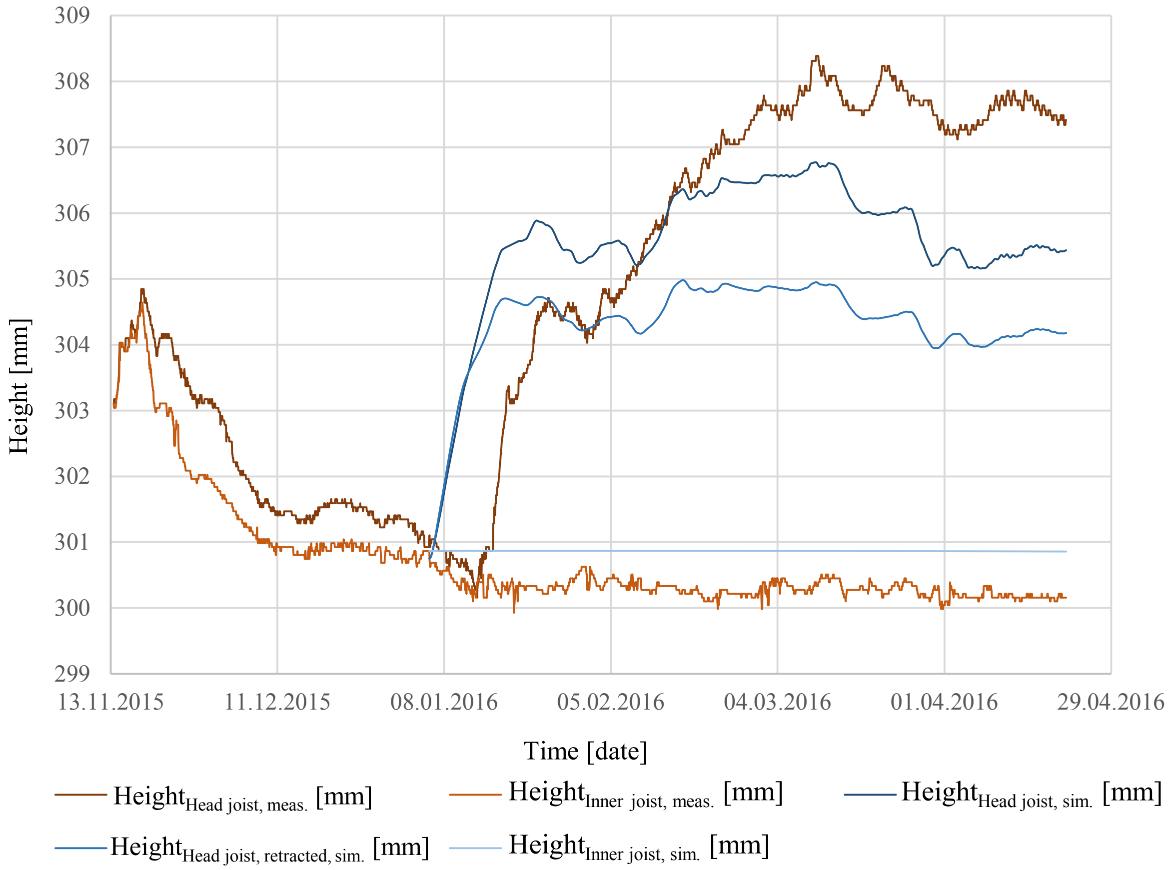

Figure 32: *Heights of the head joist and inner joist over time, with values from in-situ measurements and simulations*

These heights are compared, to find the expected height difference between the head joist and inner joist, at all times. See figure 33.

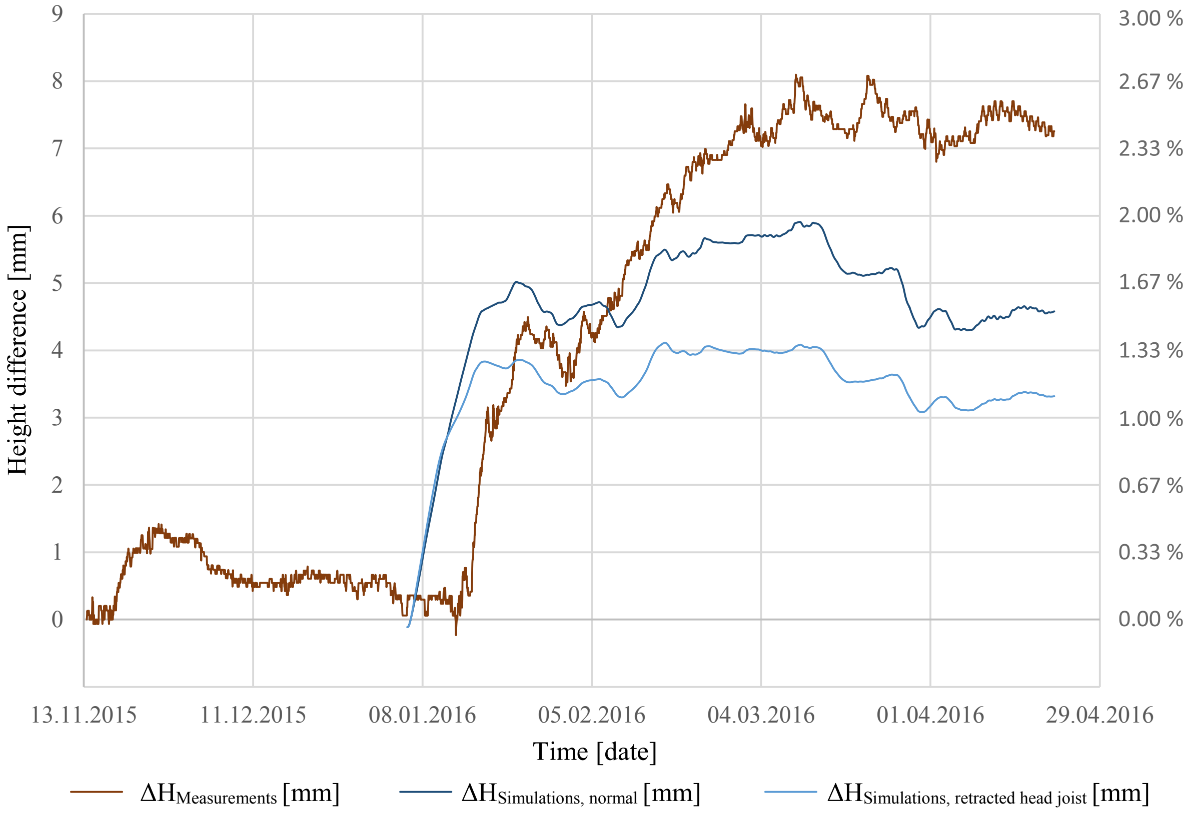

Figure 33*: Height difference between head joist and inner joist over time. Three different graphs are displayed: difference based on the measurements, simulated head case and simulated case with retracted head joist*

The results show large dimensional differences in the in-situ measurements. A total height difference of 7-8 mm is calculated between the head joists and the inner joist, approximately one meter from the edge, of the bedroom in the monitored building. Comparing this to the tolerances given by the Norwegian standard, of less than 3 mm on lengths under two meter, this shows that the building producer should consider changing their constructions.

In the simulated cases, the height difference is approximately 1-2 mm smaller with the retracted, insulated head joist. The results still show a total height difference of more than 3 mm, in both of the cases. This indicates that more than 50 mm insulation outside the head joist in required to have control of the tolerances. Since the height deformation is only reduced by 1-2 mm with 50 mm extra insulation, the assumption that a large amount of insulation is required to reduce the deformations accordingly to the tolerances is made. This might cause problems in the production and assembling of the construction, and other solutions to the problems might be better.

Replacing the head joist with, for example an I-beam, could be a good solution. This would have reduced the height swellings of the joist and the total deformations on the floor system. Another solution could be to create a construction where the vapour barrier is continuous between the first and the second floor, to prevent moisture from the indoor climate to enter the head joist.

6. Conclusion

Laboratory experiments verify that linear swelling and shrinkage of the K-beams under alternating climates is expected. The orientation of the annual growth rings have a significant influence on the maximum deformations, and the experiment proves that K-beams will experience less swelling in height direction, than solid wood beams with similar dimensions, under the same climatic conditions.

The analyses of the in-situ measurements show that the head joists are largely affected by outdoor climate. The temperature around the joist is nearly the same as outdoor temperature, and the moisture level is equivalent to the highest moisture levels measured in the outside air at the current time period. The climate in the inner joists follow indoor climate and a warm and dry climate inside results in a low water content of the joists. This proves that high moisture- and temperature gradients between the outdoor and indoor climate is the main reason for the large differences in water content between the head joist and the inner joist, and imply that larger differences may occur in cases where the gradients are even higher.

Correct values for indoor and outdoor climate throughout the whole simulation period is crucial for achieving accurate simulations. Large changes in indoor and outdoor temperature are especially difficult to simulate, causing the simulated values during the heating period of a new building to deviate from the measured values of the same case.

The difference in water content measured between the head joist and the inner joist of the floor system will result in a considerable height difference and sloping of the floor. The building producer is working on finding a solution to this problem, which will increase the tolerances of the floor system. By retracting the head beam 50 mm and adding insulation on the outside, the construction is improved, but the expected height difference is still too large, and the producer should consider moving the head beam even further in or change the construction in another way.

7. Limitations and further studies

Further studies on the data from the monitored building should definitely be performed. The sensors will register values for temperature, relative humidity and moisture content of the joists for several years to come. Analyses of these measurements can show if the problems is persistent throughout all seasons, if the moisture content of the head joist will decrease and if the deformational differences will be limited over time.

The studies has been limited to one building, due to time issues and the amount of resources and measurement equipment available. In-site measurements from several locations, where the climate is different, would give a better understanding of the climate-induced impacts. If new measurements are performed, they should include buildings assembled in all seasons, to see how this affects the total deformations, as well as sensors registering the water content of the inner joist in areas closer to the head joist, to capture the potential water transfer from the head joist to the inner joists.

If the simulations are improved and start to resemble the in-situ measurements better, simulations of similar constructions with beams of a smaller dimensions or other types of beams, for example I-beams, should be performed. The simulations and laboratory experiment should also be improved, to include the hysteresis effect.

When studying the expected dimensional deformations, only the moisture-induced deformations are included, and deformations due to load stresses are not evaluated. Since the main deformations occur in the floor system of the buildings, the load stresses from the second floor, roof construction and exterior factors, like wind and snow loads, might influence on the total deformation of the joists. These stresses has been ignored in order to simplify the calculations, and further studies should be made, where these factors are included.

Further studies of the changes in width dimension of the joists, and how these affect the total deformations in the building, is also of interest. This statement is based on the calculation showing relatively large deformations in the width dimensions, despite a narrow cross-section.

Another aspect, only briefly evaluated in this thesis, is the problems in the joists regarding mould and rot. A water content of 23 % has previously resulted in mould on the joists, and assumptions that these problems also occur in several other buildings is made. Measures to avoid the problems, as well as analyses of the structural defects it has on the building components, should be included in further studies.

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Appendix A: Calculations for maximum swelling

Height

$$Height_{green} = 0.6519 * WC_{green} + 293.55\ mm$$
$$Height_{green} = 0.6519 * WC_{green} + 293.55\ mm$$
$$Height_{green} = 313.11\ mm$$

$$Height_{dry} = 0.6519 * WC_{dry} + 293.55\ mm$$
$$Height_{dry} = 0.6519 * 0 + 293.55\ mm$$
$$Height_{dry} = 293.55\ mm$$

$$Maximum\ height\ swelling = \frac{Height_{green} - Height_{dry}}{Height_{dry}} * 100\ \%$$
$$Maximum\ height\ swelling = \frac{313.11 - 293.55}{293.55} * 100\ \%$$

$$Maximum\ height\ swelling = 6.66\ \%$$

Width

$$Width_{green} = 0.1276 * WC_{green} + 46.90\ mm$$
$$Width_{green} = 0.1276 * 30 + 90\ mm$$
$$Width_{green} = 50.72\ mm$$

$$Width_{dry} = 0.1276 * WC_{dry} + 46.90\ mm$$
$$Width_{dry} = 0.1276 * 0 + 46.90\ mm$$
$$Width_{dry} = 46.90\ mm$$

$$Maximum\ width\ swelling = \frac{Width_{green} - Width_{dry}}{Width_{dry}} * 100\ \%$$
$$Maximum\ width\ swelling = \frac{50.72 - 46.90}{46.90} * 100\ \%$$

$$Maximum\ width\ swelling = 8.14\ \%$$

These calculations are based on a water content of 30 % when green and 0 % when dry.

Appendix B: Article for the WCTE

WCTE 2016
World Conference on
Timber Engineering
August 22-25, 2016 | Vienna, Austria

MOISTURE INDUCED DEFORMATIONS IN PREFABRICATED WOODEN BUILDING MODULES

May-Linn Sortland[1], Thomas Kringlebotn Thiis[2], Dimitrios Kraniotis[3], Kristine Nore[4]

ABSTRACT: Variation in micro climate induce shrinkage and swelling of wooden beams. The dimensional changes depend of the orientation of the annual growth rings and the moisture content of the beams. This causes laminated timber to experience different deformations than solid wood. A producer of element buildings with joists of laminated wood, have experienced deformations and sloping of the floor structure in several buildings, and believe that these might be caused by moisture. This paper combines in-situ measurements with simulations and a laboratory experiment, to make a survey of where in the buildings these problems are most likely to occur, and to estimate how much deformation the producer can expected in these areas. The results show that the largest deformations occur in a bedroom facing north, with low solar radiation and high moisture gradients between indoor and outdoor climate. In this room, a 13 % difference in moisture content is measured between the head joist and inner joist, one meter from the edge of the floor system. This results in an estimated height difference of almost 8 mm, a value higher than the tolerances for finished surfaces. The producer will improve their construction accordingly.

KEYWORDS: Element buildings, moisture, deformations, in-situ measurements, numerical simulations

1 INTRODUCTION

Changes in moisture content results in swelling and shrinkage of wooden materials. In the range from zero to 30% moisture content, a perfect sample of spruce swells and shrinks approximately linearly. [1] The dimensional deformations vary between the three main directions of the wood. For a perfect sample of spruce, the total shrinkage from green to dry is approximately 7.8 % in tangential direction, 3.6 % in radial direction and 0.3 % in longitudinal direction. [2] The cross section of a typical solid wood beam and the main directions of the wood can be seen in figure 4b. Air with high relative humidity causes wood to swell, while dry air induce shrinkage.

Mårtensson [3], describes deformations in the sill and beam supports to be typical deformations perpendicular to grain, and claims these are the dominant deformations in, for example, multi-story wood framed buildings. The directions of the annual growth rings in joists of laminated timber are different from solid wood. In extreme cases, the radial and tangential directions are shifted compared to solid wood joist. This will lead to different dimensional deformations in a building with joists of laminated timber than in a similar building with joists of solid wood.

Dimensional instabilities has resulted in problems for a Norwegian producer of prefabricated element buildings. Deformations occur in the head joists of the floor system, likely caused by moisture and swelling. See figure 1. The head joist changes dimensions relative to the surrounding climate, and the whole floor system bends and slopes inward. This has led to problems when installing balconies and wall elements of the second floor.

The producer has observed that climate on site plays an important role, and the worst cases registered have been in the north of Norway, in areas where the temperature is low and the climate is humid. The orientation of the building, indoor climate and season, may also influence on the problem.

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[1] May-Linn Sortland, Norwegian University of Life Sciences, may-linn.sortland@nmbu.no

[2] Thomas Kringlebotn Thiis, Norwegian University of Life Sciences, thomas.thiis@nmbu.no

[3] Dimitrios Kraniotis, Norwegian Institute of Wood Technology, dimitrios.kraniotis@treteknisk.no

4 Kristine Nore, Norwegian Institute of Wood Technology, kristine.nore@treteknisk.no

This paper presents a case study from a two-story, semi-detached module building in Trondheim, situated at 63 degrees North, in Norway. The building construction is made of prefabricated elements, produced in an indoor climatically controlled industrial hall. The assembling of the building started in November 2015.

All the joists in the floor and roof systems of the building are made of laminated timber of Nordic spruce, with dimensions 48*300 mm. This type of joist is specifically designed for roof and floor constructions that need a high degree of stability in dimension. [4] When assembling the construction, the floor element is placed between the two wall elements, the wind barrier is fastened and a cardboard sealing and cladding is installed on the outside of the head joist. See figure 1.

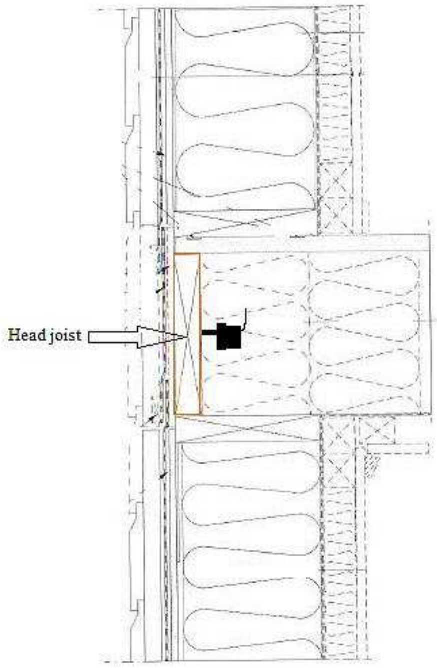

Figure 1*: Cross section of the construction, with sensor*

The head joist is close to the cladding, and will experience large variations in temperature, and in some periods temperatures below freezing point. This means that the micro scale climate and the orientation of the building will influence on the thermal and moisture conditions of the head joist.

According to the Norwegian Standards, the sloping tolerances of finished surfaces is maximum 7.5 mm on lengths more than 5 meters, 1.5 ‰ for lengths between 2 – 5 meters, and 3 mm if the length is shorter than 2 meters. [5] Since moisture is important for these tolerances, critical moisture level, defined as the highest moisture content a material can have without experiencing moisture related damages, is suggested to be 20% in walls and 12% in floors. [6]

The objective of this paper is to determine if the experienced dimensional deformations can be explained by the moisture content of the joists. Secondly, the moisture induced deformations expected between the head joist and the inner joist of the floor system is of interest for the building producer.

2 METHOD AND MATERIALS

Measurements from the case studies are used to verify numerical simulations of heat and moisture in the floor system. The moisture induced dimensional variation of the joists has been determined in controlled climates in laboratory experiments.

2.1 LABORATORY EXPERIMENTS

To define the moisture induced dimensional variations, laboratory experiments are performed. A regression model of dimensional deformations under different water content levels is created from the measurement results. This model is used to determine the dimensional variations over time, with input of moisture content from the measurements in the case study and from the numerical simulations.

The experiment involves twelve samples of K-beams, exposed to four different climates. The edges of the samples were sealed, to avoid moisture absorption in longitudinal direction. The samples were distributed between four climate chambers with the climates described in table 1.

Table 1*: The four climates examined*

Climate	Samples	RH [%]	T [°C]
1	1 – 3	43	20
2	4 – 6	65	
3	7 – 9	86	
4	10 – 12	99	

After moisture stabilization, the weight of the samples and the dimensions of the cross sections was measured. The height of the samples was measured at three positions. See the black lines on figure 2. The width was measured at five positions, to find an average width of the joists. To keep track of the water content, sensors were installed on each sample.

To see the extreme values, four samples, one from each of the previous climates were submerged in water and subsequently dried.

Figure 2: *The twelve samples studied in the laboratory experiment, with sensors and measurement positions*

2.2 IN-SITU MEASUREMENTS

Data is collected from a building located south-west of Trondheim city in Norway. The site is 197 meters above sea level, and is climatically exposed to wind, rain and solar radiation.

Fifteen sensors, measuring temperature and moisture content, is installed in the building. Thirteen of these sensors are in the floor construction between the first and the second floor, distributed between the head joists and the inner joists of the floor system. The remaining two sensors are placed in the roof construction. With these sensors, the difference in water content between the head joist of the roof construction and the head joist of the floor slab can be reviewed. A total of seven rooms were instrumented, with a mixture of heated and unheated rooms. Figure 3a and 3b show the location of all the sensors.

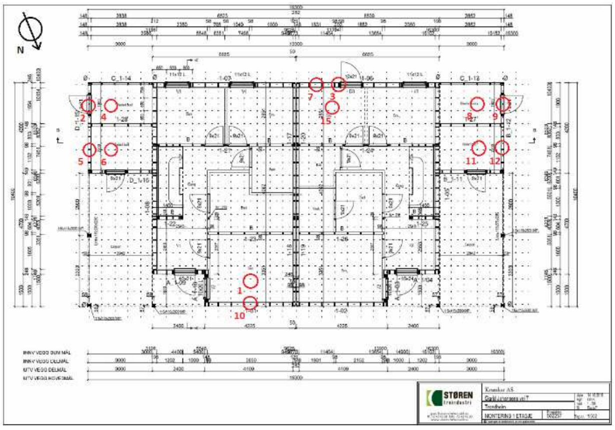

Figure 3a: *Sensors in the platform construction between the floors, indicated with circles*

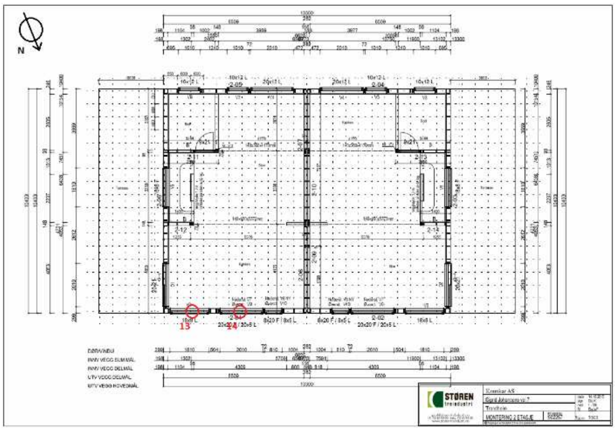

Figure 3b: *Sensors in the roof construction, indicated with circles*

All the joists in the floor system are made of glued laminated timber of spruce. The cross section consists of two 47 mm thick outer lamellas and ten 2.06 mm thick inner lamellas, glued together by moisture resistant Emulsion Polymer Isocynate (EPI) adhesive glue. The outer lamellas are normally 6000 mm long. The inner lamellas are shorter, between 240-900 mm, and are finger jointed to a length of 6000 mm. This type of beam is developed by the Norwegian company Kjeldstad, and is called a "K-beam". [7] See figure 4a.

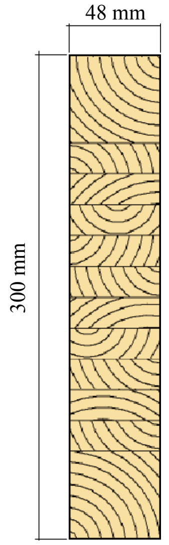

Figure 4a: *K-beam*

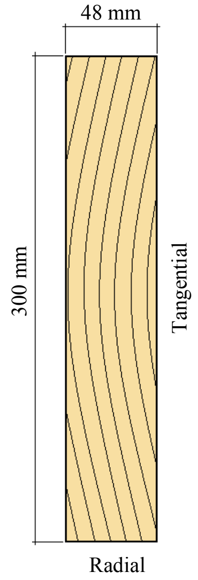

Figure 4b: *Beam of solid wood*

2.3 NUMERICAL SIMULATIONS

2.3.1 Program description

WUFI-2D, a two-dimensional, hydrothermal, State of the art Heat and Moisture (HAM) simulation tool is used to perform the simulations of the problem. Based on the finite element method, WUFI-2D analyses heat and moisture transfer of building envelope constructions, by developing a closed differential equation system, which calculates the moisture behavior of multi-layered building components under natural climatic boundary conditions. It is based on a derivation of a coupled equation system and a numerical solution technique. [8]

The program introduces two potentials for moisture flow: the liquid transport flux, which depends on relative humidity, and the vapour diffusion flux, which depends on vapour pressure. The airflow is not considered in the assessment of moisture behavior. [9]

Energy transfer is calculated by the following equation

$$\frac{dH}{d\vartheta} * \frac{\delta\vartheta}{\delta t} = \nabla * \left(\lambda\nabla\vartheta\right) + h_v\nabla * \left(\delta_p\nabla(\varphi p_{sat})\right) \tag{1}$$

Moisture transfer is calculated by the following equation

$$\frac{dw}{d\varphi} * \frac{\delta\varphi}{\delta t} = \nabla * \left(D_\varphi\nabla\varphi + \delta_p\nabla(\varphi p_{sat})\right) \tag{2}$$

Where

$\frac{dH}{d\vartheta}$	[J/m^{3}K]	heat storage capacity
$\frac{dw}{d\varphi}$	[kg/m^3]	moisture storage capacity
λ	[W/mK]	thermal conductivity
D_φ	[kg/ms]	liquid conduction coefficient
δ_p	[kg/msPa]	water vapour permability
h_v	[J/kg]	water evaporation enthalpy

p_{sat}	[Pa]	water vapour saturation pressure
ϑ	[°C]	temperature
φ	[-]	relative humidity

2.3.2 Simulation input

Two cases are simulated. The reference case is similar to the detail given by the producer, seen in figure 1. The setup for this geometry is displayed in figure 5a. The other simulation is similar to the reference case, but contains an extra 50 mm thick insulation layer on the outside of the head joist. See figure 5b. This case is simulated in order to see if this detail will lead to better results regarding moisture and temperature.

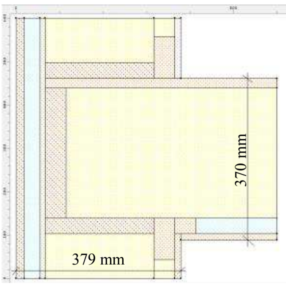

***Figure 5a**: Geometry of the reference case*

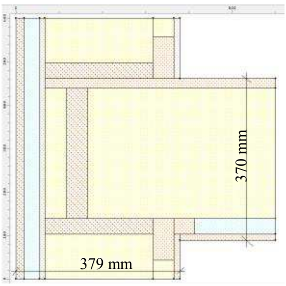

***Figure 5b**: Geometry of the case with retracted head joist*

The numerical grid is refined in the areas where large gradients of temperature and moisture is expected. A description of materials and dimensions can be seen in table 2. The simulations start when the building is taken in to use. Initial conditions of the materials at this time, is obtained from the in-situ measurements of the building.

Table 2: ***Material data***

		Bulk density [kg/m³]	**Thermal Cond.** [W/mK]	**δ - Value** [-]	
				x	y
Wall element	Ext. cladding	430	0.13	50	83.3
	Air, 36mm	1.3	0.21	0.415	
	Wind barrier	130	2.3	20	
	Cardboard	235	0.049	20	
	Insulation	60	1.3	0.037	
	Vapour barrier	130	2.3	1000000	
	Int. cladding	510	0.13	50	
Floor element	Subfloor	550	0.14	50	
	Head joist	430	0.13	83.3	50
	Inner joists	430	0.13	4.3	50
	Insulation	60	1.3	0.037	
	Air, 36mm	1.3	0.21	0.415	
	Ceiling	510	0.13	50	

The simulated cases are oriented towards north, and based on the assumption of a normal indoor climate defined in EN 15026. [10] With these assumptions, high moisture gradients between indoor and outdoor temperature and low solar radiation is expected. Temperature and moisture in both the head joist and inner joists is simulated.

For the outer surface, weather data obtained from a nearby weather station in Trondheim is used. This includes hourly values of temperature, relative air humidity, air pressure, rain, wind direction, wind speed and solar radiation.

3 RESULTS AND DISCUSSION

3.1 LABORATORY EXPERIMENTS

The changes in dimensions and weight of the different samples was considerable. A summary of the results can be seen in table 3. This paper focuses mainly on the changes in height in relation to the water content of the joists. The water content during drying and submersion was not monitored, excluding these measurements from the graph showing height versus moisture content.

***Table 3**: Data from the laboratory experiment*

	RH [%]	**WC** [%]	**Height** [mm]	**Width** [mm]	**Weight** [g]
Dry	~0	-	295.8	46.6	863.6
			296.4	46.9	851.9
			296.7	46.6	846.7
			296.8	46.6	837.0
After climate chambers	43	8.3	298.8	48.0	940.4
		8.6	299.0	48.0	948.8
		8.8	299.3	47.9	937.6
	65	9.4	299.4	48.1	966.9
		9.7	300.6	48.2	960.9
		10.2	300.3	48.3	951.5
	86	12.2	301.7	48.7	1011.9
		12.4	301.3	48.5	963.0
		12.6	301.8	48.2	991.3
	99	18.0	305.4	49.0	1038.2
		18.1	305.3	49.2	1054.4
		18.3	305.4	49.4	1013.7
Wet	100	-	306.1	49.9	1264.4
			307.5	50.1	1300.2
			309.6	50.1	1297.4
			310.8	50.5	1311.3

The measurement results after three weeks of exposure in the climate chambers is displayed in figure 6. With these results, a linear regression model is made. See equation 3. This model has a coefficient of determination (R^2) of 0,989.

$$Height = 0.6519 * WC + 293.55 \qquad [mm] \tag{3}$$

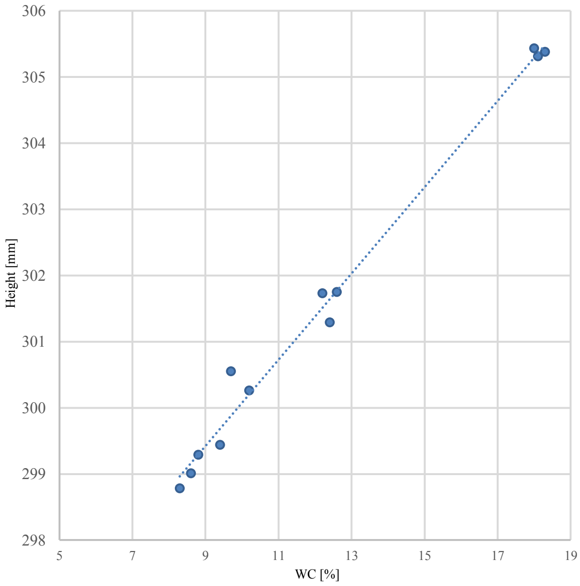

Figure 6*: Measurement points of water content versus height and the regression model created between these points*

This model will mainly be used to calculate the heights of the joists in the monitored building over time, but it can also be used to calculate the maximum swelling of the K-beams, based on the assumption of linear swelling and shrinkage. Maximum swelling is calculated by the following equation

$$Maximum\ swelling = \frac{Height_{green} - Height_{0\%\,WC}}{Height_{0\%\,WC}} * 100\% \qquad (4)$$

With a presumed water content of 30% when green, the maximum swelling of the height dimension on the K-beam is calculated to be 6.7%. This value is compared to the maximum swelling in the tangential direction of solid wood beams, of 7.8%. For a perfect sample of spruce, tangential direction equals height direction in solid wood beams. See figure 4b. The results from this comparison, confirms that the K-beams swell proportionately less in height dimension compared to solid wood beams.

Another important observation from the experiment is how the beams tend to bend under high moisture loads. Bending occurs on all of the samples submerged in water, and the degree of deformation increases with the moisture content, with the largest deformations on sample 12, previously exposed to climate 4. See figure 7.

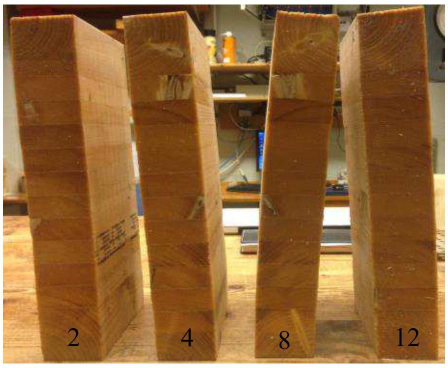

Figure 7*: Sample 2, 4, 8 and 12, after submersion in water.*

All the twelve samples in this experiment have approximately the same orientation of the annual growth rings, as explained in figure 8a. This is different from the expected cross section, given by the producer of the beams, shown in figure 4a. With all the lamellas oriented in the same direction, the total beam will bend, and a larger height dimension will occur on one of the sides than on the other, increasing the maximum height deformation of the beam. This problem could be avoided by changing the orientation of every other lamella, as shown in figure 8b.

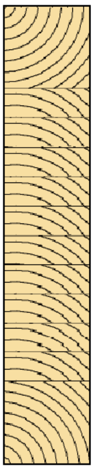

Figure 8a: *Current cross section*

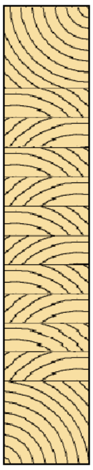

Figure 8b*: Improved cross section*

The study was restricted to four climates. Exposure to additional climate chambers would have improved the accuracy of the experiment. Additionally, the samples should have been exposed to the same climate for a longer period, to ensure complete stabilization of the water content. Preferably, the experiment should have started with dry samples, and increased the humidity at all samples step-by-step, until the samples were fully saturated. When all samples had reached water saturation point, the process should have been reversed, and the samples dried. With this type of measurement, the hysteresis could have been included, by having measurement points both under submersion and drying.

The present procedure was chosen due to time limitations, and it is believed that the accuracy of the experiment is sufficient for the scope of the problem.

The measurements of the dimensions could be more accurate to enhance the regression model, but the high coefficient of determination show that no large measurement errors has been made and the measurement equipment is good enough for this type of experiment.

The high water content has resulted in cracks in the samples. This will not be emphasized in this paper, since it has little direct effect on the deformations of the beams, but the producers should still consider it, since it might have an impact on the structural properties of the beams.

3.2 IN-SITU MEASUREMENTS

3.2.1 Orientation

Based on moisture load and indoor climate it is sensible to compare bedrooms and storage rooms with different orientations.

Significant changes in the water content occur in the head joists in the bedroom as the indoor climate changes, when residents move in to the building. Since the building is a semi-detached house, the date of moving in is not exactly the same for both of the apartments, and the increase in water content starts a few days earlier in the northern facing bedroom than in the southern facing bedroom.

In some occasions, the water content of the head joists in the southern facing bedroom is higher than in the northern facing bedroom. This only lasts for a few days, and after a period of fluctuating water content values in the southern bedroom, the values stabilize, and the water content starts to decrease. In the northern bedroom, the values continues to stay high, making this the worst case of the two bedrooms.

In insulated and uninsulated storage rooms, the water content increases in both the head joists and the inner joists, as the building is taken into use. This separates these measurements from the measurements in the bedrooms, where the water content of the inner joists were not affected by the changes indoor climate.

The insulated storage rooms experience a larger difference in water content between the head joists and cross-lying joists, than the uninsulated storage rooms. The orientation of the room has less influence, but based on analyzes of the relative humidity, the insulated storage room towards west is reckoned as the worst case of the four storage rooms.

3.2.2 Heated vs. unheated rooms

Studying the moisture content of the joists in the view of room temperature, three rooms are compared: The northern facing bedroom, the insulated storage room towards west and the roof construction in the kitchen. Based on the temperature measurements, the storage room is reckoned as a cold room.

In the kitchen, no measurements are performed on the joists inside the roof structure. The measurements from the head joist suggest that the difference in water content between the head joist and the inner joist of this room is smaller than the equivalent difference in the bedroom.

Figure 9 show the water content of the head joist and inner joist of the bedroom and storage room, as well as the head joist in the roof construction in the kitchen. Sensors were installed as the building parts were assembled on site, and the measurements start with different intervals.

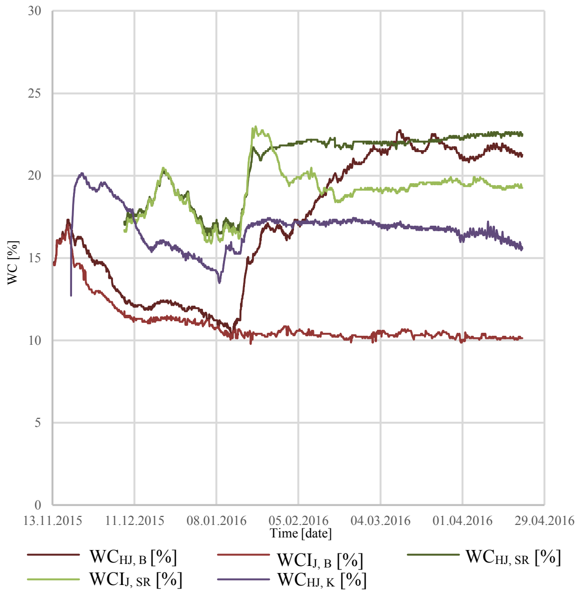

***Figure 9**: Water content in joists in the insulated storage room, bedroom and roof construction over time.*
HJ = head joist, IJ = inner joist, B = bedroom, K = Kitchen, SR = Storage room

Between assembling and the time when the building is taken into use, the water content decreases in all of the joists. When heating of the building occurs, the water content increases in all other joists than the inner joist of the floor system in the bedroom. This indicated that low water content of the inner joists might be a part of the problem, and an influencing factor on the deformations and sloping of the floor. The water content in the roof construction increases the least, and stabilizes faster than in the other rooms. Less deformational problems will occur in this room.

The total difference in water content between the head joist and the joists inside the floor system is a lot higher in the bedroom than in the storage room. This is a caused by the constant water content of the joists in the bedroom, and makes dimensional differences and sloping more likely to occur in this room than the other rooms monitored.

3.2.3 The worst case

The largest differences in water content between the head joist and the inner joists occur in the bedroom towards north. This result corresponds well with previous observations made by the producer, from buildings where the same construction is used. Changes in water content over time is displayed in figure 10.

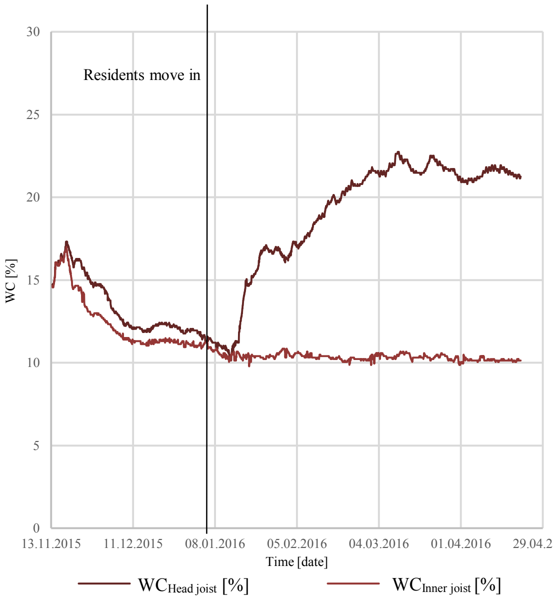

***Figure 10**: Water content in head joist and inner joist of the bedroom towards north*

The maximum difference in water content measured between the head joist and inner joist is approximately 13 %. This is a significant difference, which most likely will result in deformations and sloping. The water content in the joist inside the floor system has stabilized at around 10 %, a normal value for this kind of wooden floor system during the winter season in Norway. In the edge beam, the water content has been over 20 % for a long period, with maximum values of around 23 %. This is higher than normal values, and in addition to the deformational changes, it will most likely also results in problems regarding mould and rot, if the situation persists. This will again have a negative influence on the indoor air quality.

Until residents move in to the building, the temperature around the head joist and the joist inside the floor system is approximately the same. In the start of January the outdoor temperature experiences a sharp fall, and in eight days, the temperature drops from 8.1°C to -17.1°C. In the middle of this cold period, on January 5, residents move in to the apartment, and a periode of rapid indoor heating to achieve comfort temperature occurs. This makes the temperature around the joists increase significantly. See figure 11.

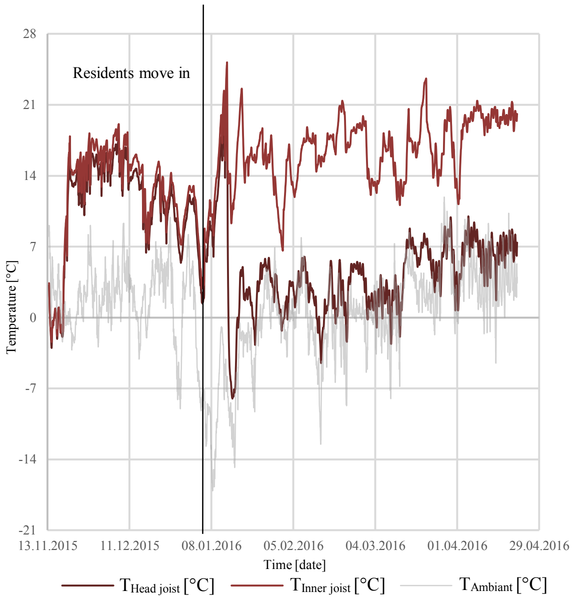

***Figure 11**: Temperature in bedroom joists compared to outdoor temperature*

At the end of the initial heating period, the air around the joists has achieved 23°C. The large difference in temperature that then occurs between the air around the head joist and the outdoor air causes a condensation process. This condensation process, takes heat from the surrounding building materials causing the surface temperature to drop. In just 48 hours, the temperature has decreased with more than 30°C. Since the temperature around the joists inside the floor system is close to the indoor temperature, the difference in temperature is smaller, and a condensation is avoided.

After the temperature drop, the head joists adjusts to the outdoor climate. The joist inside the floor system is not affected by the outdoor climate, and the temperature continues to stay high.

Until residents move in, studies of the relative humidity shows that the climate around the joists is getting dryer with a final relative humidity around 30%. After the residents move in, simultaneously with as surface condensation occurs, the relative humidity in the edge joist increases dramatically, from 30 to 90 % in just a few days due to the temperature drop. This is explained by the fact that cold air has a lower ability to store moisture than warm air. As the temperature continuous to stay low, the relative humidity also continuous to stay high. See figure 12.

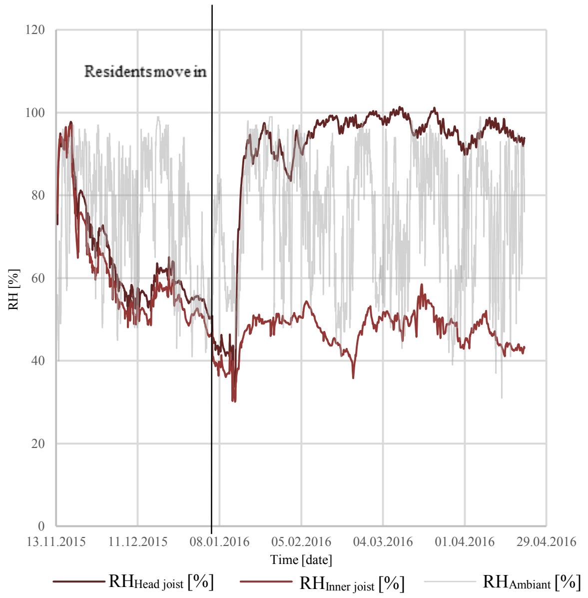

***Figure 12**: Relative humidity in bedroom joists compared to outdoor humidity*

3.3 SIMULATIONS

Figure 13 shows the results from the two simulations of the water content in the head joist and the inner joist. The measurements from figure 10 is included for comparison.

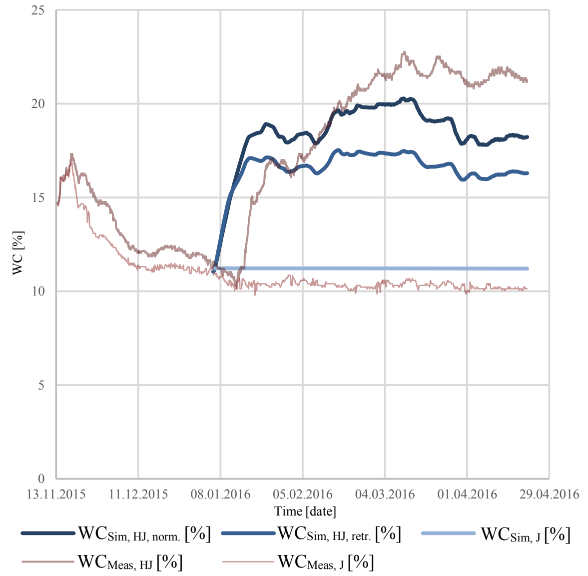

***Figure 13**: Comparison of measured and simulated water content of the joists over time*

The simulation results shows the same general pattern as the measurements, and a similar increase is observed until January 26. The water content in both the simulations and the measurements increase rapidly and gradually start to decrease. The measured water content continues to increase after a few days. This is also observed in the simulations, but the increase is a lot smaller and the water content soon stabilize and starts to decrease.

The difference between the measurement and the simulations might be caused by inaccurate data for the outdoor climate. Simulations of the water content of the inner joist show approximately no change in water content. This is as expected, since the simulations are based on a non-varying indoor climate, and do not include the changes in indoor climate as the building is taken in to use.

This result in a smaller simulated difference in water content between the head joist and the inner joist compared to the in-situ measurements of the same case.

By adding 50 mm of insulation on the outside of the head joist, the average water content is reduced by more than 2 %. The difference between the head joist and the inner joist of the floor system is reduced accordingly.

3.4 DEFORMATIONS

With the regression model in equation 3, the height of the joists is calculated. Combining the regression model with the water content gives the time dependent dimensional changes. This is performed with values from both the in-situ measurements and the simulations, and is displayed in figure 14.

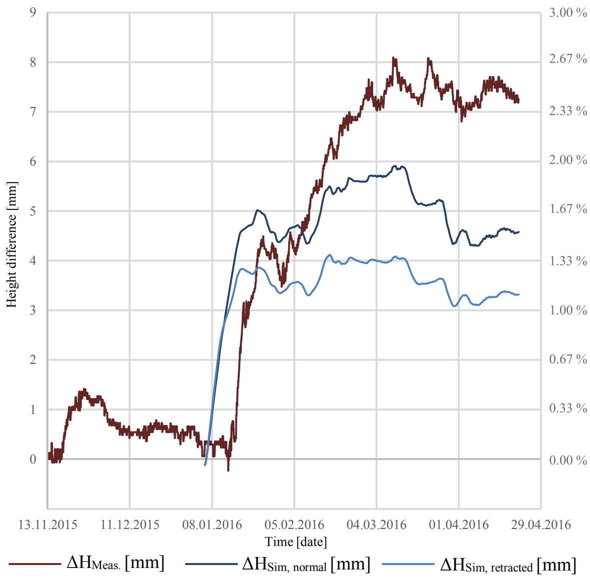

***Figure 14**: Height difference between head joist and inner joist over time. Three different graphs are displayed: difference based on the measurements, simulated head case and simulated case with retracted head joist*

The results show large dimensional differences in the in-situ measurements. A total height difference of 7-8 mm is calculated between the head joists and the inner joist, approximately one meter from the edge, of the bedroom in the monitored building. Comparing this to the tolerances given by the Norwegian standard, of less than 3 mm on lengths under two meter, this shows that the building producer should consider changing their constructions.

In the simulated cases, the height difference is approximately 1-2 mm smaller with the retracted, insulated head joist. The results still show a total height difference of more than 3 mm, in both of the cases.

This indicates that more than 50 mm insulation outside the head joist in required to have control of the tolerances. Since the height deformation is only reduced by 1-2 mm with 50 mm extra insulation, the assumption that a large amount of insulation is required to reduce the deformations accordingly to the tolerances is made. This might cause problems in the production and assembling of the construction, and other solutions to the problems might be better.

To replace the head joist with, for example an I-beam, could be a good solution. This would have reduced the height swellings of the joist and the total deformations on the floor system. Another solution could be to create a construction where the vapour barrier is continuous between the first and the second floor, to prevent moisture from the indoor climate to enter the head joist.

4 CONCLUSION

Laboratory experiments verify that linear swelling and shrinkage of the K-beams under alternating climates is expected. The orientation of the annual growth rings have a significant influence on the maximum deformations, and the experiment proves that K-beams will experience less swelling in height direction, than solid wood beams with similar dimensions, under the same climatic conditions.

The analyses of the in-situ measurements show that the head joists are largely affected by outdoor climate. The temperature around the joist is nearly the same as outdoor temperature, and the moisture level is equivalent to the highest moisture levels measured in the outside air at the current time period. The climate in the inner joists follow indoor climate and a warm and dry climate inside results in a low water content of the joists. This proves that high moisture- and temperature gradients between the outdoor and indoor climate is the main reason for the large differences in water content between the head joist and the inner joist, and imply that larger differences may occur in cases where the gradients are even higher.

Correct values for indoor and outdoor climate throughout the whole simulation period is crucial for achieving accurate simulations. Large changes in indoor and outdoor temperature are especially difficult to simulate, causing the simulated values during the heating period of a new building to deviate from the measured values of the same case.

The difference in water content measured between the head joist and the inner joist of the floor system will result in a considerable height difference and sloping of the floor. The building producer is working on finding a solution to this problem, which will increase the tolerances of the floor system. By retracting the head beam 50 mm and adding insulation on the outside, the construction is improved, but the expected height difference is still too large, and the producer should consider moving the head beam even further in or change the construction in another way.

ACKNOWLEDGEMENT

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Norwegian University
of Life Sciences

Postboks 5003
NO-1432 Ås, Norway
+47 67 23 00 00
www.nmbu.no