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DENSITY CALIBRATION USING X-RAY EQUIPMENT FOR IN-SITU ASSESSMENT OF TIMBER STRUCTURES

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ABSTRACT:
Wood density is related to several properties that have a large influence on its quality. In this article, an X-ray image calibration procedure is presented which allows the determination of density properties for in-situ assessment of timber structures. This non-destructive method is useful for evaluation of the internal condition for global assessment of the structure. The density calibration method of X-ray images was verified on a timber beam specimen with good agreement and an average accuracy of 97%. The values obtained from the image calibration presented very good linear correlation coefficients (R^2) between the measured density and the greyscale from X-ray images ranging from 0.90-0.98. Besides the opportunity of determining mechanical properties of timber, its main advantage over conventional techniques is the detection and quantification of internal damage, defects, disturbances and deterioration that reduce mechanical properties of the structure. Furthermore, this study indicates a good opportunity for the development of a successful future tool for in-situ assessment of timber structures and can also be used in the analysis of the structural behaviour.

KEYWORDS: in-situ assessment, density, timber structures, X-ray, digital radiography, non-destructive testing (NDT), digital image processing

1 INTRODUCTION

1.1 ASSESSMENT OF TIMBER STRUCTURES USING A 'HOLISTIC APPROACH'

In the continuous maintenance of timber structures, there are occasions when in-situ assessment of their structural performance becomes necessary. This is the case when ageing of the structure can be suspected to have diminished its strength or stiffness, and changes in the intended use or abnormal structural behaviour has been discovered. A research project is currently carried out aiming at facilitating in-situ assessment of timber structures with respect to structural soundness using a 'holistic approach'.

Judging structural soundness implies getting knowledge of forces and deformations. This can be done (and, in most cases, should be done) with the aid of structural mechanics. The calculated forces and deformations depend on assumptions made regarding: *geometry, joints, conditions at the supports, materials and loads*. In order for the calculations to represent the true behaviour of the real structure, these five parameters must all be appropriately explored and described in the process, see Figure 1. Recognizing this approach, thus avoiding unreflected or precipitated focus on a single parameter, implies taking a 'holistic approach' to the assessment of timber structures in service.

Moreover, *deformations and damage* should be investigated and recorded, as they can produce important information on the actual structural behaviour of the system at hand. The presence of tensile forces might show a distance between jointed parts and high bending moments may show bent members, etc.

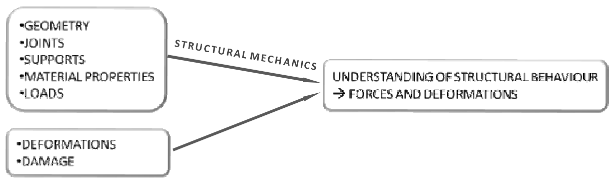

Figure 1: *In the judgement of the structural behaviour of an existing structure, there are a number of parameters that are equally important to explore and to describe.*

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1.2 AIM AND SCOPE

The aim of this study is to establish a reliable relation between measured density and greyscale from X-ray images. Variations in density are well visible from X-ray images; they appear as differences in grey nuances. The purpose here is to explore whether an even more elaborated result can be reached: is it possible to generate absolute values of density from X-ray images?
The scope was to include 15 wood specimens with significant differences in density ranging from about 390-800 kg/m^3, see Section 3.1, Table 1.

2 OPPORTUNITIES FOR X-RAY ASSESSMENT

The first stage of this project will focus on investigation and verification of the opportunities and difficulties of X-ray equipment in order to be able to relate the results to a holistic model.
X-ray equipment has already, to some extent, been used for investigation purposes and some results have been published in scientific contexts. The opportunities for X-ray investigation has until recently been used for qualitative assessment of timber structures, but the opportunities to carry out quantitative evaluation are of great importance. There can be a number of applications revised in this paper for using X-ray equipment on site.

2.1 EXPLORING GEOMETRY

Quantitative determination of hidden geometry
The opportunities to achieve dimensions of non-visible fasteners or cross section reductions as well as connection of joints that are decisive for the judgement of boundary conditions give great opportunities for further interpretation in the structural analysis [1].

Detection of corroded area
Since corrosion in metal fasteners might cause severe failure, radiographic equipment as a tool can be used to detect corrosion inside the structure which through appropriate action can prevent collapse of the structure [2]. Using commercial image editing programs, distances can be measured quite accurately towards some reference unit and the actual capacity of the fastener can be recalculated. Figure 2 shows a corroded nail as a result of a shrinkage crack in timber. No information on whether the nail is galvanized or not is provided.

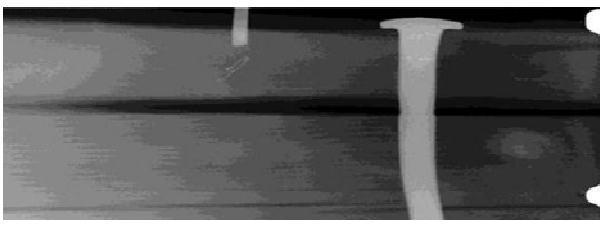


Figure 2: Clear deterioration of the metal fastener due to corrosion in the shrinkage crack of the beam [3].

Reduction of cross-section
Old timber might have lost its full capacity due to deterioration either by insect attacks or due to shrinking cracks [4]. When accessibility with X-ray camera along fibre direction is guaranteed, a prediction of the maximum allowable stresses at a specific point might be defined with a reduced cross section before any strengthening or remedial work is carried out.

'Timber-to-timber' hidden geometry
While it is obvious that hidden metal details in a timber structure can be assessed with the use of X-ray, it does not necessarily mean that hidden timber parts can be visualized with satisfactory accuracy. As part of the current investigation, a preliminary study has been carried out showing promising results in this field, cf. Figure 9.

2.2 EXPLORING MATERIAL PROPERTIES

X-rays are already in use today by means to determine material properties and to strength grade timber. The currently used methods are not suitable for in-situ assessment and are out of the scope for this article.
Nevertheless, in-situ methods to determine material properties most likely exist for materials with great homogenity such as steel [5]. As timber is a material of great variation these methods cannot be applied without further reflection.

A special focus is directed to the prediction of density for the in-situ assessment of material properties of timber by usage of x-ray imaging combined with image calibration, even though knowing that there exist a number of other valid techniques to achieve density properties on site which are of more local character. Therefore, a correlation has been established between the greyscale of the radiographic image and the density of the wooden test specimens. There is no way to deny the density as the most significant indicator of wood properties [6].

Density distribution in components
Through development of the equipment and the methods of digital image analysis it has been possible to determine variations of apparent density values and distribution in timber and wood composites. These differences can be detected through the attenuation of X-rays passing through the material [7, 8], see Figure 7.

Determination of material properties through image calibration
There exists an accepted relation between density and strength and stiffness properties in timber [6]. As this paper will show, the X-ray images of beams and at joints can be calibrated in a further step towards its density by a calibration specimen built up upon different wood specimens with different density characteristics. This calibrated specimen must be represented on each image.

2.3 EXPLORING DAMAGE AND DEFORMATIONS

Mapping deterioration together with the help of resistograph

Since the most of the portable X-ray equipments deliver images in a two-dimensional perspective, additional help by a Resistograph® might be needed for a volumetric mapping of deterioration by insect attacks. In many cases, a two dimensional picture is satisfying for determining the severeness and progress of the invisible damage [3, 9, 10], as decay due to rot and high moisture content can be seen in Figure 3 and be determined by measuring the area of the void (dark area).

Figure 4 shows a simulated termite attack that makes the determination of a cross section loss possible through image enhancement, whereas on the other hand decay does not leave an abrupt change in wood and makes the detection of gradual transition for cross section loss problematic.

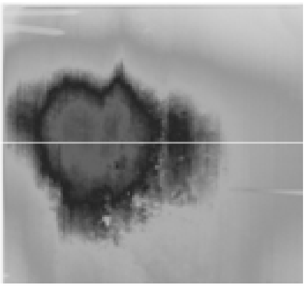


Figure 3: *The X-ray image shows rot (dark area) in an external wall due to bad detailing and high moisture. [1].*

Figure 4: *Simulated deterioration that caused loss of cross section results in an deviation of the greyscale on the X-ray image [1].*

Failure modes in metal fasteners

In-situ X-ray imaging also provides the opportunity to determine the actual behaviour of dowels in joints, see Figure 5 [2]. Moreover, the exact position of the plastic hinges can be determined.

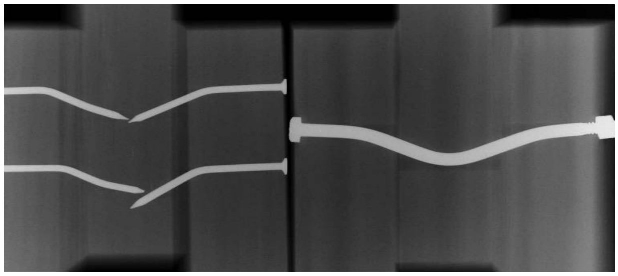


Figure 5: *The X-ray images show the behaviour of a nailed joint (left) and a bolted connection (right) [1].*

3 MATERIALS AND METHOD

3.1 PROCEDURE

To verify density using X-ray equipment, 15 wood specimens with dimensions b x h x t = 64 x 94 x 28 [in mm] were prepared, weighed and X-ray scanned, but disregarding the air-dried reference density (only actual density of the specimens was measured). Since the imager does not recognize the material, it is only the density of the material that is of importance. For prediction of accurate stiffness and strength properties the calibration of the wood specimens towards air-dried density (MC 12%) is of considerable significance.

Providing a large variation of density, various wood species with significant differences in density, ranging from about 390-800 kg/m^3, were used, see Table 1. Specimen no. 15 does not represent a typical species and was therefore excluded in the evaluation. The specimens were set up in different configurations for X-ray investigation, see Figure 6.

Furthermore, the distances from the generator to the X-rayed object varied between 2.5 and 3 meters in order to minimize the effects of the exit angle from the X-ray that casts shadows on the image and that gives considerable change in the grey scale on the image, i.e. the centre of the radiographic film receives larger dosage than the edges. This distance almost vanished this effect and the distribution of dosages give an maximum calculated error of 0.4% [11].

The objects were excited with 99 pulses from the generator and scanned with a resolution of 300 dpi and 8-bit depth on an 8”x17” image plate. The images were taken in the lab under controlled light conditions, i.e. no light at all; either day or artificial light influenced the testing.

The images in a further step were evaluated with digital image processing software and the results were plotted in graphs towards the actual density of the specimens.

Table 1: *Specimens used to correlate density to absorbed energy through X-rays.*

No.	Species Name [SWE - ENG]	Botanical Name [latin]	ρ [kg/m³]
1	Ceder - cedar	Cedrus brevifolius	389
2	Tall - Southern Pine	Pinus spp (palustris)	394
3	Gran - Norway spruce	Picea abies	395
4	Abachi - African whitewood	Triplochiton scleroxylon	398
5	Gran - Norway spruce	Picea abies	404
6	Gran - Norway spruce	Picea abies	451
7	Al - alder	Alnus glutinosa	495
8	Lind - linden	Tilia (cordata)	501
9	Tall/Furu - pine	Pinus sylvestris	512
10	Rödbok - European beech	Fagus sylvatica	540
11	Valnöt - walnut tree	Juglans regia	689
12	Ek - oak-tree	Quercus (alba/ robur)	696
13	Björk (flammig) - birch	Betula papyrifera	707
14	Ask - ash	Fraxinus excelsior	775
15	Pockenholz - Lignum Vitae	Guaiacum officinale spp, Lignum Guajacum	1301

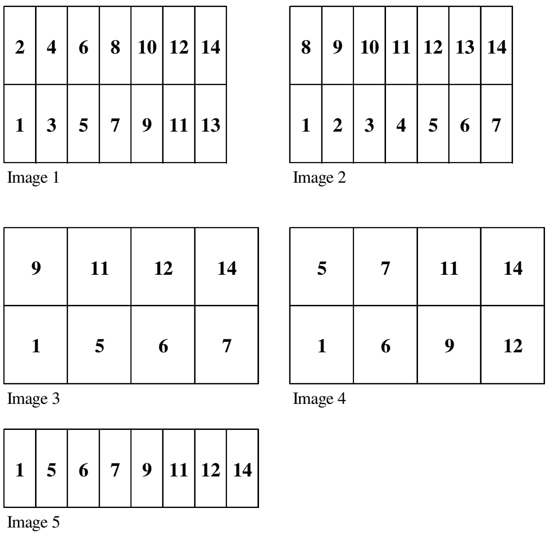


Figure 6: *Image configuration of the specimens. The numbers corresponds to the species number in Table 1.*

3.2 THEORY OF X-RAYS [9, 12, 13]

X-rays are short wave electromagnetic radiations that rely on the mass density and the thickness when penetrating through an object. The radiation energy is absorbed and attenuated when X-rays passes through. This attenuation or intensity loss, which is effected by the type of material, can be calculated using Beer's law. X-rays are produced by electrons that are emitted when heated to incandescence. Hereby, the electrons are accelerated and generate X-rays. Penetration of the material is made capable by the radiation energy that is controlled by the electrical potential in the X-ray tube and the exposure time. The emitted X-rays appears on an image plate as lighter or darker, i.e. in grey scale spectra of the scanned image that ranges from white to black due to the intensity loss. An X-ray detector is required to be able to assess the intensity loss through an object.

3.3 THE X-RAY SYSTEM [1, 13, 14]

The X-ray-system consists of an X-ray generator, a digital imaging system and a reusable phosphor layered imaging plate that capture the intensity levels from the X-ray exposed objectives, see Figure 7.

The battery-powered portable X-ray source, Inspector XR200®, from Golden Engineering Inc. was used for this study. This generator produces pulsed short duration X-rays up to an energy level of 150 kV across the x-ray vacuum tube. The pulses can be set from 1-99. Both the distance to the object and the intensity level steered by the pulses should be adapted to achieve the right exposure level. The X-rays leave the tube in a 40 degree exit angle, which is decisive for the minimum distance to the specific object for maximum utilization of the imaging plate.

The digital image plate system DIMAP® from Logos Imaging Inc. was applied to scan the photographic X-ray images. The laser scanner releases the accumulated energy from the image plate and stores the image at selectable resolution on the laptop's imaging software where every single image can be post-processed regarding particular details.

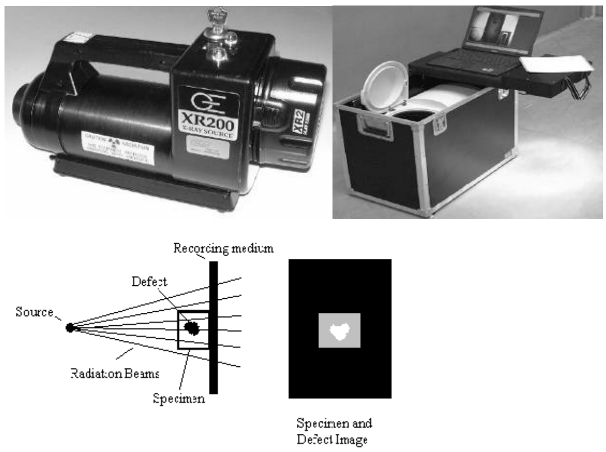


Figure 7: *X-ray system and X-ray recording process [9]* Technical issues related to the X-ray equipment, see www.elp-gmbh.de

3.4 DIGITAL IMAGE PROCESSING

Image Enhancement

Throughout the previous decade image enhancement using commercial software, among those Photoshop®, MatLab® and ImageJ®, increased the qualitative opportunities in the evaluation and interpretation of X-ray images as well as the quantitative engineering evaluation and assessment, see Figures 8-9. Small defects, not visible for the human eye, such as starting corrosion, decay and mini cracking / delamination can now be detected in an early stage and therefore prevented from further deterioration.

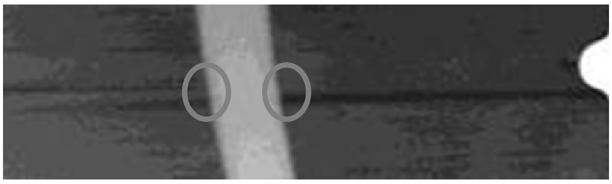


Figure 8: *Starting corrosion in the zoomed area of the shrinkage crack from Figure 1 [3].*

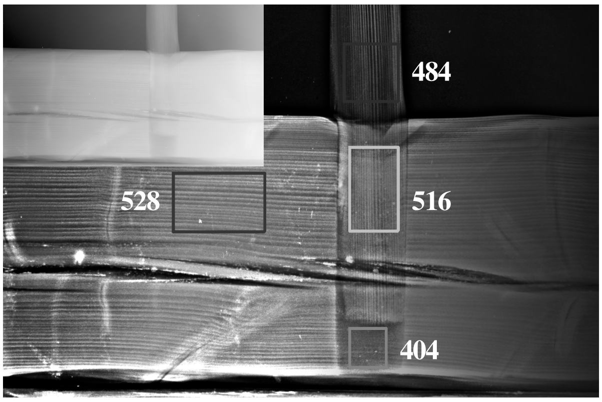


Figure 9: *A hidden dowel with approximately the same density as the surrounding wood can be detected with the use of X-ray. Original X-ray image (top left corner) vs. edited image. The numbers correspond to the mean density through the thickness of the beam at different positions.*

Depending on the material properties of the inspected object, energy absorption, chemical properties, density and thickness are reflected by the photographic image [2]. Through comparison of the measured intensities on a radiograph, the extent of deterioration in wood members could be quantified using imaging processing techniques [1, 2].

In digital form, the image can be expressed as a matrix. ImageJ®, open access engineering software, contains an image processing toolbox supporting this feature and can be used to quantify the investigated phenomenon by simply counting pixels of different intensities and comparing their relative position.

A disadvantage of image processing of the in-situ X-ray images is that the 3D-object is reproduced as a 2D-image. These differences in density cause a differential attenuation of the emitted photons. It also has to be considered that the density data produced by the image represents the average density of the member through the thickness, which makes the evaluation of radiographic elements difficult [9], but creates the opportunity to derive the correlation between grey scale and material density and is taken advantage of.

3.5 METHOD TO MEASURE THE IN-SITU DENSITY

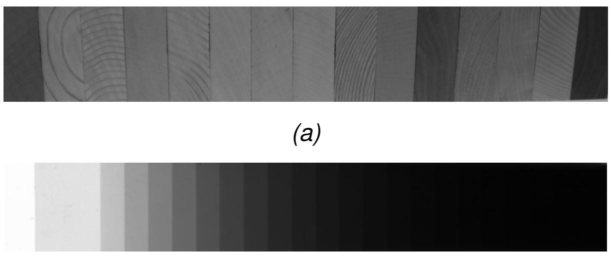
There exists an accepted relation between density and strength and stiffness properties in timber [6]. The X-ray images of beams and at joints can be calibrated in a further step towards its density by a calibration specimen built up upon different wood specimens with different density characteristics, see Figure 10. This calibrated wedge specimen must be represented on each image since each image's optical density is unique and therefore has to be calibrated every time. The wedge should be assembled without any defects and disturbances from wood.

3.6 CONDITIONING OF "CALIBRATION" WEDGE

The specimens have to be conditioned to a moisture content of 12% (air-dried reference condition) before attaching to each other. This calibrated condition of the specimen must be assured before usage in order to achieve accurate density and material property predictions for the in-situ investigations.

The conditioning process has to be performed by placing the specimens in a climate controlled box where a saline solution maintains the relative humidity (RH) at about 65% which corresponds to a moisture content of 12%. The conditioning temperature is being kept on a constant level of 20ºC. It is assumed that this process only requires a few days to achieve the air-dried reference condition of 12% MC since it is small ideal timber specimens.

Due to the hysteresis effect between absorption and desorption processes, the RH at 66% is chosen for conditioning the specimens as estimation to reach the air-dried condition of the specimens. An accurate measurement will be carried out right before attaching the specimens together. The moisture content during experiment has to be known accurately since it was shown that moisture content has a particularly strong influence on the mechanical properties in timber [6].



(a)

(b)

Figure 10: *Calibration wedge (a) composed of wood/timber specimens with increasing density in comparison to the 8-bit image calibrated greyscale "step-tablet" from Canon (b). The X-ray image of the wedge would be more similar to the "step tablet"*

4 RESULTS AND DISCUSSION

X-ray images of the different evaluated image configurations and their associated graphic results are presented in Figures 11-15. The result of calibrating / predicting the density using X-ray radiation showed strong relationships between the densities of the test specimens and the greyscale of the recorded X-ray image. The relation up to a certain level provides excellent linear correlation. This is especially valid for soft material as wood/timber up to a level of 1000-1200 kg/m^3. An extreme test of materials with large differences in density, steel, timber and concrete, resulted in a correlation that is exponential/potential. This test was used to invest the possibilities to carry on with the research, but is not presented here.

The correlation values (R^2) vary between 0.90-0.98. This variation shows the sensitivity of small differences in density, the influence of radiation energy, the dosage that reach the single object and small deviations in the accuracy of the perpendicular position of the generator towards the object.

The marked areas on the images, see Figures 11-15 show the areas used in the different species for the output of the mean greyscale. The decision on the size of the areas were subjective due to the influence of visible deviations of not evenly distributed shades over the pictures. This is due to several reasons, mentioned in Section 4.2. A mean area distribution spreads the influence of not significant extreme min. and max. values for the evaluation and therefore shows a representative result.

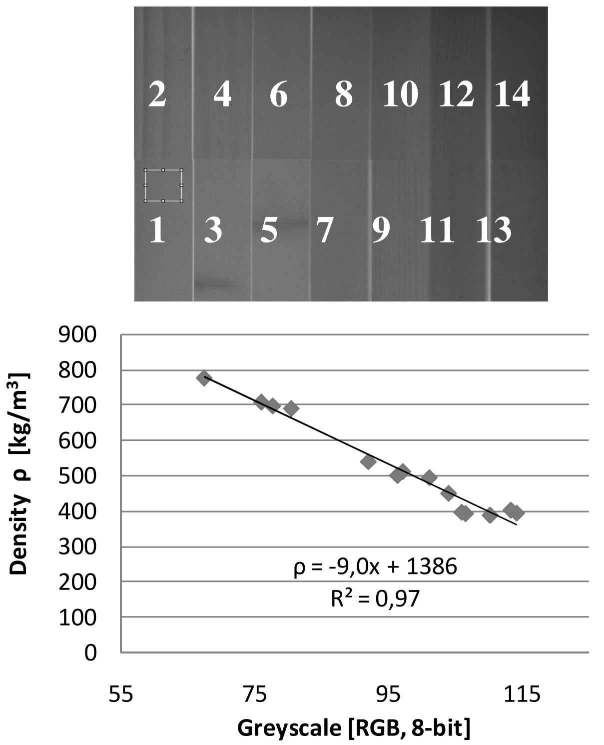


Figure 11: *Results from Image 1 configuration show the relationship between density and mean greyscale of the marked area.*

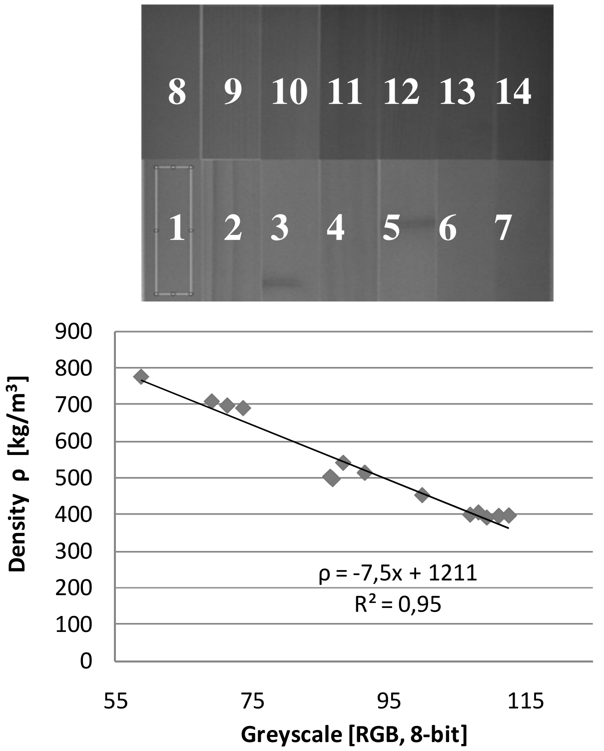


Figure 12: *Results from Image 2 configuration show the relationship between density and mean greyscale of the marked area.*

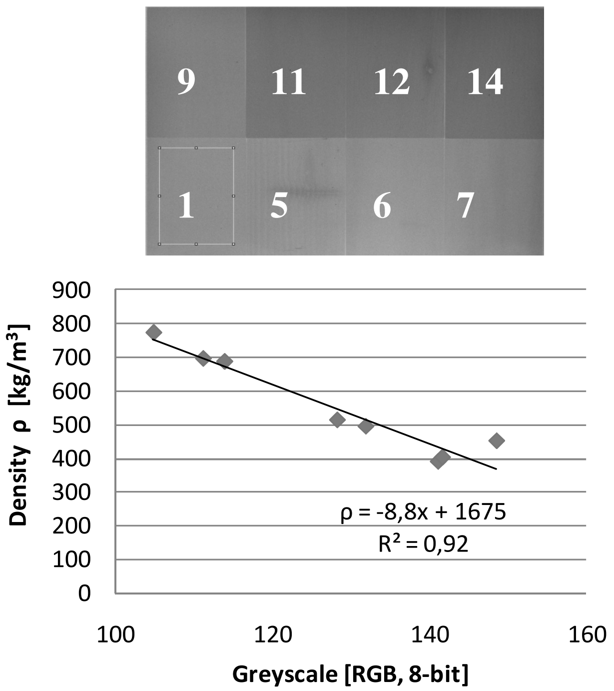


Figure 13: *Results from Image 3 configuration show the relationship between density and mean greyscale of the marked area.*

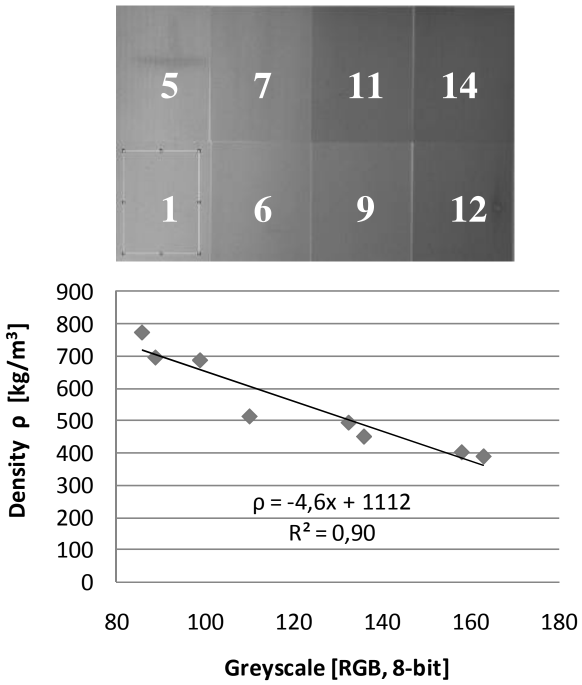


Figure 14: *Results from Image 4 configuration show the relationship between density and mean greyscale of the marked area.*

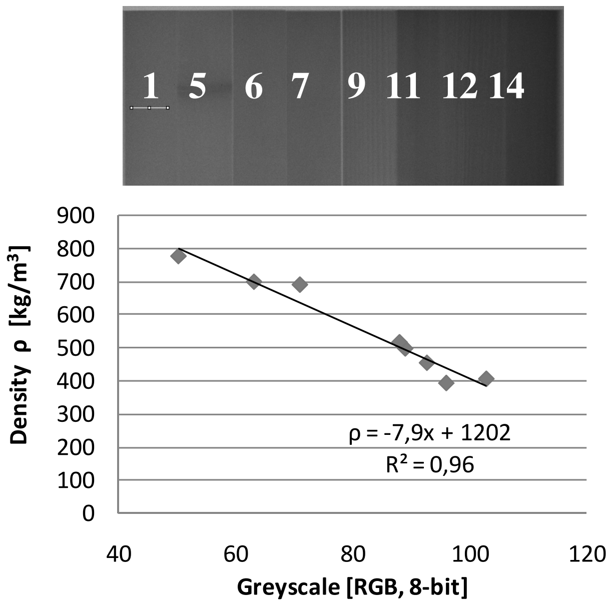


Figure 15: *Results from Image 5 configuration show the relationship between density and mean greyscale of the marked area.*

4.1 VERIFICATION OF THE METHOD

The in-situ density measurement assessment was applied and verified on a timber specimen. This verification was carried out before the calibration wedge was constructed, so the reference specimens from image configuration 5 were used, see Figure 6. Good agreement was achieved between the non-destructive determination of the density, using X-ray and image calibration, and the real density of the specimen. The density reference specimens achieved a linear correlation value (R^2) of 0.98. The received equation was used to calculate the density of the beam (Norway spruce) using the mean value of greyscale for the beam, which resulted in 511-527 kg/m^3 (greyscale of 95-98) compared to the measured density of 534 kg/m^3. An average accuracy of 97% could be stated from this study which has to be regarded as very satisfying and successful for the use in in-situ assessment. The result is shown in Figure 16.

The configuration specimens were of similar thickness as the beam otherwise greater deviations would have been detected since the distance of either the beam or the calibration wedge to the imager would have created differences in greyscale [8]. This was also verified by X-raying a beam of about double the thickness compared to the reference specimens, which resulted in an overestimation of the density properties about 18-25%. A relation factor for thickness has therefore to be investigated further on as well as the influence of different moisture conditions in order to achieve as high accuracy as possible.

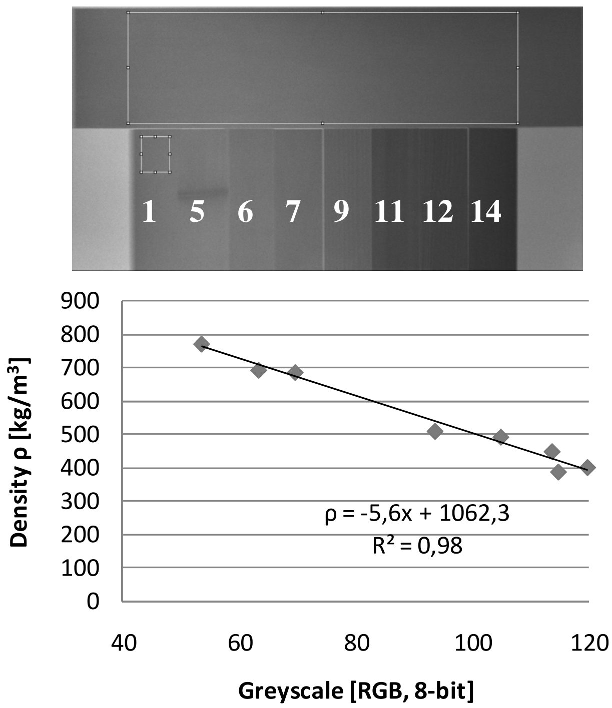


Figure 16: *Verification of the greyscale density calibration method on a timber specimen (top beam).*

4.2 FURHTER VIEW POINTS ON THE ESTABLISHED METHOD

Further view points of this investigation are:

1. The calibration of the images for the in-situ evaluation occurs from a subjective view point and has to be performed each time an image is taken. Nevertheless, it requires just a fraction of a minute.
2. The results can just be presented as correlation value (R^2) due to the fact that every image might differ in grey scale intensity and therefore is unique.
3. The even distribution of dosage of radiation, which influences the image contrast, is restricted by the distance of the X-ray generator to the specific object. This influence of the x-ray light has to be considered in the establishment of the density calibration for the images. These shadowed areas at the edges can easily be discovered and excluded from evaluation.
4. The image plates' size is restricted and a global evaluation of a structural member provides better information on the structural capacity of the member. This can be achieved by scanning the whole structural component.
5. The moisture content of the concerned component has to be measured additionally in order to provide appropriate increase/reduction for the strength and stiffness properties of the member. Therefore, it is of great importance to calibrate the wedge to air-dried condition (MC ~12%). Furthermore, a reduction factor which has influence on moisture differences must be established since it influences the output of the image in terms of greyscale.
6. The method must also be calibrated towards the thickness of the in-situ specimen and the distance of the wedge in relation to the image plate [9]. This might be insignificant for small differences in thickness, but having considerable effect on components of great depths. That relationship of different widths has been shown by [9] and has to be calibrated for field investigations .

5 CONCLUSIONS

Based on the results of this study, the following conclusions can be drawn:

1. It has been proved possible to achieve very accurate estimates of in-situ density of timber structural components using X-ray in combination with digital image processing.
2. A strong correlation between densities of wood pieces and greyscale images was achieved, but adjustment for different thickness and the moisture has to be performed.
3. The linear correlation is valid for a range from 350 kg/m^3 to 1300 kg/m^3. Above this level the correlation becomes potential/ exponential. Since common wood species for structural use range from 300 kg/m^3 to about 800 kg/m^3, the linear correlation gives a better approximation.

As a general conclusion, digital radioscopy is on its way to become a powerful tool for in-situ examination and evaluation of timber structures, and its possibilities are far beyond from being totally explored. It also contributes to detection of failures and deterioration of the material in early stages that in its turn gains the service life and durability of the structure.

The study indicates a good opportunity for the development of a successful future tool for in-situ assessment of timber structures. As commonly stated in timber engineering purposes, the density governs the stiffness and to some extent also the mechanical strength properties. The method can therefore be used in the analysis of structural behaviour.

Density properties of timber components are also relevant for the examination and evaluation of mechanical connections. This method cannot yet be applied on composite materials, walls or other composite components. This part needs further investigations.

6 FUTURE RESEARCH

The research on the opportunities for achieving as high accuracy as possible is not yet completed and has therefore to be complemented by identifying the influence of moisture on the greyscale as well as the relationship between the thicknesses of the specimen to the distance of the image plate which is of great importance for the accuracy of the wedge calibration.

Furthermore, in-situ mapping of deterioration in damaged structures and investigation of joints for prediction of their actual capacity will be carried out; both with the help of X-ray equipment and resistographic measurements in order to explore the limits of X-ray examination.

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