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The Use of X-ray Computed Tomography in Timber Construction Research

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ABSTRACT: X-ray computed tomography (CT), which was introduced in the medical field in the early 1970s, is also a powerful tool for the non-destructive measurement of dynamic processes in wood. For more than 20 years, CT has been used in wood research at Luleå University of Technology. The uniqueness of the CT equipment means that processes such as drying, modification, water absorption, internal and external cracking and material deformation can be studied in temperature- and humidity-controlled environments. The data recorded by the CT during the process is converted into two- or three-dimensional images that for instance can show dynamic moisture behavior in wood drying.

This paper gives an overview of the possibilities of using CT in timber construction research, and shows examples of applications and results which can be particularly difficult to achieve using other methods. A specific focus is on studies on wood products for construction, and how to deal with different material combinations such as wood and metal.

The practical application of the result is that CT-scanning, combined with image processing, can be used for non-destructive and non-contact 3-D studies of exterior constructions elements during water sorption and desorption, to study swelling and shrinking behaviour, delamination phenomena, crack development, etc.

KEYWORDS: CT, Non-destructive testing, Crack development, Image processing

1 INTRODUCTION

The objective of this study was to evaluate the use of CT-scanning for the stud of different timber construction parts exposed to a changing moisture environment.

1.1 TIMBER CONSTRUCTION

In their natural state, bio-based materials from the forest and the agricultural sector are biodegradable and strongly hygroscopic, in contrast to materials from non-renewable sources. When new bio-based materials are introduced into e.g. the building sector, new challenges related to how the materials and structures interact with moisture also arise.

In timber constructions, different kinds of semi-finished wood-based components are joined together to function as a system. Dowelled joints are the most common type of fastener for wood elements, and they transfer forces through shear in mechanical fasteners mounted at an angle to the force direction. The fasteners are in general made of a ductile steel material, and are designed for a large variety of different functions.

Metal fasteners and connectors are examples where climate change is of great importance for the function of the structure. Other constructional elements that are exposed to weathering are windows and doors that often consist of a combination of wood, glass, aluminum and adhesive. In use, moisture changes in the wood material result in shrinkage and swelling, and these movements can reduce the long-term operation of the construction element by e.g. impaired adhesion, corrosion or cracking. If the long-term impact of the external environment can be more accurately predicted, safer and more efficient constructional elements can be designed.

X-ray computed tomography is a useful method for the non-destructive monitoring of dynamic processes in materials in real time. Major problems with this technique are that X-ray radiation in CT scanners cannot penetrate steel which is the material generally used for e.g. connectors in timber engineering.

1.2 X-RAY COMPUTED TOMOGRAPHY (CT)

A CT-scanner works simply by passing X-rays through the body of some material and receiving information with a detector on the other side. The X-ray source and the detector are interconnected and rotate around the body during the scanning period. X-rays are electromagnetic waves, and the main reason why X- rays are used in diagnosis is because different substances differ in their ability to absorb X-rays. Low-density substances, such as low-density wood with a low moisture content and especially air, are more permeable to X-rays, while high-density substances, such as wet wood and knots, are less permeable. The information acquired is computer processed, resulting in a cross-sectional image of in general 512×512 pixels in which the densities at different positions in the object are shown in grey-scale form. High-density substances appear white on a CT image, while low-density substances appear as a darker grey. The air and the cavities filled with air appear black.

The expression “tomography” dates back to the early 1900s, when the Italian radiologist Alessandro Vallebona proposed a method to represent a single slice of the body on radiographic film. X-ray computed tomography (CT) involves the recording of 2D X-ray images (radiography) from various angles around an object, followed by digital 3D reconstruction [1-2]. The technology follows the principles presented by the Austrian mathematician Johann Radon who around 1917 theoretically demonstrated that the internal structure of an object can be reconstructed from single or multiple projections of the object, depending on the number of directions considered [3]. The word "tomography" is derived from the Greek tomos (slice) and graphein (to write).

The transmitted X-ray radiation can be related to the attenuation of the X-ray by the object by the Lambert–Beer exponential law under the assumptions that the ray is monochromatic ray and that the propagation of the beam in the object is linear [4]:

$$I = I_0 \mathrm{e}^{-\mu \mathrm{d}} \qquad (1)$$

where I in the intensity of the transmitted X-ray beam, I_0 is the intensity of the incident X-ray beam, μ is the linear attenuation coefficient of the material along the transmission path, d is the thickness of the samples that is penetrated by the X-ray beam. The attenuation coefficient of wood is determined by the moisture content, the wood density and atomic numbers and thus on the chemical composition of the wood. For wood, the gross chemical composition can be assumed to be fairly constant.

The spatial resolution of CT scanners ranges from the milli-scale to the nano-scale, and hence the different scanners are termed CT, microCT and nanoCT. Medical CT scanning is most well-known and is widely used for non-destructive imaging of the internal organs of the human body using X-rays. Industrial CT is a specialized form of CT scanning intended specifically for non-medical applications. Industrial CT scanning has been utilized in many areas of industry for the internal inspection of materials and components, failure analysis, metrology, and assembly analysis. CT scanning is also employed in the study of museum artefacts and in transport security. The method has been reviewed recently for applications in food sciences [2], geosciences [5], materials sciences [6], and wood applications [7].

2 MATERIAL AND METHODS

2.1 PHENOMENA STUDIED IN STRUCTURAL ELEMENTS

In this study, three different phenomena in wooden construction elements have been studied:

1) metal enclosed in wood,
2) cracks in wood, and
3) moisture content close to metal.

2.1.1 Metal enclosed in wood

Metallic material that is found above aluminium in the periodic system is not suitable for CT scanning since the energy of the X-ray radiation of a medical CT is low. Therefore, ordinarily used metals have been replaced with aluminium and a glulam beam (115x315x400 mm^3) with an aluminium plate with a thickness of 5 mm and dowels 10 mm in diameter and 100 mm in length were studied by CT, Figure 1.

Figure 1: *Glulam beam with aluminium plate and dowel. The distance from the end grain of the first couple of dowels was 50 mm. The next pair of dowels was 150 mm from the cross-section surface.*

2.1.2 Cracks in wood

In wood, cracks and delamination of different sizes often occur and may lower the strength of the constructional element. It is therefore of interest to know how these are distributed in the wood. It is possible in a CT image to study cracks (area or volume) in e.g. a wooden beam, but there is no information as to how accurately it is possible to measure and which reconstruction algorithm in the CT-scanner gives reliable results.

A Scots pine beam with dimensions of 120x250x1706 mm^3 was CT-scanned and the crack areas at different locations in the beam were studied, Figure 2.

Figure 2: *The beam of Scots pine used for crack analysis with the help of CT scanning.*

2.1.3 Moisture content close to metal

In areas where wood meets metal, it is difficult to obtain reliable measurements from the CT-scanning because of abrupt changes in density at the border between wood and metal. To study how to measure moisture content in such a region, two pieces of wood were glued together with a 3 mm thick aluminium plate between them. The specimen was conditioned to 12% moisture content and then scanned by the CT. The specimen was thereafter soaked for 24 hours in water and scanned again.

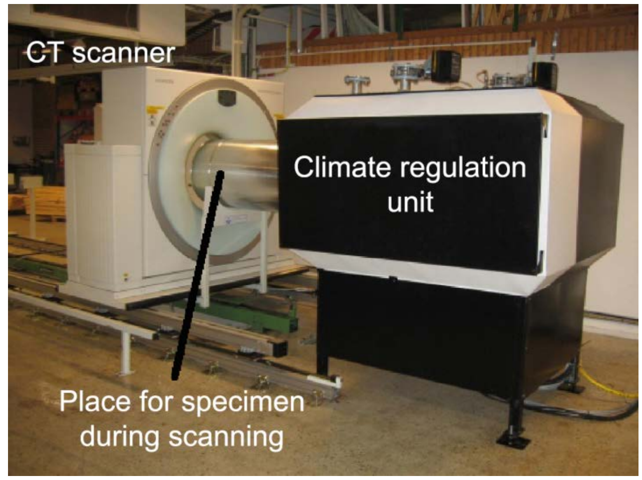
2.2 CT-SCANNING

2.2.1 CT Laboratory at LTU

Wood Science and Engineering at Luleå University of Technology (LTU) in Skellefteå has access to unique equipment for the non-destructive monitoring of dynamic processes. The uniqueness of this equipment is that processes such as drying, modification, internal and external cracking and material deformation can be studied using X-ray computer tomography (CT) *in a temperature- and humidity-controlled environment*. Both adsorption and desorption can be studied over a wide temperature and humidity range. The CT-scanner (Siemens Somatom Emotion) is combined with a specially designed climate chamber, Figure 3. The X-ray tube in the scanner is of the Tungsten-anode type with an acceleration voltage of 110 kV. The width of the X-ray beam was 5 mm.

2.2.2 The Swedish stem bank

The CT-scanner has been used to build up a stem bank of scanned trees that can be used for further studies such as anatomical studies, modelling of the sawmill process or the process of peeling veneer, wood component processes, and for developing automatic applications for the sorting of logs and sawn timber. The Stem Bank contains



Figur 3: *X-ray computed tomography (CT) with the climate chamber installed for CT measurements.*

information about 200 Scots pine trees felled at permanent sample plots, 144 Norway spruce trees from Sweden, Finland and France, and a dozen oak logs.

2.2.3 Principles of the equipment

CT maps a cross section of a material by passing X-rays through the material. The information about absorb X-rays is computer-processed, resulting in a cross-sectional image in which the densities at different places in the object are shown in a grey-scale form, Figure 4. Optical flow analysis can be used on a 4D data set to produce a motion field showing the movement of water over time in 3D.

The climate chamber is designed to work together with the CT-scanner. This is the only existing equipment in the world were a CT-scanner is combined with a climate chamber. In simple terms, the climate chamber is designed

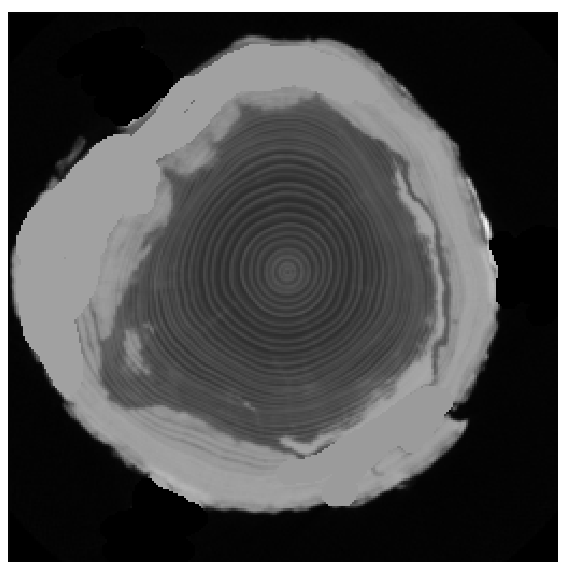


Figure 4: *A cross-sectional image of a Scots pine log in which the densities at different positions in the object are shown in grey-scale form. High-density wood (wet sapwood) appears light in a CT image, while the dry heartwood appears darker grey.*

with an inner and outer tube, where the air, driven by a fan, flows through the heating coils and then into the inner tube, where the material is placed for e.g. drying. At the end of the inner tube, the air flows to the fan via the outer tube, Figure 5.

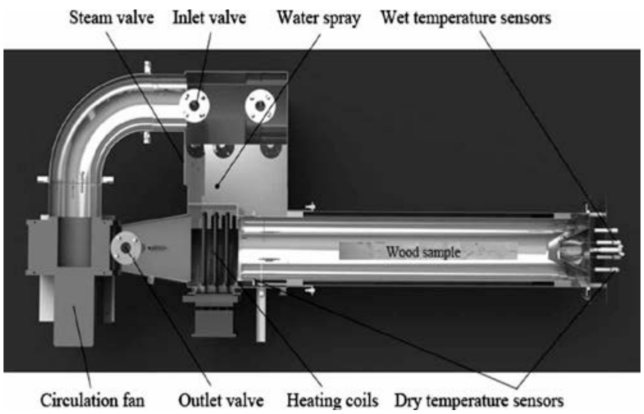


Figure 5: *Exploded drawing of the climate chamber.*

To increase the humidity in the chamber, a steam generator is used. The climate chamber can also be used for conditioning with a water spray and steam in order to equalize the moisture gradient which may have been caused by intense drying. High- and low-temperature drying processes can also be studied in the kiln. The control schedule is built up by assigning different control parameters in different phases.

2.3 IMAGE PROCESSING

The CT-scanner generates a 2D image of a section of a sample, an xy-image, representing the width and height of the sample. If several sections at different positions along the sample are assembled into an image stack, we have a 3D image, where the z-axis shows the depth of the sample. Imaging the same sample several times can be used to show changes in the material over time, introducing the time dimension. If a single section is captured repeatedly over time, an xyt image set is generated. Capturing a stack of sections repeatedly over time (t) generates an xyzt image set, called a 4D image.

2.3.1 CT-numbers

The CT scanning produces images with 512x512 pixels and by applying image processing techniques to the images it is possible to detect density, moisture content, and dimensional changes. For the analysis, the software ImageJ [8] was used. To make it possible to use the absorption coefficients of the CT-detector for further data processing, the absorption coefficient is converted to so-called CT-numbers [9]. The computed radiography linear coefficient is normalized with respect to the absorption coefficient of water μ_{water} and the absorption coefficient of the tested material μ_x:

$$CT^{No} = 1000 \text{ x } \frac{\mu_{x} - \mu_{water}}{\mu_{water}} \qquad (1)$$

Each CT-number is given a specific gray value depending on the density variation in the sample and can thereby be evaluated by conventional image analysis. Based on a number of projections, a two-dimensional cross-sectional image of the test object is built up. The individual images are built up of elements (pixels) representing a volume of a certain width on the X-ray beam. By assembling a number of images along the specimen, a three-dimensional reconstructions of the studied material can be built up.

2.3.2 Moisture content measurements

Performing 3D scans as described above introduces an offset in acquisition time between sections, which have an impact when the sample data are analyzed for changes over time, (capillary flow, moisture movement etc.). The problem becomes more complicated when the sample changes shape and the moisture movement in the local coordinate system of the sample moves with respect to the global coordinate system of the scanner, introducing errors when using image processing to perform optical flow analysis.

The determination of the moisture content based on CT images and image processing has to be done in several steps, since the CT-number is linked to the density of the specimen. As mentioned, the density appears as different gray-scale values in the images. To determine the moisture content, two density measurements (CT-scans) must be carried out, one of which is when the specimen has an known moisture content (the reference image, $CT_{Reference}$). To calculate the moisture content below the fibre saturation point, the second image has to be transformed by image processing so that the pixels of the two images match each other [4, 10]. The CT-numbers of the transformed image ($CT_{Transformed}$) can then be subtracted from those of the reference image and the CT-number representing the moisture content (CT_{MC}) is given by:

$$CT_{MC}^{No} = CT_{Reference}^{No} - CT_{Transformed}^{No} \qquad (2)$$

These CT-numbers are used in an algorithm to determine the moisture content, where a change of 1% moisture content corresponds to a change by a factor of 2.2 of the CT-number below the fibre saturation point. Above the fibre saturation point, the factor is 4.4.

Other methods determining the moisture content by CT-scanning are under development, where a dual-energy CT-scanning method looks promising [11].

2.4 ACCURACY IN THE MEASUREMENTS

The accuracy of measurements in the CT-scanner was determined with some specially designed experiments.

2.4.1 Reconstruction algorithms

The CT-scanner has several reconstruction algorithms that influence the accuracy with which the CT-number can be determined. In addition, a standard algorithm called Shepps reconstructive algorithm [12] was tested.

A Norway spruce specimen with cross-sectional dimensions of 50x100 mm was used for the study. The specimen was scanned twice with the same algorithm, and the two images were the subtracted (see Equation 2) to give results which are the measurement noise of the CT-number. To guarantee the repositioning of the specimen between the two scans, reference points of graphite were placed in holes drilled in the specimen.

Figure 6 shows the measurement noise in the CT scanner with the different reconstruction algorithms. The greatest noise is with reconstruction algorithm “B80s very sharp”, due to the contrast becoming larger, so that the positioning accuracy has a significant impact. The noise was very low for all the smoothening algorithms (B20s smooth, S30s smooth and B30s medium smooth). The difference between the “S30s” and “S80s” algorithms is that “S80s” has a higher spatial resolution that is better able to distinguish small objects in the image. The noise value is, however, very low (±2 CT-number) and we can therefore expect a measurement accuracy of ± 2 kg/m^3 in a volume of 1x1x5 mm^3, equivalent to ± 1 percentage point moisture content.

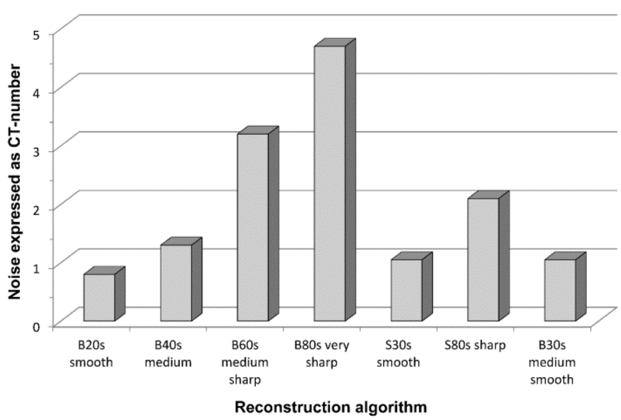


Figure 6: *Measurement noise expressed as CT-number for different reconstruction algorithms in CT-scanner. Algorithms specified with a capital S at the beginning (e.g. S80s) are Shepps reconstruction algorithms*

2.4.2 Edge reconstruction

The border between areas with a large difference in CT-number (i.e. a large difference in density) is difficult to reconstruct, i.e. the CT image does not show as sharp an edge as in reality, because the Fourier transform used cannot reconstruct a step function (Gibbs phenomenon). Preferable is that the border is within a few pixels in width. Three different algorithms to reconstruct the boundary between air (-1000 in CT number) and wood (ca. -500 CT number) were studied to evaluate the “width” of the edge of the wood specimen. The specimen was scanned once and the border between air and wood was evaluated with different algorithms in a defined location, Figure 7.

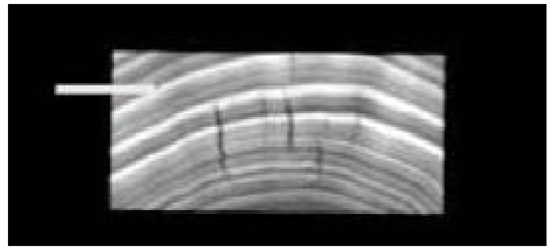


Figure 7: *Cross-section view of the area evaluated for edge reconstruction marked with a white line (scanning line)*

Figure 8 show the variation in the CT-number of a scan ranging from air to wood when different reconstruction algorithms of the CT-scanner used. The algorithm “B20s” results in a border width between air and wood of 8 pixels, and the algorithm “B80s” needs a width of about 4 pixels to define the same border. The algorithm “S80s”, a Shepps algorithm, results in a border with 6 pixels widths. The results indicate that the edge between a wood specimen and air can be detected with an accuracy of ±2 mm.

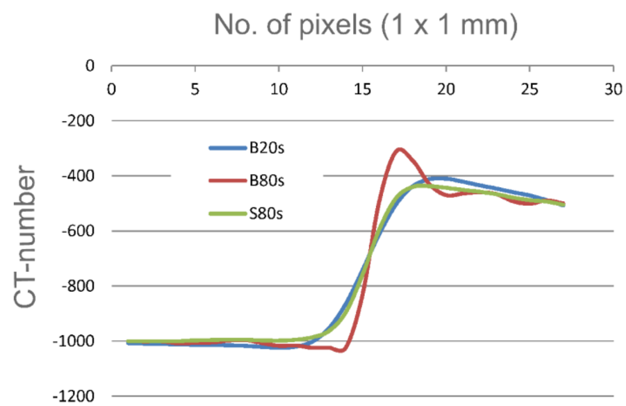


Figure 8: *Detection of the edge of a wood specimen in CT-scanning using different reconstruction algorithms*

3 RESULTS AND DISCUSSION

3.1 METALS ENCLOSED IN WOOD

Figure 9 shows a CT image of a 5 mm thick aluminium plate and two aluminium dowels (diameter 10 mm and length 100 mm) embedded in a glulam beam. The lower dowel is sealed with a sealant. At the bottom left, a small white dot on the surface of the beam comes from a copper part on a folding rule that was used to mount the specimen in the CT scanner.

The result shows that it is not difficult to CT scan aluminium enclosed in wood, which means that it is possible to replace steel connectors with similar connectors of aluminium to study the construction element with the help of CT-scanning. There can however be a problem in the precision of the density measurement close to the metal surface (see 3.3).

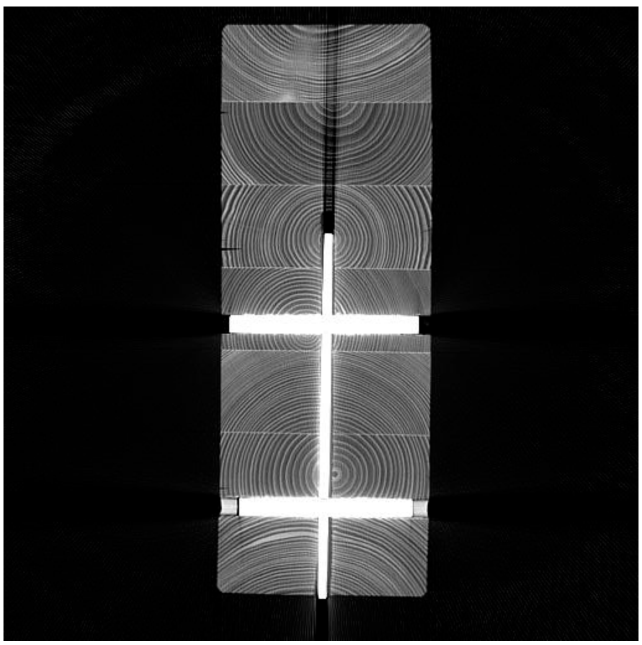


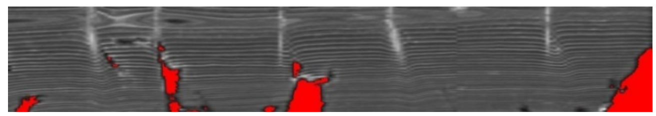
Figure 9: *Cross-sectional view of a glulam beam of Norway spruce with an aluminium plate anchored with two aluminium dowels. The lower dowel is sealed with a silicon sealant. In the cross section, aluminium can be seen as white areas*

3.2 CRACKS IN WOOD

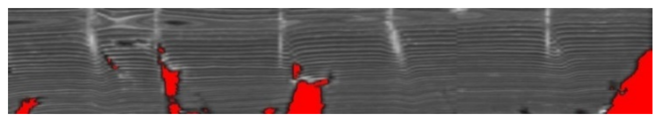
Figure 10 shows an example of the analysis of cracks in a beam. The cracks are shown as red areas and the four images are side views in the xz-plane at different locations within the wood in the y-direction.

The result shows that CT-scanning is a powerful tool to study internal cavities, such as cracks. It is also possible to follow how the cracks develop within the volume of wood with both time and changing moisture content.

a)



b)



c)

d)

e)

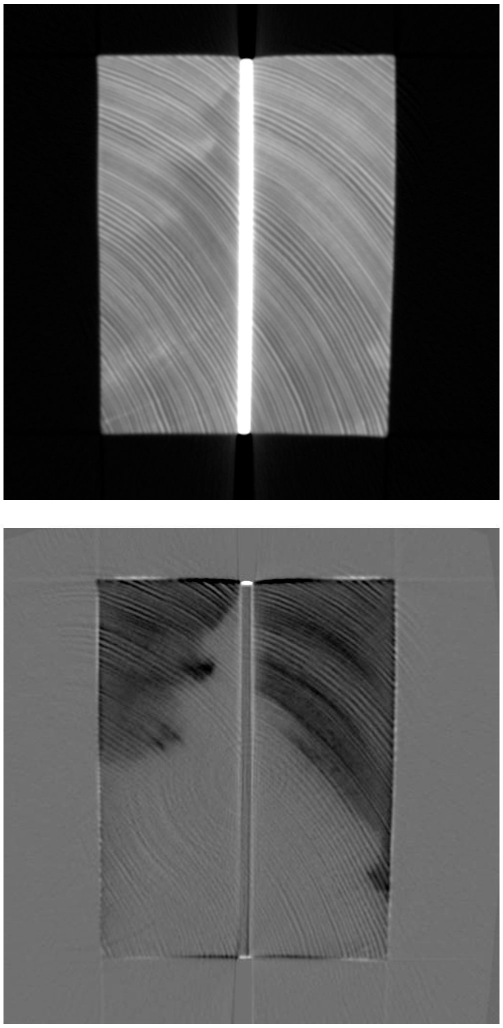
Figure 10: *Crack area (red) in four different transverse sections of the beam shown in Figure 2.*
a) Cross-section view of the beam showing x- and y-directions.
b) y=109 mm and crack area 4.6% of total section area
c) y=111 mm and crack area 7.5% of total section area
d) y=115 mm and crack area 17.9% of total section area
e) y=117 mm and crack area 21.3% of total section area

3.3 MOISTURE CONTENT CLOSE TO METAL

Figure 11 show a cross-section view of a CT image of two pieces of wood glued together with an intermediate aluminium plate. In the image at 12% moisture content (Figure 11a) the aluminium plate is clearly visible and the border between wood and metal appears to be sharp.

After soaking the wood in water, the difference between sapwood and heartwood is clear in the Ct image. The dark region in the image is sapwood with a high moisture content, while the light areas is heartwood with a low moisture content.

Close to the metal plate there is an abrupt change in material density, and there is a clear risk that phenomena similar as to the change between wood and air occur.



a)

b)

Figure 11: *CT-scan of cross-section of two pieces of wood glued together with an intermediate plate of aluminium: a) at 12% moisture content, and b) after 24 hours of soaking in water.*

Figure 12 show the variation in CT-number through the soaked specimen in Figure 11b. The maximum value for the aluminium is reached about 1 mm from the metal surface, and a stable value for the CT-number of the wood material is obtained about the same distance from the plate. In this test the resolution was 4 pixels/mm.

A CT-scanner is a laboratory equipment, but it can be combined with different kinds of non-destructive scanning techniques such as infrared, visible, NIR or X-ray [13], NMR [14]. Both solid materials in load-bearing structures and porous insulation materials can be studied. A fundamental limitation of the CT-scanner used in this study is, however, that a test object with a diameter greater than 70 cm cannot be examined in the equipment.

One problem in the CT scanning of building components is that the radiation in a medical CT scanner is relatively weak, so that the radiation does not pass through steel,

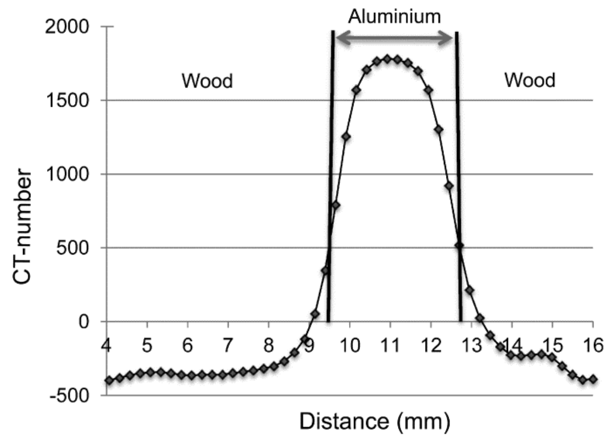


Figure 12: *CT-number (CT_{MC} in Equation 2) showing moisture content variations in the wood-aluminium-wood direction of the specimen shown in Figure 11b*

copper, etc. which are components of many building products. If the metals are replaced with aluminium, realistic experiments can be performed.

4 CONCLUSIONS

Wood Science and Engineering at Luleå University of Technology has currently one of the few medical CT-scanners in the world specifically adapted for material studies. The CT-scanner also has an additional chamber for real time scanning under different climate conditions, e.g. drying and thermal treatment.

X-ray computed tomography (CT) scanning *in temperature- and humidity-controlled environments*, combined with image processing, is a powerful tool for continuous non-destructive and non-contact 4D-studies of bio-based building materials exposed to water.

The measurement accuracy is high, i.e. within ± 2 kg/m^3 in a 3x3x5 mm^3 measurement volume at the 95% confidence level. This corresponds to ±1% in moisture content.

Cracks in wood material are difficult to measure, but threshold method has been developed which makes it possible to measure fracture extension with an accuracy of 0.1-0.2 mm.

The practical examples given in this paper provide an overview of the possibilities and limits of the CT-scanning technique for testing different timber engineering elements in which wood, metal and moisture interact and strongly influence the performance.

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