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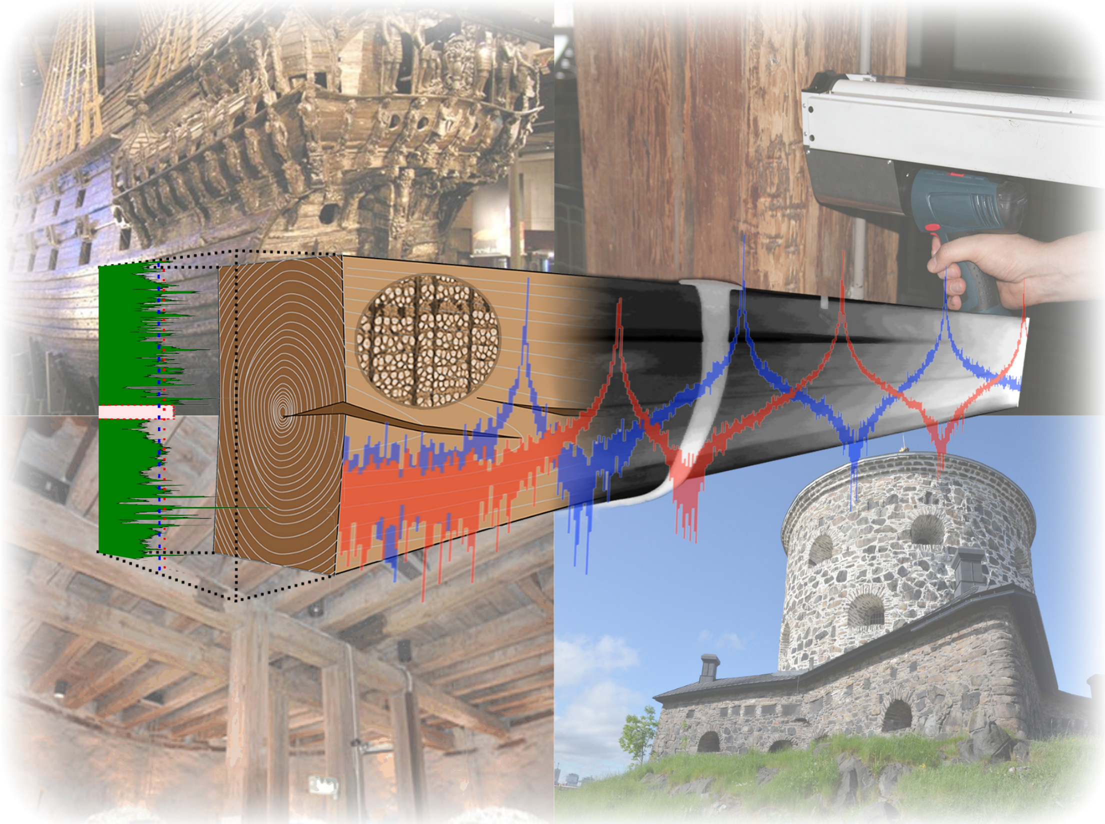

In-situ assessment of timber structures

Assessment methods and case studies

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THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

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Cover:
The cover picture shows a compilation of the various research tasks included in this thesis.

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ABSTRACT

In the assessment of timber structures, diagnostic investigations with reference to the condition and structural performance of these structures are necessary and often require appropriate health monitoring techniques. This thesis covers four aspects within the research area of the *in-situ* assessment of timber structures based on scientific knowledge and guidelines to perform assessment of existing timber structures:

I Determination of density of wood with portable X-ray
The mechanical performance of timber is often strongly related to the density of wood. This work focused on the development of an *in-situ* calibration procedure to determine the density using X-ray, thereby enabling the prediction of the mechanical properties of timber as well as to evaluate the internal condition of the structure.

II Property assessment of oak from the *Vasa* warship
X-ray density measurements combined with mechanical tests from present and previous studies were used in the evaluation to non-destructively predict the mechanical properties in the proposed methodology for the special case of *Vasa* oak.

III *In-situ* assessment of historical timber structures
Systematic assessment strategies were applied to assess the mechanical performance and structural health monitoring techniques to preserve historical structures without interfering with their structural integrity and capacity. This is of vital importance to minimise interventions and prolong the service life of timber structures.

IV Pilot study of the assessment of stresses in loaded structures
A resonance frequency analysis procedure was investigated in this pilot study to evaluate the opportunity to determine the tensile capacity on site for peaks of unexpected increased loads and to detect the most loaded vulnerable members.

It has been shown that a systematic assessment strategy is valuable and effective in the evaluation of the structural condition and performance of the structure in order to preserve (historical) timber structures to the greatest extent possible. The combination of structural health monitoring techniques is necessary to achieve accurate results for the analysis of the structural performance and they require further specific development.

Keywords: *In-situ* assessment, timber structures, assessment methods, non-destructive testing (NDT), density, X-ray, historical structures, mechanical properties

Tillståndsbedömning av befintliga träkonstruktioner – Icke-förstörande testmetoder och fallstudier

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SAMMANFATTNING

Vid bedömning och diagnostiska undersökningar av träkonstruktioner med avseende på deras tillstånd och prestanda ställs ofta krav på lämpliga undersökningsmetoder och utvärderingsstrategier. Denna avhandling behandlar fyra huvudaspekter inom forskningsområdet för tillståndsbedömning av träkonstruktioner baserad på befintlig vetenskaplig kunskap samt anvisningar för *in-situ*-bedömningar av tillståndet hos befintliga träkonstruktioner:

I Bestämning av densitet hos trä på plats med hjälp av röntgenanalys:
De mekaniska egenskaperna och konstruktionens prestanda är ofta starkt korrelerade med densiteten hos trä. I det arbetet har en röntgenbaserad kalibreringsmetod för bestämning av träets densitet *in-situ* tagits fram och utvecklats som möjliggör rimliga uppskattningar för mekaniska parametrar hos trä.

II Bedömning av mekaniska egenskaper hos ekmaterialet i regalskeppet Vasa:
Densitetsmätningar med röntgen i kombination med mekaniska tester från både aktuella och tidigare studier användes här i utvärderingssyfte för att göra rimliga uppskattningar av mekaniska egenskaper hos ekmaterialet i regalskeppet Vasa med en föreslagen icke-förstörande metodik.

III Tillståndsbedömning av befintliga historiska träkonstruktioner:
Systematiska bedömningsstrategier och icke-förstörande testmetoder användes för att utvärdera ett bärverks prestanda i syfte att bevara (historiska) konstruktioner och byggnader utan att försämra konstruktionens beständighet och bärförmåga. Det är mycket viktigt för att både kunna minimera underhållsarbetet och även kunna förlänga äldre träkonstruktioners livslängd.

IV Pilotstudie för bedömning av aktuella spänningsnivåer i belastade konstruktioner:
Med en resonansfrekvensanalytisk metodik undersöktes i denna pilotstudie möjligheterna att kunna bestämma dragkraftsförmågan på plats vid oväntade maximallaster och för att upptäcka de mest utsatta och mest belastade konstruktionselementen.

Det visade sig att systematiska undersökningsstrategier är värdefulla och effektiva verktyg vid utvärdering av träkonstruktioners tillstånd och prestanda och med syfte att i största möjliga utsträckning bevara träkonstruktioner, särskilt i historiska byggnader. Användandet av flera olika icke-förstörande testmetoder och kombinationer av sådana är nödvändiga för att erhålla så noggranna resultat som möjligt vid analysen och utvärdering av träkonstruktioners prestanda och deras tillstånd, samt behovet av underhåll och utveckling.

Nyckelord: Tillståndsbedömning, träkonstruktioner, icke-förstörande testmetoder, röntgenanalys, materialegenskaper, mekaniska egenskaper, historiska konstruktioner

LIST OF PUBLICATIONS

This thesis is based on the work contained in the following papers:

Paper I

Lechner T., Sandin Y. and Kliger I. R. (2013): Assessment of Density in Timber Using X-ray Equipment. *International Journal of Architectural Heritage: Conservation, Analysis and Restoration,* Vol. 7 (4), pp. 416-433.

Paper II

Lechner T., Bjurhager I. and Kliger I. R. (2013): Strategy for developing a future support system for the *Vasa* warship and evaluating its mechanical properties. Accepted for publication in *Journal of Heritage Science*.

Paper III

Lechner T., Bjurhager I., Almkvist G. and Segués E. (2013): Use of a non-invasive and non-destructive methodology for the MOE prediction of oak wood from the warship *Vasa* using the X-ray technique. Submitted for publication to *Journal of Cultural Heritage*.

Paper IV

Lechner T., Bjurhager I. and Almkvist G. (2013): Method for the non-destructive prediction of the moduli of elasticity of oak wood from the warship *Vasa* using an X-ray technique. To be submitted to *Journal of Cultural Heritage*.

Paper V

Lechner T., Nowak T. and Kliger I. R. (2013): *In-situ* assessment of the timber floor structure of the *Skansen Lejonet* fortification, Sweden. Submitted for publication to *Journal of Construction and Building Materials*.

Paper VI

Lechner T., Laux S. and Sandin D. (2013): Stress level prediction in axially-loaded timber beams using resonance frequency analysis: A pilot study. *Advanced Materials Research*, Vol.778 (2013), pp. 454-461.

THE AUTHOR’S CONTRIBUTIONS TO JOINTLY PUBLISHED PAPERS

The contribution of the author of this doctoral thesis to the appended papers is described here. The development of the X-ray calibration technique to assess the density of timber and its applications in case studies is the author’s main contribution.

I. Responsible for the writing and for the major part of the planning of the paper. Provided the idea for assessing the density of timber. Planned, performed and evaluated the tests.

II. Responsible for the writing and for the major part of the planning of the paper.

III. Responsible for the writing and for the major part of the planning of the paper. Involved in planning and partly responsible for the execution of the experiments.

IV. Responsible for the writing and for the major part of the planning of the paper. Involved in planning and partly responsible for the execution of the experiments.

V. Responsible for the writing and for the major part of the planning of the paper. Planned the major part of the experiments and was responsible for the execution of the experiments.

VI. Responsible for the writing and for the major part of the planning of the paper. Involved in planning the experiments and partly responsible for the execution of the experiments.

ADDITIONAL PUBLICATIONS & CONTRIBUTIONS BY THE AUTHOR

Riggio M., Anthony R., Augelli F., Kasal B., Lechner T., Muller W. and Tannert T. (2013): In situ assessment of structural timber using non-destructive techniques. *Materials and Structures*, 2013:1-18. (doi: 10.1617/s11527-013-0093-6).

Kruglowa T. and Kliger I. R. (2012): Non-destructive investigation of material properties of the Vasa warship: a pilot study. In *Proceedings of the 8th International Conference on Structural Analysis of Historical Constructions*, Wroclaw, Poland, 15-17 October 2012.

Kruglowa T. (2012): *In-situ assessment of density and material properties in timber structures by non-destructive and semi-destructive testing*. Degree for Licentiate of Engineering, Licentiate Thesis, Civil and Environmental Engineering, Chalmers University of Technology, pp. 69.

Kruglowa T. (2012): *In-Situ* Determination of Density in Timber structures using X-ray: A Guideline. ISSN 1652-9162, Chalmers Report No. 2012:03.

Kruglowa T., Kliger I. R. and Sandin Y. (2011): On-Site X-ray Assessment of Density in Timber Structures. *Proceedings of the International Conference on Structural Health Assessment of Timber Structures 2011*, Lisbon, Portugal, 16-17 June 2011.

Kruglowa T., Sandin Y. and Kliger I. R. (2010): Density Calibration Using X-ray Equipment for *In-Situ* Assessment of Timber Structures. *Proceedings of the 11th World Conference on Timber Engineering*, Riva Del Garda, Italy, 20-24 June 2010.

Jónsson G.P. and Kruglowa T. (2009): *Determination of Design Values for Stress-Laminated Timber Decks: Non-Destructive Experimental and Analytical Evaluation*. Master’s Thesis, Department of Civil and Environmental Engineering, Chalmers University of Technology, Gothenburg, Sweden, pp.108.

Contents

”The best teachers are those who show you where to look,
but don’t tell you what to see.” - Alexandra K. Trenfor

Preface

The research that is presented in this thesis was carried out from July 2009 to September 2013 at the Division of Structural Engineering, Chalmers University of Technology, Sweden. The project involved the *in-situ* assessment of timber structures. This research project was financed by a research grant from The Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS, No. 243-2008-1246). I would also like to acknowledge the Nils and Dorthi Troëdsson Research Fund for providing Chalmers University of Technology with appropriate testing equipment.

Winter sports connected to the Scandinavian countries during the late 1990s were the initial reason for my journey to Sweden in 2001. My initial plans to move back to Austria to start my studies were never realised during the past 13 years. Finally, after having seen, lived and moved through Sweden from the very north to the south, I ended up studying at Chalmers, for which I can thank rather than blame my outstanding friend Simon Pallin, who encouraged me to study for a master's degree.

As I enjoyed the warm atmosphere at the Division of Structural Engineering, especially during my master's thesis, together with Grétar Páll Jónsson, supervised by Prof. Roberto Crocetti and Kristoffer Ekholm, I decided to accept the challenge of doctoral studies – but also being completely blind to what would be expected of me. I was worried and doubtful many times during this journey, which finally reached its final phase. I wish to express my special gratitude to my main supervisor and examiner, Prof. Robert Kliger, for all his good advice on technical matters, planning, writing my papers and performing the tests, his support on personal issues, as well as his sharp pushing motivation when I really needed it and doubted myself.

My co-supervisor during the first part of my research period, Ylva Sandin, including her husband Daniel Sandin, and Ingela Bjurhager (UU), who became my co-supervisor during the final phase of my studies, are warmly thanked for their help with planning and their extensive knowledge came in very handy when writing my papers and performing the tests. Further, I also appreciate the co-operation with Prof. Kristoffer Gamstedt (UU), Gunnar Almkvist (SLU) and the Vasa Unit and its staff, especially Magnus Olofsson, Anders Ahlgren and Malin Sahlstedt. I would also like to express my gratitude to Mrs. Jeanette Kliger for her professional language review of my publications.

I would also like to thank all of my friends and colleagues outside and inside Chalmers throughout the years, for their presence, co-operation and involvement, both privately and at work.

Warm thanks are also directed to my industry-related mentor during the past three years, Jan Olofsson, Skanska, for good advice, listening to personal and work-related perspectives, as well as inspiration, experience and motivation. I am also very grateful to my parents and my sisters for their unconditional support and distraction from work-related thoughts during every phase of life.

Finally, special thanks and respect are given to and deserved by a person that is irreplaceable for me and that I highly respect and appreciate for mindfulness and guidance to find my way back to myself, to my own strength and to set glamour and priorities in daily life. You know who you are.

THOMAS LECHNER

Gothenburg, October 2013

1 Introduction

1.1 Background

Timber structures are generally complicated when it comes to condition assessment. This is particularly true in the case of structures and buildings of historical value, when ageing can be suspected of having a diminishing effect on their strength and stiffness or abnormal structural behaviour has been discovered. The same applies to newer buildings and wooden bridges if they are damaged due to lack of maintenance, poor design, poor workmanship or events such as fire, floods or earthquakes.

Historical structures represent a part of the cultural heritage of every nation and societies pay considerable attention to their preservation and maintenance. Cultural heritage is regarded as an asset for society rather than a maintenance cost for the stakeholders. In historical structures, it is important to preserve the original structure to the greatest extent possible. Much of the damage observed in historical structures can be attributed to biodegradation. The deterioration of structural members results in changes in geometry and a reduction in load-bearing capacity. The replacement of deteriorated members may not be an acceptable option for structures of historical significance and re-design may be necessary to sustain the functionality of the structure. The preservation of historical structures represents, however, many challenges ranging from social and economic issues to technical methods and solutions for condition assessment and verification.

It is therefore of great importance to adopt structural health-monitoring techniques to assess the remaining load-bearing capacity of timber structures. Through the reliable and appropriate assessment and monitoring of timber structures, it is possible to detect any weaknesses at an early stage and appropriate action can be taken to extend the service life of the structures. This kind of assessment often requires appropriate non-destructive testing (NDT) and quasi-non-destructive testing techniques. Improved and new methods based on scientific knowledge and guidelines are needed for their application. This project focuses on technical challenges associated with the *in-situ* evaluation of timber in structures in general.

1.2 Research objectives and methodology

The principal objective of the project presented in this thesis was to improve advanced assessment methods and to verify the efficiency of guidelines and recommendations on how to perform assessments of existing timber structures with reference to their condition.

The methodology applied in this project includes literature studies, the development of NDT techniques and practical case studies and applications. A systematic combination of these aspects led to an actual approximated description and predictions of the material quality and served as valuable input in the evaluation of structures. This schematic procedure is illustrated in Figure 1.1 and also follows the main aspects of the framework.

Within this overall objective and the framework of the thesis, there were a number of specific stages that relate to different stages of the research project.

- To apply an appropriate assessment methodology and strategies and to screen existing timber structures for potential problem areas
- To develop advanced radiography to predict the density of timber and propose a guideline for this assessment
- To propose procedures to determine physical and mechanical properties *in situ* of timber structural members and mechanical connections using NDT to obtain input data to model the assumed behaviour of various existing structures
- To carry out detailed investigations of the internal condition of timber members and connections using NDT methods, such as advanced radiography, combined with other existing tests and to be able to interpret the results in a satisfactory way
- To evaluate the obtained density to predict stiffness and strength parameters from the NDT techniques
- To verify estimations of some mechanical properties for input in the structural analyses
- To verify the methodology and assessment techniques by applying them in case studies

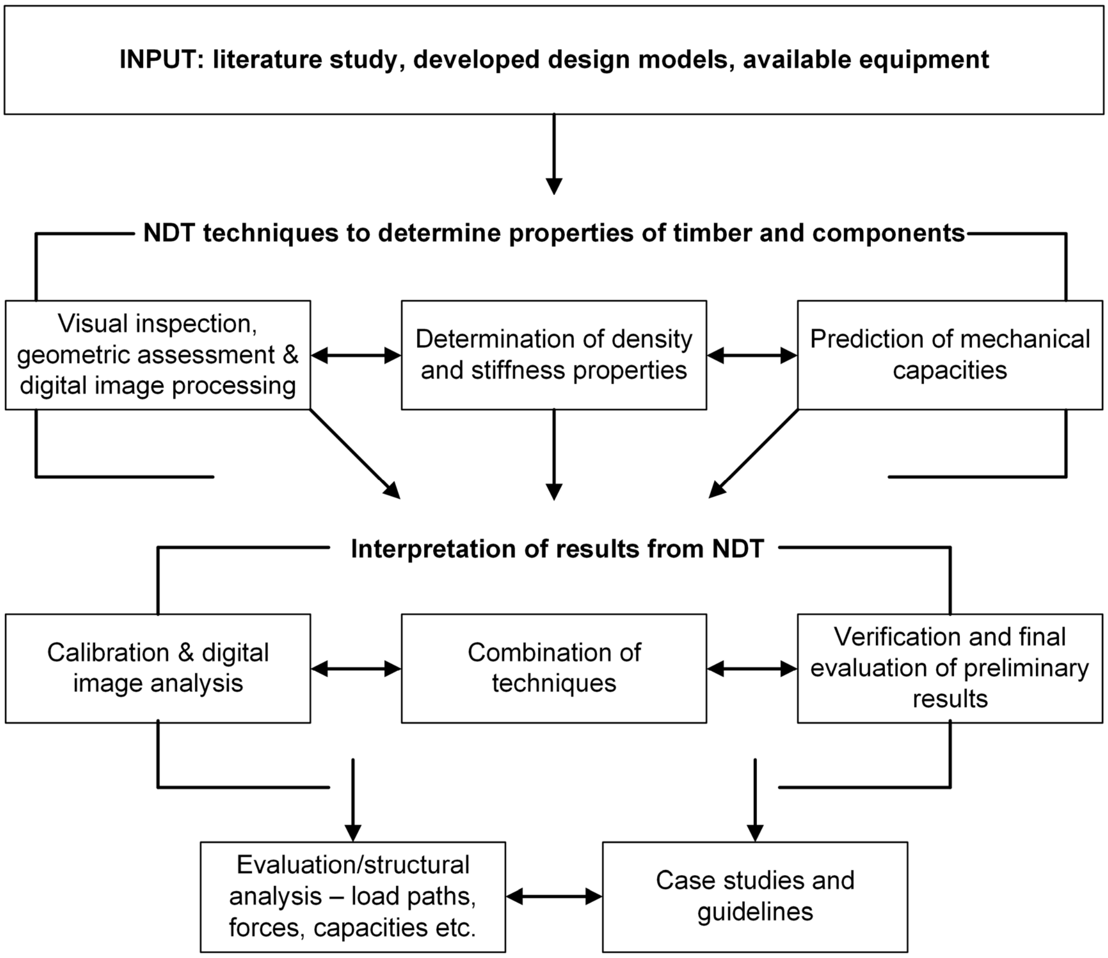

Figure 1.1 Schematic illustration of the scientific approach.

The literature review includes investigation techniques and assessment procedures within this research field that were important in order to address the relevant knowledge. Non-destructive testing techniques were explored and used to investigate the internal condition and health of the individual structural elements and to determine and/or predict the material and mechanical properties of the members. More specifically, density in timber is strongly related to the stiffness and strength properties (Kollmann et al., 1968, Dinwoodie, 2000) and this was used in the non-destructive evaluation of the investigated structural elements. Mechanical small-scale testing was combined with NDT methods in the analysis and the interpretation of the strength and stiffness parameters that served/might serve as input in the evaluation and analysis of the structural performance of timber structures.

This thesis covers the following four main aspects within the framework of structural assessment and assessment methods.

I Determination of density of wood with portable X-ray
The mechanical performance of timber is often strongly related to the density of wood. This work focused on the development of an *in-situ* calibration procedure to determine the density using X-ray, thereby enabling the prediction of the mechanical properties of timber (**Paper I**).

II Property assessment of oak from the *Vasa* warship
X-ray density measurements combined with mechanical tests from present and previous studies were used in the evaluation non-destructively to predict the mechanical properties in the proposed methodology for the special case of *Vasa* oak (**Papers III & IV**).

III *In-situ* assessment of historical timber structures
Systematic assessment strategies were applied to assess the mechanical performance and structural health-monitoring techniques to preserve historical structures without interfering with their structural integrity and capacity. This is of vital importance to minimise the interventions and prolong the service life of timber structures (**Papers II & V**).

IV Pilot study of the assessment of stresses in loaded structures
A resonance frequency analysis procedure was investigated in this pilot study to evaluate the opportunity to determine the tensile capacity on site for peaks of unexpected increased loads and to detect the most loaded vulnerable members (**Paper VI**).

1.3 Scope of the thesis

In order to realise the goals of the thesis, several aspects were investigated. These aspects are:

- Generally accepted methodologies, strategies and recommendations for structural assessment defined by standards were studied and set in context using case studies (**Paper II** and **Paper V**)
- A literature study was carried out on relevant different NDT and quasi-NDT techniques to investigate the physical and mechanical properties of timber structures on site
- The high correlation between the density properties and the strength and stiffness of timber initiated and justified the use and application of X-ray

equipment in the investigations to explore the potential for predicting density on site. For this purpose, clear-wood specimens with varying density were used to establish a calibration procedure for *in-situ* assessment (**Paper I**). This paper provides the main foundation throughout the study for application in the case studies and investigation procedures of the *Vasa* warship and the *Skansen Lejonet* fortification

- **Papers III** and **IV** are based on the application of the proposed method in the investigation of the density and stiffness properties of the *Vasa* warship in order to determine input values for numerical models. The test specimens that were used in this investigation were recent oak (*Quercus robur*), which served as reference specimens, and *Vasa* oak (archaeological wood) from the warship
- The final verification of this method was achieved in the application in the two mentioned case studies, where the proposed procedure is put into context and evaluated (**Papers IV** and **V**)
- The structural performance and safety of a structure by estimating actual stress levels in structural members was investigated in a pilot study (**Paper VI**). The prediction of stress levels on axially loaded timber beams was carried out using frequency analysis.

1.4 Limitations

The limitations of this thesis and the included papers can be summarised as follows.

- Intervention work, such as repairs, strengthening and maintenance, was not part of this thesis.
- The verification of the predicted mechanical properties of structural elements by mechanical testing based on the density of X-ray was not performed.
- The sample size of the specimens from historical structures was limited by the availability of elaborative specimens, which led to the decision not to perform advanced statistical processing of the data.
- The *in-situ* grading of structural timber was not included.
- The pilot study was limited to basic knowledge of frequency analysis and parameters. The development of this procedure, which is in its starting phase, and deepening of the knowledge and understanding of the frequency analysis of complex members was not part of the present study.
- Each individual study had its specific assumptions and limitations and the reader is referred to the appended papers.

2 Methodology for assessment of timber structures

The *in-situ* assessment of timber elements is essential in the continuous maintenance and preservation of historical timber structures such as warships, bridges, churches and so on. This is especially valid for occasions where causes of abnormal structural behaviour in the anticipated structural performance have been observed and the survival of the historical timber structures in the long term is to be guaranteed.

Abnormal structural behaviour can be suspected when excessive deflection in and deterioration of the structures have a diminishing effect, due to conservation work, changes in climate, the natural characteristics of old timber (Mohager, 1987, Rug et al., 1991), as well as the compatibility of material in connections that might affect the properties and result in changes in load-bearing capacity.

It is also important to be aware that, when evaluating timber structures, especially those of historical value, these structures are not always sound in terms of structure. It is also important to be aware of common problems that arise and alter the structural behaviour of the system. These problems can be insufficient support conditions and joint capacity, undesired excessive loads as a result of poor craftsmanship, insufficient capacity due to unfavourable load distribution, lack of knowledge that causes the degradation of elements, imprecise geometry and so on. However, these errors can be avoided and in many cases the structural complexity can be controlled by structural engineers to achieve and guarantee the safety and function of the structure for its continuous use.

Strategies and recommendations for the analysis of objects of highly significant cultural value must therefore be established and applied to identify the research needs that are related to the assessment and maintenance activities. This methodology should apply to all kinds of timber structure. The focal point of this study was the general assessment, excluding intervention and maintenance.

2.1 Holistic approach

A general methodology for the assessment of historical timber structures is outlined, based on on-going and existing standardisation activities and agreements, e.g. ISO13822 (*Bases for design of structures – Assessment of existing structures*), ICOMOS (*Principles for the preservation of historic timber structures*), ISCARSAH (*Recommendations for the analysis, conservation and structural restoration of architectural heritage)*, ASCE standard (*Guideline for Structural Condition Assessment of Existing Buildings*), UNI 11119 and UNI 11138 (Italian standardisation body). These existing standards and recommendations are designed to serve as a basis for the assessment procedures for existing structures and to preserve the value of the heritage (ICOMOS, 2005, Macchioni et al., 2006).

To summarise, the assessment methodology can be divided into four principal stages; anamnesis, diagnosis, therapy and prognosis (ICOMOS, 2005). In the anamnesis, all available information should be gathered about the history of and alterations to the investigated object in the past. The diagnosis then involves the actual measurements and all complementary information relating to the structure, such as the material characteristics, an on-site survey, a static analysis and an assessment of the stability of the load-bearing structure. This information makes it possible to retrieve the causes of the observed alterations and damage, which leads to final decisions in terms of an intervention plan for the investigated object. As a final step and after the intervention work, a prognosis to value the life span of the structure regarding durability and service life aspects, which is a difficult problem, needs to be made (ICOMOS, 2005, Magnus, 2008). It should also be pointed out that all investigations and actions should always be properly documented to facilitate future investigations and decisions.

The structural investigation procedure that was borne in mind throughout the project and applied and verified in a case study (**Paper V**) is based on adapting a general assessment methodology (ISCARSAH, 2003, ICOMOS, 2005, Macchioni et al., 2006, Cruz et al., 2013) to evaluate the structural condition and the mechanical performance. This procedure is also well in line with the *ISO13822* standard.

The methodology comprises the following steps, see also Figure 2.1:

(1) Diagnosis of the structure from previous repair work and actions during service life
(2) Preliminary assessment and visual inspection
(3) Detailed assessment and investigation including material testing with non-destructive and quasi-non-destructive testing methods at critical sections
(4) Evaluation of the results of the material tests
(5) Structural analysis and evaluation of results.

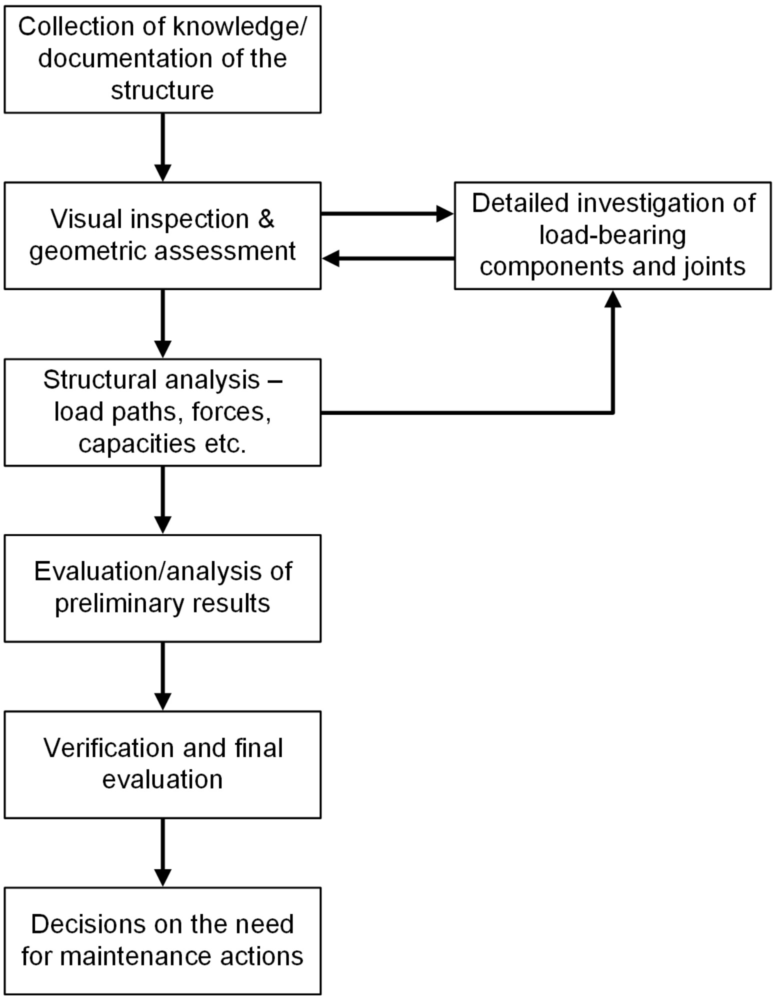

Figure 2.1 Applied assessment strategy based on existing standards.

Each investigated object needs to be treated separately as a unique structure under given circumstances and conditions. Factors, such as the load paths, load distribution, the condition of the connections, support conditions, alterations in the load-bearing behaviour, environmental impact on single members in the structure, seasonal climate changes, moisture impact, indoor climate, age, damage, microbial activities and so on, have to be considered individually in the evaluation process. As mentioned before, a general investigation and analysis procedure can and should be followed.

There are two main approaches in the investigation procedure that can be identified and have to be treated in order to obtain the most accurate information about the actual behaviour of the structure. One deals with the material characteristics, both qualitatively and quantitatively, and takes place at element level, whereas the other approach takes place at structural level, dealing with the characteristics of load transfer and distribution in the structural system. These approaches are mutually related and dependent on one another, but they can be ranked in importance in relation to their consequences and their relevance and efficiency, which needs to be discussed separately. The question of whether to start with one or the other has to be solved, as well as the input of appropriate parameters, to identify the most accurate predicted behaviour of the structure possible in order to estimate the condition and mechanical performance. It is, however, believed that a combination of both investigations produces the most accurate prediction of the real behaviour.

However, a visual inspection should always be the first step in each condition assessment project and it is the basis of any *in-situ* assessment procedure providing information about the structural soundness of timber structures (Riggio et al., 2013).

Using visual inspections, critical areas and all visible signs of possible deterioration (e.g. stains, leakage, discoloration, insect attacks) that effect the mechanical performance of the structure and have a significant influence on the load distribution in the structure can be identified in the early stages and appropriate measurements, such as moisture content, can be evaluated. Moreover, the relative position of natural defects can be located to prevent the structure from progressively continuing to deteriorate (Kasal, 2010). For example, the knot area ratio and its positions are correlated to the tensile strength and influence its strength capacity (Ravenshorst et al., 2004). The amount of degradation in the critical sections has to be determined using additional tools and detailed inspections.

At this stage, the investigated structure can also be assigned and documented with accurate information regarding geometry and dimensions (**Paper V**), which also has a major impact on the stiffness and thereby also on the behaviour of the structure.

2.2 Assessment of structural systems

After the first preliminary inspection of the structure, a preliminary model of the structural system can be created, assigning preliminary and relevant material characteristics and dimensional properties, in order to analyse the general aspects that have a major impact on the structural behaviour. These aspects serve as a basis for decisions and judgements related to interventions and inspection strategies, where specific knowledge and expertise is required to obtain data relevant to the mechanical behaviour of structural timber elements, and are in line with an holistic approach, with the aim of facilitating the *in-situ* assessment of timber structures (**Paper V**).

Knowledge of the force distribution and deformation is required in order to analyse the mechanics of the structure. The calculated forces and deformation depend on the assumptions made regarding geometry, joints and conditions at the supports, materials and loads. In particular, the detailed modelling and investigation of joints and their function and the assumptions relating to the boundary conditions are of great importance, as they make an important contribution to system behaviour (Branco et al., 2010). The importance of boundary conditions and their effect on structural behaviour were investigated and illustrated in a parametric study of historical roof structures of Swedish churches by Sandin (2005). However, a small number of studies taking account of both the structural analysis and material testing also exist, such as those carried out by Branco et al. (2010), Esteban et al. (2010) and **Paper V.**

In order for the evaluation to represent the true behaviour of the real structure and the remaining load-bearing capacity, these parameters must all be appropriately explored and described in the process, before decisions relating to the continuous maintenance and restoration work are made, as these parameters are also directly related to the system evaluation.

At the preliminary stage, a general model with relevant material properties is sufficient, but there are scenarios in which detailed information about the mechanical properties and the material characteristics have a major impact on the decision of whether to preserve existing material, strengthen or replace it. When joints and supports are appropriately designed, however, the material parameters can govern the decision of whether a structure can be upgraded and evaluated in terms of its load-bearing capacity in a further and more detailed investigation of the mechanical performance and condition of the individual elements (**Paper V**).

2.3 Assessment of material and mechanical properties

The structural system and model are primarily created in practice, before any other detailed material properties are assigned and investigated. The need for further testing is then defined. Decisions on the need for further testing are based on the actual future scenario that is being investigated, where account is taken of the opportunity to upgrade a structure due to a change in its intended use or a future load increase because of safety requirements or changing environmental impact and where the structural components do not necessarily exceed the requirements of the standards. Another scenario, which is at least as important, could be described when the removal of or damage to one primary member leads to the load being distributed to other structural components in the system that are then suddenly exposed to higher loads than they were designed for from the beginning and this can lead to peak loads. In these cases, the actual capacity and strength of those members that take the extra load need to be determined, but not purely from a visual strength-grading viewpoint with a lower bound assumption. An overall survey of the material should therefore be the aim, taking account of each individual structural member of the load-bearing structure to assure the accuracy of the assessment using non-destructive assessment techniques.

As wood is an anisotropic material, the characteristics vary between the different directions, but, due to its natural characteristics which cannot be controlled by the production process, the material characteristics depend mainly on the wood species, moisture content, natural growth defects and type of structure. This also affects the reliability of the data and it is important to remember that there is inherent uncertainty in the NDT method (Kasal, 2010). As a result, common certified standards for *in-situ* material testing using non-destructive tests to assign material strengths for structural evaluation as accurately and correctly as possible should be established. Defined procedures and the available results and correlations of the material parameters from non-destructive testing show large variations (Feio, 2006, Íñiguez et al., 2008, Esteban et al., 2010, Machado et al., 2011). The estimation of the static modulus of elasticity from the dynamic modulus of elasticity, for example, using stress-wave timing results in differences of up to 20% to 30%, depending on which correlation function is used.

This makes it difficult in the evaluation to judge and argue about whether to use one or the other correlation, as the estimations are designed to obtain the most precise values possible and not highly underestimated values. Due to the author's experience of previous testing, a correlated function for estimating the static modulus of elasticity from stress-wave measurements by Íñiguez (2007), which tested large cross-sections of coniferous sawn timber, was used to evaluate the structural timber components in **Paper V**. The estimation of the bending and shear strength in the same study was even more crucial, due to the fact that the correlation between the modulus of elasticity and the bending strength introduces further uncertainty that weakens the power of estimating those parameters (Kasal, 2010). A correlation that corresponds to lower bound estimations of strength parameters, similar to those in visual strength grading, was therefore used in the evaluation.

However, in order to improve the accuracy of the assessment of the *in-situ* material and mechanical properties from non-destructive testing techniques, the information needs to be cross-validated (which was not the aim in this project) by combining non-destructive and destructive large-scale testing (Machado et al., 2011).

Since one of the main purposes of the study in **Paper V** was the investigation of material properties *in situ*, the extent to which non-destructive testing methods are useful for obtaining actual wood characteristics is discussed. As important material, strength and stiffness properties are mutually related to one another, these correlations can be and were taken advantage of in an overall survey of historical structures using non-destructive testing methods to evaluate the on-site material properties. These estimations of material characteristics, despite their large expected variability due to the lack of accessed material, are, however, the best estimate that can be obtained for evaluation.

2.4 Summary and key findings

- The study in **Paper V** showed that the framework of the existing standards and procedures itself is an efficient tool for the evaluation and investigation of structures and does not necessarily need improvement.
- The guidelines for the assessment of *in-situ* material and mechanical properties from non-destructive testing need to be further developed and improved to increase the accuracy of the investigated parameters.
- Experience from practice and studies shows that the evaluation of the structural system and joint behaviour is at least as important as the investigation of the material properties in order to preserve the existing structures and their components to the greatest extent possible.
- Studies taking a holistic approach into account should be further focused on.

3 Assessment methods to evaluate the material and mechanical properties of timber

A short overview of the different non-destructive testing (NDT) and quasi-NDT techniques and their relevance in terms of possible applicability for a global survey is given, as well as a local assessment and characteristics for the evaluation of mechanical and material properties as input for numerical analysis. Quasi-non-destructive testing techniques are methods that do not interfere with the structural performance and safety of the structure and they are referred to as NDT methods in what follows. These methods also form the foundation of both the assessment strategy and the development and improvement of assessment methods and procedures that were consequently used in all the projects (**Papers I-VI**).

Non-destructive testing methods for timber structures are mainly used to detect local damage and the internal condition of timber (Brozovsky et al., 2008) but also to determine material and mechanical parameters. The main focus is the opportunity to conduct the *in-situ* determination of physical and mechanical properties using NDT techniques. Among timber investigation techniques, there are several methods that are commonly used for the assessment of both qualitative and quantitative parameters of timber structures (Ross et al., 2000, Kasal et al., 2004, Anthony et al., 2007).

The prediction of material parameters is more uncertain in the case of structures with large restrictions in relation to access to material to test many specimens (**Papers III & IV**). The available methods might produce differences in the test results, depending on the specific test method that has been used. For this reason, a combination of both destructive and non-destructive methods might produce greater accuracy in the prediction of mechanical and physical parameters (Kasal et al., 2004). Since historical structures often provide limited access to material for destructive testing, NDT methods are preferred in order to assess the condition and material characteristics of the structure. However, the use of NDT methods is extremely valuable as a support tool for the diagnosis and the control of intervention work in the on-site assessment of structures.

The sequence with which the different NDT methods should be applied in order to optimise the assessment can be discussed and the different methods therefore have different characteristics and suitability in relation to the type of structure being assessed. In the particular case of the floor structure at *Skansen Lejonet* (**Paper V**), the preferred test sequence was firstly stress-wave timing, secondly X-ray and thirdly resistance drilling. When locations are exposed to suspected damage, a detailed investigation using the test method requiring the least effort is preferred to verify the section that has deteriorated and the extent of the deterioration and its impact on the structure (Kasal et al., 2004).

It is important to conclude that, due to the size and complexity of the material structure, an efficient global strategy for the *in-situ assessment* of the material properties should be established, i.e. a rapid, easy procedure to scan the global parameters and analyse the critical sections. The first scan should then be documented accurately to decide on further investigations of the critical sections.

The most appropriate method for determining the *in-situ* density of the material is the density calibration procedure using X-ray equipment (**Paper I**), which showed good agreement between the greyscale and the density of the evaluated timber specimens.

In combination with the determination of density, ultrasonic and stress-wave-based measurements are of great interest when it comes to determining and mapping the stiffness and strength of the load-bearing capacity of the structure. The stress-wave techniques for the determination of the E-modulus are mainly governed by the speed of the wave propagation. It is, however, dependent on the density of the material, the internal condition of the timber and the moisture content. Complementary measurements could be made with the drilling resistance in order to verify the soundness of the structure (**Paper V**). The values that are obtained for the E-modulus should be verified with additional static tests. The stress-wave techniques are also appropriate for determining the internal condition of the timber.

Frequency analysis in order to determine the safety of a structure may be promising, but it still has to be developed further, especially when it comes to timber structures (**Paper VI**).

There are other NDT methods that have good correlations with the physical and mechanical parameters but also with compressive strength and the E-modulus (Kasal et al., 2010, Riggio et al., 2013). These methods have not been used in the studies related to this thesis.

3.1 Digital radiography (X-ray)

The application of digital imaging processing and increasing resolution has made it possible to use quantitative assessments of components, such as the internal deformation of fasteners, the dimensions of hidden elements and strains (Kasal et al., 2008). The basic principles of X-ray were used in the study to establish an *in-situ* calibration procedure to predict density on site (**Paper I**). Some background on the applicability and practical applications using portable X-ray equipment is given in this chapter. Only practical equipment for *in*-situ investigations was explored.

X-rays are short-wavelength electromagnetic radiation travelling at the speed of light. These rays are not affected by electromagnetic fields and can be diffracted but not deflected. Emitted X-rays lose intensity, which appears as lighter/darker in terms of greyscale values (RGB) on the imager (N.C.P.T.T., 2005).

The penetration capability and intensity of the radiation are controlled by the electric potential (kV), the current (intensity, mA) of the X-ray tube and the exposure time. The penetration is the intensity projection on the image plate and is governed by:

- The type of material and the material characteristics
- The material composition
- The density of the material
- The porosity of the material and its moisture inclusion
- The attenuation factor (μ)
- The penetration thickness of the X-rayed object.

In digital form, the image can be expressed as a matrix and processed in an image-processing toolbox such as the one in Matlab® to quantify and compare relative positions in real-time radiography, for example.

The equipment used in the studies was a battery-powered portable X-ray source, Inspector XR200® from Golden Engineering Inc., see Figure 3.1. However, other X-ray equipment can be used *in situ*. The digital image plate system, DIMAP® from Logos Imaging Inc., was used to scan the photographic X-ray images.

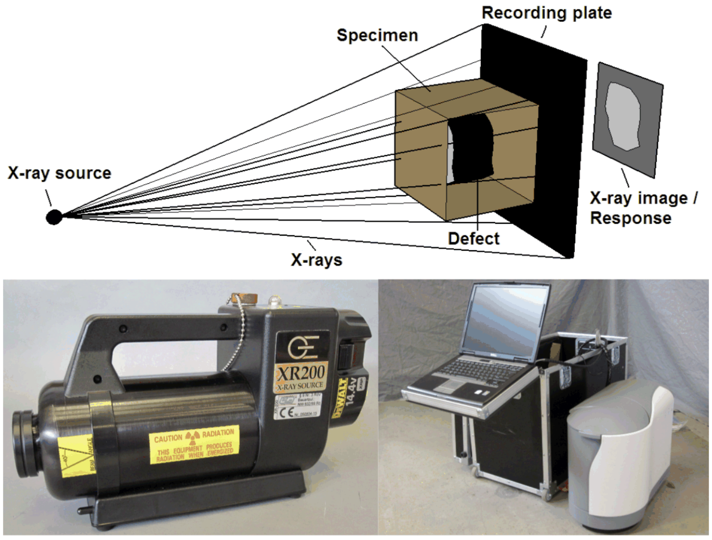

Figure 3.1 Example of X-ray system and recording process.

3.1.1 X-ray image-evaluation procedure

Due to the cone beam effect of the portable X-ray equipment, where the dosages of the image were not evenly spread in the raw X-ray image, image corrections using imaging software, e.g. ImageJ®, are a great advantage in digital images, where the relevant attenuation ratio (I/I_0) is measured, where I is the intensity of the X-ray beam after penetration of the sample and I_0 is the initial intensity. The ratio can then be calculated as an average value over the complete energy spectrum (Badel et al., 2002).

In order to correct the defaults/noise level of the raw image, several small steps must be applied to evaluate the noise level and subtract it from the complementary background image without illumination. A further image with X-ray illumination accounting for the non-uniformity of the cone beam effect to reach the final pixel grey value is needed. This principle of image correction due to background noise level was applied in the *in-situ* determination of the material density in the different projects. This image correction procedure is illustrated in Figure 3.2.

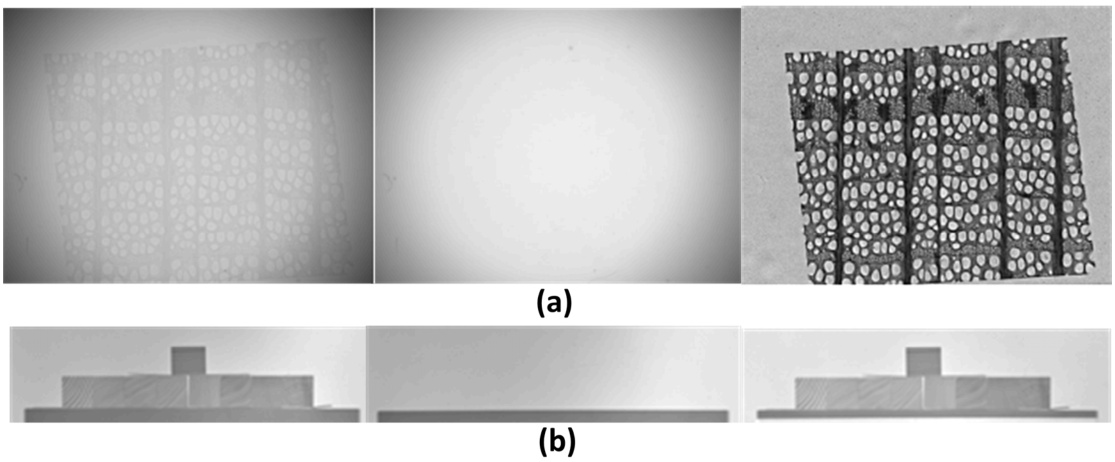

Figure 3.2 The procedure in principal for image background correction due to the cone beam effect, (a) according to Badel et al. 2002 at micro-level and (b) an example from the correction procedure in these studies.

3.1.2 Applications of X-ray investigations

An overview of possible applications using X-ray equipment for the evaluation of timber structures is presented in this chapter. Until recently, the opportunities for X-ray investigation have been used for the qualitative assessment of timber structures, but the opportunities to carry out quantitative evaluation are of great importance. A number of applications for using X-ray equipment on site, which can be useful for the evaluation of structural behaviour, are revised in this work.

Depending on the material properties of the inspected object, energy absorption, chemical properties, density and thickness are reflected by the photographic image (Anthony, 2003). Anthony also investigated termite activity using infrared thermography and acoustic non-destructive methods but without satisfactory success when it came to quantifying the loss of material (Anthony, 2003). By comparing the measured intensities on a radiograph, the extent of deterioration in wood members could be quantified using imaging processing techniques (Anthony, 2003, N.C.P.T.T., 2005).

Several different imaging enhancement techniques can be used for the interpretation of deteriorated wood. The primary benefit when using X-rays is the opportunity to determine the condition of structures on site without disturbance. Another advantage is the ability to acquire precise dimensions by measuring the distances between the X-ray source, the imager and the object of interest. Further advantages are the ability to identify the physical condition of wood, by checking the structural examination of the building pattern, identify the types of connection, such as nails, bolts and so on, and identify the construction details for historical dating (N.C.P.T.T., 2005). All these advantages involve some difficulties, especially in crack identification, which requires an adequate size of at least 2% of the member thickness and must be oriented parallel to the radiation in order to be detected (Lear, 2005). Limitations to the intensity or energy level can also limit the investigation (Lear, 2005).

Real-time radiography (radioscopy) allows the study of component behaviour under moderate loads and is particularly suitable for timber structures due to the density differences.

Detection of corroded area

As corrosion in metal fasteners might cause severe failure, radiographic equipment can be used as a tool to detect corrosion inside the structure and, as a result of appropriate action, this could prevent the collapse of the structure (Anthony, 2003). Using commercial image-editing programs, distances can be measured fairly accurately in relation to some reference unit and the actual capacity of the fastener can be re-calculated. Figure 3.3 shows a corroded nail as a result of a shrinkage crack in timber.

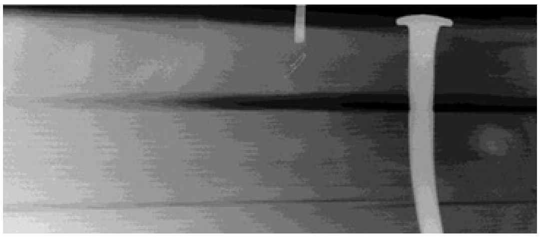

Figure 3.3 Deterioration of the metal fastener due to corrosion in the shrinkage crack of the beam.

Reduction of cross-section

Old timber may have lost its full capacity due to deterioration either as a result of insect attacks or due to shrinking cracks (Brozovsky et al., 2008). When accessibility with an X-ray camera along the fibre direction is guaranteed, a prediction of the maximum allowable stresses at a specific point could 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 using X-ray, this does not necessarily mean that hidden timber parts can be visualised with sufficient accuracy. As part of the current investigation, a preliminary study has been carried out and it shows promising results in this field, cf. Figure 3.4.

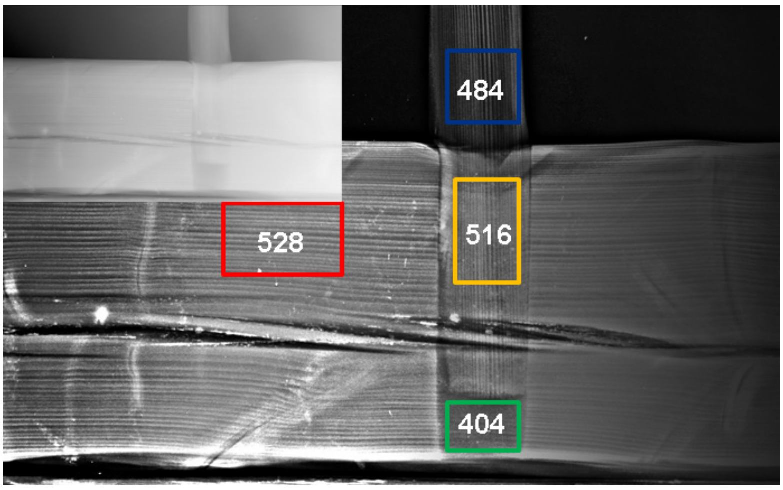

Figure 3.4 A hidden dowel with approximately the same density as the surrounding wood can be detected using of X-ray. Original X-ray image (top left corner) vs. edited image. The numbers correspond to the mean density through the thickness of the beam at different positions.

Density distribution in components

The development of the equipment and the methods of digital image analysis has made it possible to determine variations in 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 (Tomazello et al., 2008, Chen et al., 2010).

Determination of material properties through image calibration

X-rays are already in use as a means of determining material properties and strengthening grade timber. The current methods are not suitable for *in-situ* assessment and are outside the scope of this article.

Nevertheless, *in-situ* methods for determining material properties most probably exist for materials with great homogeneity, such as steel (Bateni et al., 2008). As timber is a material with large-scale variation, these methods cannot be applied without further reflection.

As shown in this thesis, the X-ray images of beams and at joints can be calibrated in a further step towards identifying density using a calibration procedure.

Mapping damage and deterioration

As most of the portable X-ray equipment delivers images in a two-dimensional perspective, additional help using resistance drilling, for example, may be needed for the volumetric mapping of deterioration as a result of insect attacks. In many cases, a two-dimensional image is sufficient for determining the severity and progress of the invisible damage (Rinn et al., 1996, Lear, 2005), as decay due to rot and high moisture content can be seen and determined by measuring the area of the void (dark area).

Figure 3.5 shows a simulated termite attack that makes the determination of cross-section loss possible through image enhancement, whereas decay, on the other hand, does not cause an abrupt change in wood and makes the detection of a gradual transition to cross-section loss problematic.

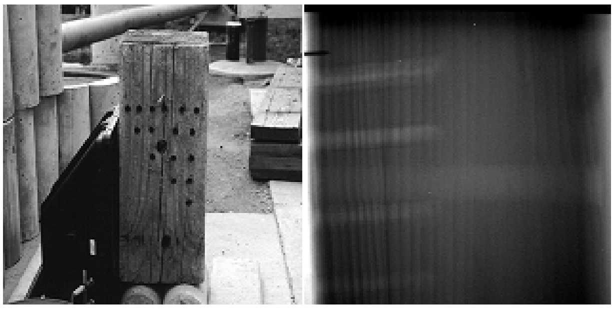

Figure 3.5 Simulated deterioration that caused the loss of cross-section resulted in a deviation in the greyscale on the X-ray image (N.C.P.T.T., 2005).

Failure modes in metal fasteners

In-situ X-ray imaging also provides an opportunity to determine the actual behaviour of dowels in joints, see Figure 3.6 (Anthony, 2003). The opportunities to obtain the dimensions of non-visible fasteners or cross-section reductions, as well as the connection of joints that are decisive for the judgement of boundary conditions, offers an excellent opportunity for further interpretation in the structural analysis (N.C.P.T.T., 2005). Moreover, the exact position of the plastic hinges can be determined.

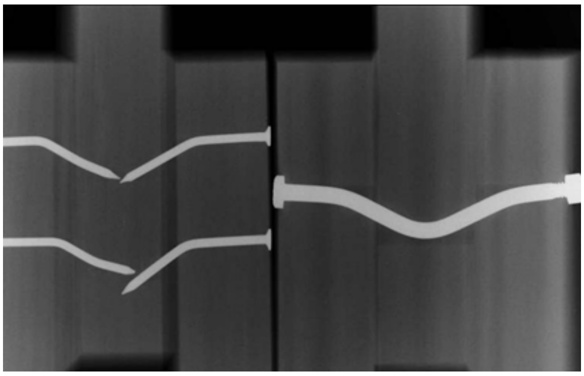

Figure 3.6 The X-ray images show the behaviour of a nailed joint (left) and a bolted connection (right) (N.C.P.T.T., 2005).

3.2 Stress-wave timing

Stress-wave measurements are a simple and effective measurement technique to identify the internal soundness and condition of structural elements but also to determine the modulus of elasticity (MOE) for structural analysis. In these tests, two piezoelectric probes are used to receive the longitudinal ultrasound wave.

One-dimensional stress-wave transmission is the most commonly used technique to measure the time that is required to travel between the piezoelectric sensors (Wang et al., 2004). The one-dimensional stress-wave theory is sufficient for wave propagation in wood, where the transmission time and the density are related to the longitudinal MOE, see Eq. (3.1). This was verified and compared with the static four-point test and good correlation was achieved (Zombori, 2001). The static MOE is approximately 90% of the dynamic MOE (Görlacher, 1991, Ross et al., 1994) and the values are usually acquired using a linear relationship equation (Feio, 2006).

$$MOE_{dynamic} = \rho \cdot v^2 \qquad \text{Eq. (3.1)}$$

where ρ is the density and v the transmission time of the stress wave.

There are several key aspects that influence the travel of the stress waves in timber. They are *the effect of wood species, moisture content, temperature, biological and chemical degradation, decay, insect attacks, grain angle and measurement direction.* These aspects have to be accounted and adjusted for in the evaluation and the interpretation of the results in order to determine quantitative parameters such as the MOE, as well as the qualitative parameters of structural soundness (Dackermann et al., 2013).

This technique requires an appropriate measurement strategy and approach in order efficiently to determine the structural performance of *in*-situ elements and successfully detect internal damage, as well as the extent of both external and internal damage. A stress wave-based condition assessment strategy of this kind is simply illustrated in Figure 3.7, where critical areas from the visual inspection were measured stepwise in different directions to identify decay and its extent in the structural element at different locations along the beam (Dackermann et al., 2013). A similar stepwise strategy can also be applied to determine the MOE of structural members and the variation in the MOE along the beam due to the natural variability of timber properties. Once degradation is localised, the extent of the cracks, hidden damage and deterioration can be assessed with transverse measurements, cf. Figure 3.8. The measurements can also be combined with additional testing methods, such as resistance drilling or X-ray, at that stage.

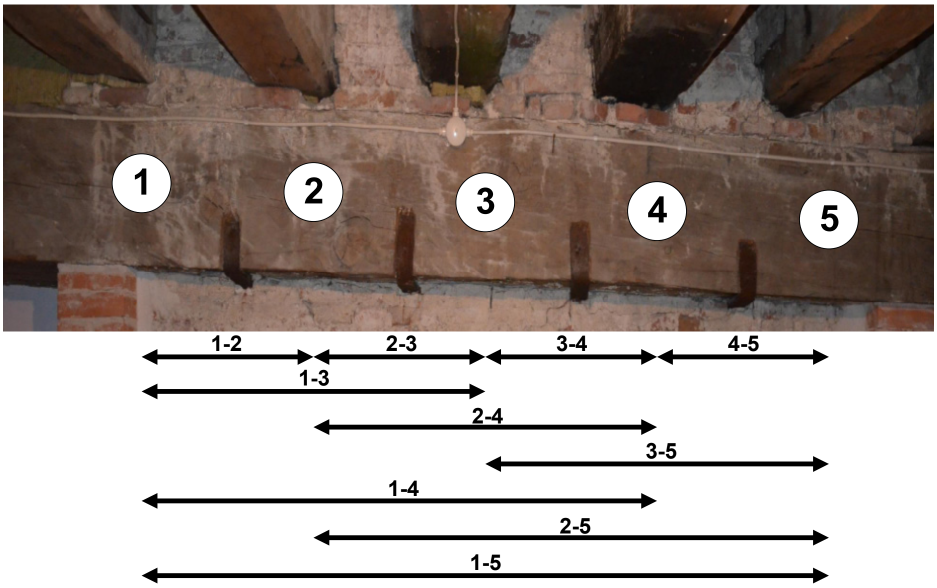

*Figure 3.7 Illustration of a stepwise stress wave based assessment approach along a structural beam for quantifying the structural soundness and assessing the quality of the beam (**Paper V**).*

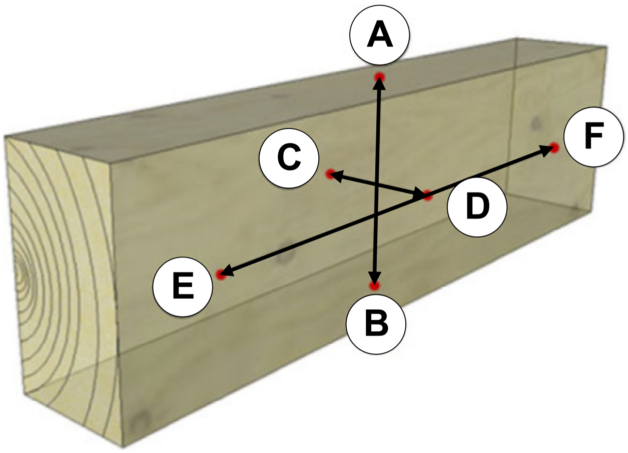

Figure 3.8 Measurements in different directions (A-B, C-D and E-F) to localise the extent of the damage/deterioration adopted from Dackermann et al. (2013).

The transverse propagation of the stress waves is about 25% of the value in the longitudinal direction (varying from 4,000 m/s to 5,500 m/s depending on the wood species) and it is mainly used as a qualitative parameter to assess the condition of structural elements (Ross et al., 2004). The transverse velocity transmission is the most effective way to detect decay and its extent, see (Ross et al., 2000). A decrease in the relative velocity of less than 10% compared with the reference velocity of the specific species is an acceptable and natural variation which shows no signs of decay, whereas larger decreases provide susceptible signs in the decayed area (Dackermann et al., 2013).

The internal condition of the wood/timber elements in a structure can be determined with fairly good accuracy by measuring the stress-wave time along the member. Decayed and degraded wood show clear increases in stress-wave transmission times, which also leads to a significant loss of strength (Pellerin et al., 2002). An increase in velocity sound of about 30% resulted in a loss of strength of about 50% (Ross et al., 2000, Dackermann et al., 2013). A strong correlation relating to these properties was reported back in the late 1980s.

The most commonly used technical stress-wave timers and ultrasound methods available are Metriguard®, Sylva-test®, Fakopp® and Pundit®.

3.3 Resistance drilling

Resistance drilling can be used to detect and quantify the internal condition and decomposition of the wood in timber structural elements. The local detection of the internal defects due to fungi can be found by sounding (Görlacher et al., 1990), but the use of ultrasound procedures is more appropriate for the detection of internal defects. In this study, the resistance drill was used to identify the internal condition at the supports and in the detailed investigation at critical sections, as well as for the cross-section reduction due to surface degradation (**Paper V**).

The use of this small-diameter, needle-like drill was introduced by Rinn (Kasal et al., 2004). Nowadays, some different commercial instruments are available, e.g. IML-RESIF400-S® and Resistograph®, cf. Figure 3.9. The drilling resistance is proportional to the relative variations in density, i.e. decreasing drilling resistance is followed by reduced torque in the drill. Areas that need less torque are therefore associated with reduced density, e.g. deteriorated parts in timber, cracks and so on (Lear, 2005). A Resistance Measure (RM) parameter was implemented to enable the comparison between the density of the drilling resistance and the mechanical and physical properties of the timber. The RM parameter is, however, defined as the integral of the area of the drilling diagram divided by the length, *l,* of the drilled perforation (Lourenço et al., 2007), see Eq. (3.2).

$$RM = \frac{\int_0^l Area}{l} \qquad \text{Eq. (3.2)}$$

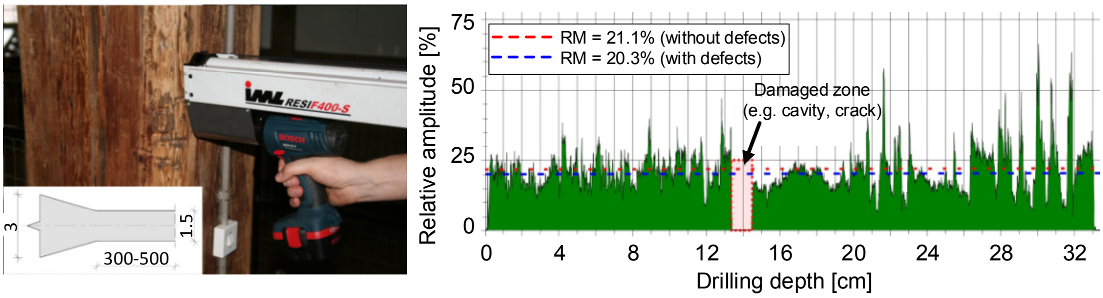

Figure 3.9 (Left) IML-RESIF400-S® and (right) density profile of resistance drill measurement showing a decayed area in a beam. Drill shape and dimensions (mm) are shown in the lower left corner.

A relatively high correlation between the drilling resistance and the density has been found by some researchers (e.g. Görlacher), although the variation differed. Ceraldi et al. reported a good correlation between the transverse axial compressive strength and the density measured by the Resistograph® (Ceraldi et al., 2001). Lourenço and Feio et al. also reported medium to high correlations between strength parameters and the RM (Feio et al., 2005, Lourenço et al., 2007), but it should be remembered that the resistance-drilling technique has not yet provided a sufficient correlation for structures tested *in situ* (Kasal et al., 2004). Several factors, such as moisture content and tree species, together with very local measurement characteristics, might influence the results and they should therefore be interpreted with care.

One of the main aspects in the use of resistance drilling is to apply appropriate drilling points and drilling direction to evaluate internal condition. The main principle is to drill perpendicularly with respect to the tree rings in order to be able to distinguish between intact wood and incipient decay from the relative density profiles (Tannert et al., 2013). For quantified evaluation, regular drilling intervals should supply sufficient information about the density profiles, whereas, for the detection of decayed areas, all doubtful areas from the visual inspection should be drilled (Tannert et al., 2013). The interpretation of the density profiles from the drilling-resistance measurements often requires expert knowledge of the composition and the inhomogeneity of wood structures.

One of the main advantages of this method is the opportunity to assess the internal condition of hidden parts and this is very useful when assessing the condition close to and at mechanical connections. Previous studies have also shown that 30% of the total damage in timber structures was in non-accessible parts and was therefore not detected through visual inspection. At the same time, internal decay in timber structures was also highly prevalent and could be detected by appropriate assessment techniques such as resistance drilling (Tannert et al., 2013). Furthermore, many structural timber elements could be preserved using resistance drill-based assessment strategies, which also led to reduced costs in the repair and maintenance work (Tannert et al., 2013).

3.4 Non-destructive investigation using frequency analysis

This section explicitly describes only the theoretical background in a simple and practical manner used in **Paper VI** to predict actual stress levels in structures using a frequency based method.

The static system is a simply supported beam with identical rotational springs at both ends. This leads to two unknown parameters, namely the axial force S and the rotational stiffness k, see Figure 3.10.

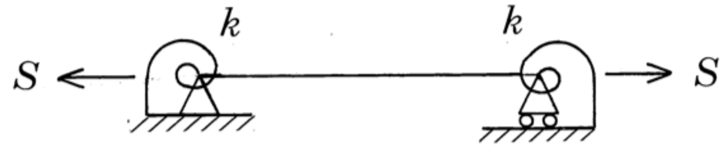

Figure 3.10 Simply supported beam under axial load with rotational spring supports (Livingston et al., 1995).

Livingston (1995) was one of the first people to introduce a method based on frequency measurements to estimate the axial load in members in steel rods. His model enabled the identification of the rotational restraint at the supports of prismatic beams. The principle is transversally to excite a beam under axial force and to determine the first frequencies using an accelerometer linked to computer software. Resonance frequency analysis then enables the derivation of the axial loads and boundary conditions from these frequencies (Livingston et al., 1995). The results were promising and the method was also used in similar applications (Maille, 2008, Amabili et al., 2010). Since one of the main application fields for timber products is roof structures and since the exact material behaviour is not entirely clear, a reliable non-destructive testing method would represent a major contribution to the safe assessment of existing structures.

Theoretical (TMA) and experimental modal analysis (EMA)

In theoretical modal analysis (TMA), the modal parameters are determined by solving the differential equation of motion. As mentioned above, shear deformations have a major influence on the frequencies of timber beams, even if they are somewhat slender. It is therefore necessary to include them according to Timoshenko's theory (Weaver et al., 1990). In this case, a continuous model was used.

The deflection pattern of a structure subjected to any excitation force can, in theory, be expressed as the linear summation of its modal shapes. The resonance frequencies can be determined using a Fourier transformation. In practice, the modal parameters can be determined experimentally. If one is, however, interested, for example, in the specific resonance frequencies of a structure, it is necessary to subject it to a force able to excite these frequencies. In this case, the force can also be measured and considered in the modal analysis of the structure. The force has to be actively controlled. For a given force function, it is possible to detect which resonance frequencies are actually excited by examining the frequency response function (FRF). The FRF is defined as the ratio of response function (Output) to force function (Input).

The force and response functions can be measured using accelerometers and force transducers. The collected data are time signals. Since the frequencies are of interest, it is necessary to convert the signals from the time domain into the frequency domain, which is done by performing a Fast Fourier Transformation (FFT).

According to Avitabile (2001), there are two ways in system analysis to find the frequencies and mode shapes of a vibrating system; either to measure at one point and excite at several points or *vice versa*. If only the frequencies are of interest and, if the mode shapes can be predicted, as is the case in a simple structure like a beam with known boundary conditions, it is also possible to determine frequencies by only making one measurement and one excitation at the same point. Accelerometers can be used to measure the response signal. The system can be excited by a hammer equipped with a piezoelectric transducer. These hammers are used for short impulses and come in different sizes and tips, depending on the frequency range that is of interest. The essential parameters are the weight of the hammer and the stiffness of the tips. The heavier the hammer, the lower the excited frequencies and, the stiffer the tip, the higher the excited frequencies. It is important to choose an appropriate hammer and tips so that the energy of the hammer blow excites the desired frequency range and a good response is obtained.

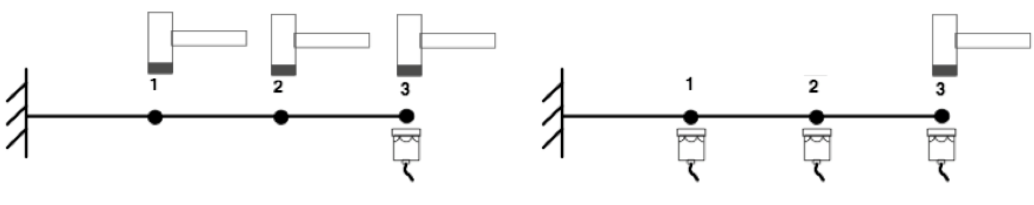

Figure 3.11 Two different approaches to determining resonance frequencies.

The results acquired by accelerometers and force transducers represent timeline data that need to be further processed to obtain the eigen frequencies. The advantage of measuring the input function is that errors originating from noise, for example, can be reduced.

Boundary conditions

Vibration techniques to determine the rotational stiffness of timber joints were made by Crovella and Kyanka (Crovella et al., 2011). When looking at the continuum of joint stiffness, it can be seen that the ratio of joint rotational stiffness and the flexural stiffness of the beam is important. If one of them is considerably higher than the other, a change in joint stiffness has a minimal effect on the frequency (McGuire, 1995).

Parameter estimation

The parameter estimation of the model in Figure 3.10 is based on the Timoshenko beam theory (continuous model). For practical purposes, the translational supports were modelled as rigid, whereas the rotational supports were modelled as springs. In this case, this leads to a system with either two or three unknown parameters, depending on whether it is assumed that the support conditions are or are not identical, see Figure 3.12. This in turn requires that the number of frequencies must correspond to the number of unknown parameters. In general, more frequencies can be used to minimise errors. However, the higher frequency modes might be more likely to contain errors that make the error minimisation unsuitable in particular for inhomogeneous materials such as timber (Laux, 2012). The solution for the unknown parameters was obtained from the intersection of the frequency modes, see Figure 3.12 (c) or (d) respectively.

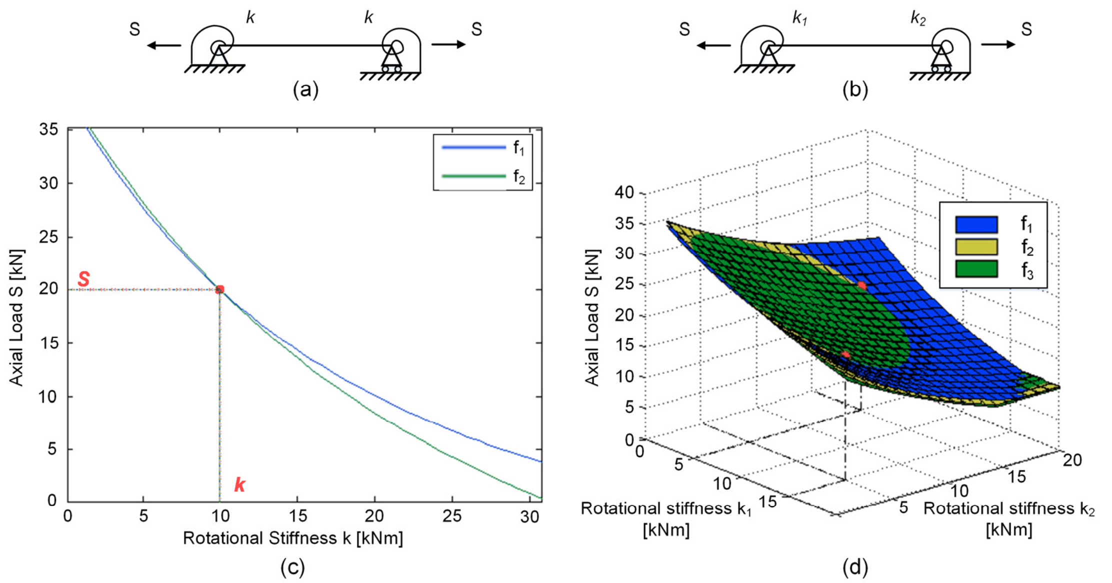

Figure 3.12 Simply supported beam under axial load (a) with spring supports of identical stiffness and (b) with spring supports of different stiffness. Illustration of (c) dual and (d) triple parameter estimation (Laux, 2012).

3.5 Summary

The main content and the use of the NDT methods described in the different studies can be summarised as follows.

- The principal background and image calibration of the density calibration procedure using X-ray that was developed (**Paper I**) is illustrated in Section 3.1.1. The application and use of this method was also investigated throughout the project in the different studies (**Papers III-V**).
- In addition to the determination of density using an X-ray technique, some examples of further applications of digital radiography for the qualitative assessment are described.
- Section 3.2 summarises the background of and an approach to the use of stress-wave transmission timing in the assessment of timber structures that was applied in **Paper V**.
- Section 3.3 gives a short summary of the usefulness of resistance drilling in the qualitative evaluation of the internal condition of structural members to detect and verify degradation, decay and damage and their extent. In **Paper V,** the drilling resistance was used to identify both damage and degradation at locations that were difficult to access with other NDT methods and to determine cross-section reduction due to previous surface degradation.
- In Section 3.4, the theoretical background used in **Paper VI** to predict actual stress levels in structures using a frequency-based method is described in a practical manner.

4 Assessment of *in-situ* density of timber using X-ray equipment

In order to evaluate and analyse historical wooden structures from a structural viewpoint, knowledge of the “real” strength and stiffness of the timber is needed. Assessments based on the visual grading of timber *in situ* often provide underestimated values for mechanical properties. This includes the visual inspection of each member, the identification of the species and the quantitative determination of material properties using very local “non-destructive” testing, such as core or resistance drilling.

As a result, material parameters using non-destructive testing are studied in this paper as the first step in the holistic evaluation process. Wood density has a strong relationship with a number of mechanical properties and can therefore be used in the evaluation of timber structures (Dinwoodie, 2000). Mechanical parameters such as the modulus of elasticity (MOE) have a good correlation with density and bending strength (MOR). Furthermore, local density is the key parameter when it comes to determining the embedment strength of mechanical timber connections (CEN, 2004).

An appropriate, completely non-destructive method for evaluating the *in-situ* density of timber structures is the use of X-ray. The evaluation of structures using X-ray measurements should be accompanied by other non-destructive techniques, such as ultrasonic measurements and stress-wave techniques. A portable X-ray tool is able both to identify damage, defects, cracks and deterioration in members and to produce a better prediction of mean density.

The aim of **Paper I** was to determine the relationship between the measured density of the wooden test specimens and the greyscale obtained from radiographic images, as variations in density appear as differences in grey nuances. Furthermore, the opportunity for generating absolute *in-situ* density values from X-ray images was explored, as well as the influence of thickness and moisture content on X-ray images.

A procedure for determining the *in-situ* density of timber structures of all kinds is therefore proposed, where the local variation in density in timber components can be reflected using photographic imaging.

4.1 Experimental procedure

The *in-situ* calibration procedure was developed and divided into four phases which are described in **Paper I**, Section 3.

1) Relationship between greyscale and density

2) Influence of material thickness on the greyscale of the image

3) Influence of moisture content on the greyscale of the image

4) Calculation of a corrected value for greyscale

In the first phase of this study, a relationship between greyscale [RGB] and density (ρ) was established. To verify density using X-ray equipment, 14 wood specimens with dimensions b x h x t = 64 x 94 x 30 [in mm] were prepared, weighed and X-ray scanned. To predict stiffness and strength properties, a calibration of the wood specimens to air-dried density conditions (MC 12%) was therefore performed. To provide a large variation in density, various wood species with significant differences in density, ranging from about 390 to 800 kg/m^3, were used; see **Paper I**, Table 1.

The second phase of the procedure was the correlation between the pixel intensity and the thickness of the member. This relationship was examined using six built-up plastic blocks with decreasing thickness and with significant differences in density, ranging from 300 to 800 kg/m^3, see **Paper I**, Figure 6. The solid plastic blocks were chosen to avoid the sensitivity of density variations that exist in timber. A correction factor (Δ_{RGB}) for the thickness-calibrated images was established for different density ranges, due to the influence of the attenuation of the intensity of radiation energy through the thickness of the member.

The third phase involved correlating the moisture content in the specimens to the greyscale of the X-ray images. This was achieved by re-using the 14 test specimens and storing them in separate conditioned climate boxes at five different relative humidity (RH) levels. The moisture levels of the specimens were related to the greyscale of the image as a correction factor for the mean greyscale (μ_{mean}) due to the scatter of the greyscale between different moisture levels. The correction factor for moisture ($\Delta\mu_{MC}$) refers to the moisture content defined as air-dried density (MC 12%), i.e. an RH of ~66%.

As a final step, following the procedure above, the corrected mean greyscale value (μ_{mean_corr}) could be calculated according to Eq. (5.1) and inserted in the trend-line equation from the evaluated X-ray image of the calibration wedge. The trend-line coefficient of determination (R^2) should achieve a value of at least 0.90 to obtain very good agreement.

$$\mu_{mean\_corr} = \mu_{mean} + (\Delta\mu_{MC}) + \Delta_{RGB} \qquad \text{Eq. (5.1)}$$

The images were evaluated using digital image processing software and the results were plotted in graphs representing the actual density, moisture content and thickness of the specimens on their axes.

4.2 Results and discussion

In-situ density

X-ray images of the different evaluated image configurations and their associated graphic results are presented in Figure 4.1. The results 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 relationship provided excellent linear correlation that is valid up to a level of 1,000-1,200 kg/m^3. The coefficients of determination (R^2) varied between 0.90-0.98.

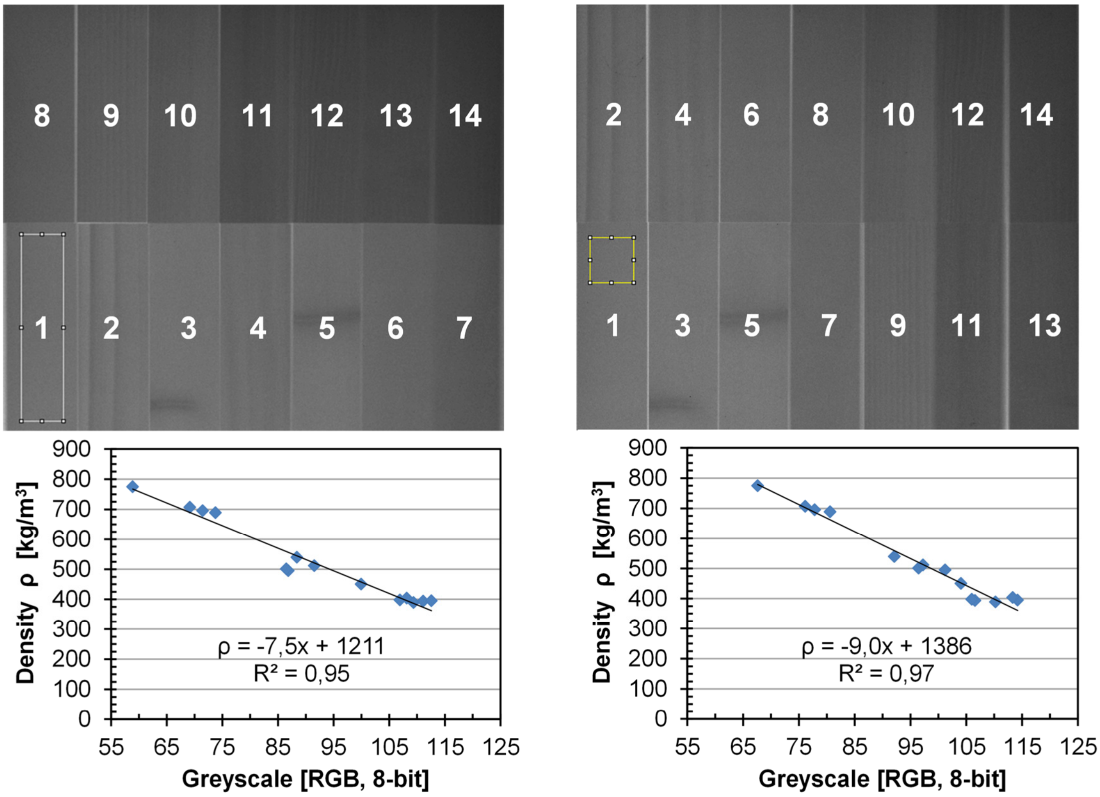

Figure 4.1 *Examples of results from the experimental procedure show the relationship between density and the mean greyscale of the marked area. The numbers in the images represent the types of wood specimen; see* ***Paper I****, Table 1.*

Influence of thickness

The procedure was also calibrated for the thickness variation in the *in-situ* specimen and the distance of the wedge in relation to the image plate. This might be insignificant for small differences in thickness between the calibration specimen and the X-rayed object, but it has a considerable effect on components with large depths. This relationship between greyscale and different thicknesses had to be calibrated for in field investigations.

The correction factor (Δ_{RGB}) for the thickness-calibrated images was defined as the difference between the greyscale of a certain thickness and a reference thickness, which, in this study, was referred to 30 millimetres, i.e. the same thickness as the calibration wedge. The coefficients of determination (R^2) between the greyscale values and the thickness of the built-up specimens were in the range of 0.93 and 0.99, which was regarded as a satisfactory result for the correction due to the influence of thickness, Figure 4.2(a). These correlation curves were used to establish the correction factor (Δ_{RGB}) for different density ranges, see Figure 4.2(b).

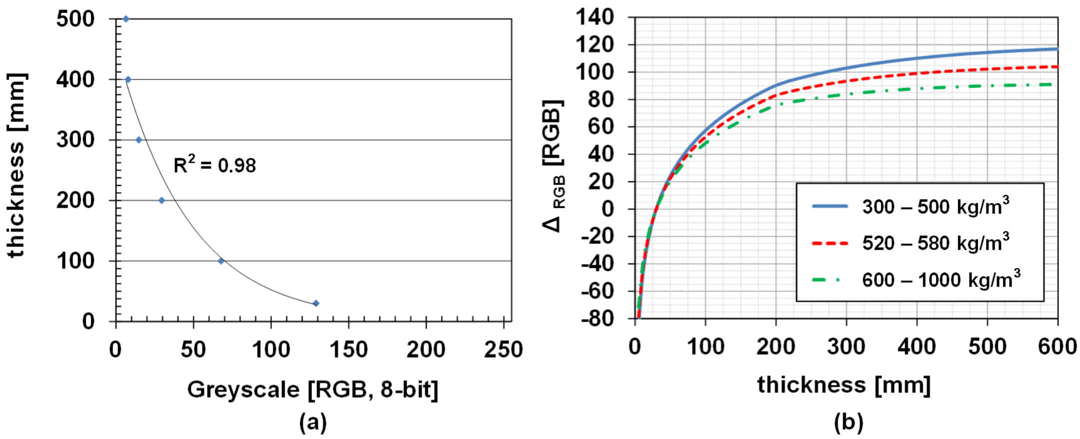

Figure 4.2 (a) Example of result of thickness calibration presented as the coefficient of determination (R^2) and (b) the correction factor (Δ_{RGB}) for different ranges of density referred to a reference thickness of 30 mm.

Effect of moisture content

The influence of the moisture content and the surrounding climate is illustrated in Figure 4.3. A clear tendency could be seen from the analysis between the mean greyscale and different equilibrium conditions of the specimens expressed in relative humidity (RH) within the species.

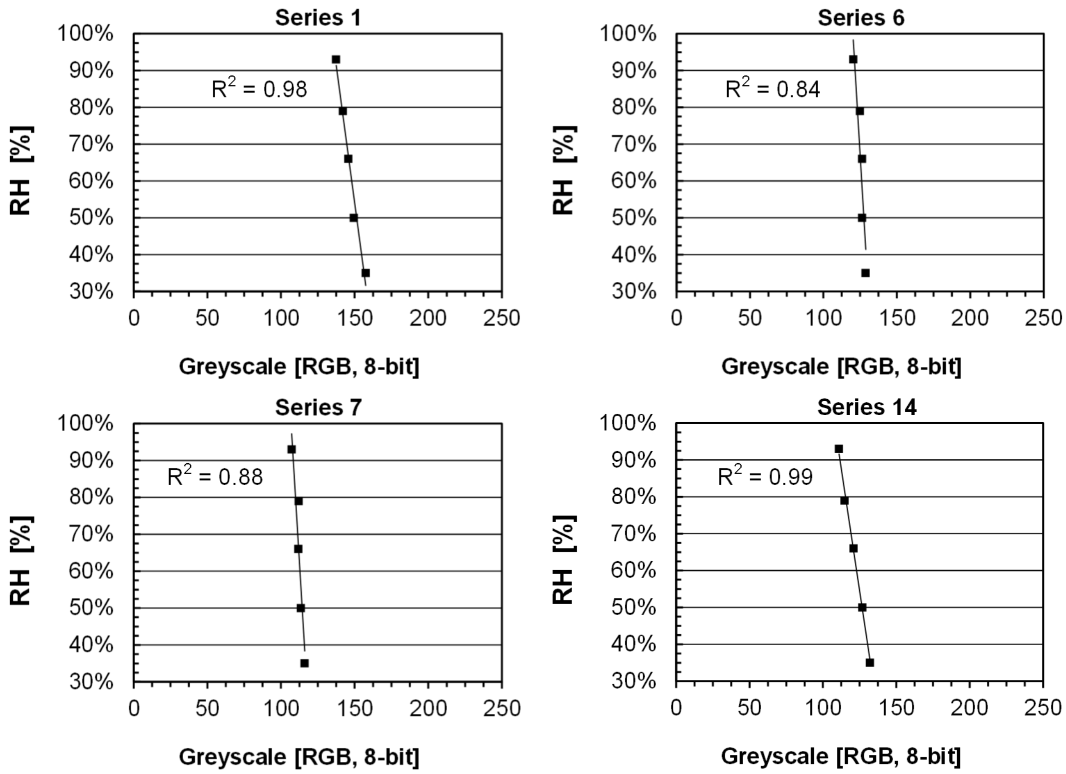

Figure 4.3 Examples of results for the differences in greyscale due to the influence of different moisture conditions.

Even though the influence of moisture on the X-ray images was slight, it could not be ignored, especially when the moisture content was above 16% and/or below 10%. Defining a scatter to determine whether or not to increase/correct the measured mean greyscale value was problematic. The spread between the minimum and maximum values for greyscale ($\Delta\mu_{MC}$) within one species lay between 14 and 35 [RGB]. The calculated mean difference ($\Delta_{mean}\_\mu_{MC}$) was ~20, which related to a reference equilibrium RH condition (~12% MC). This means that, depending on the RH/MC in the X-rayed object, the captured mean greyscale value should be corrected according to Table 4.1.

Table 4.1 Change in $\Delta\mu_{MC}$ [RGB] on the image due to the influence of different moisture conditions in timber.

~MC [%]	6%	8%	10%	12%	14%	16%	20%	22%
~RH_{equ} [%]	35%	43%	50%	66%	79%	85%	90%	93%
$\Delta\mu_{MC}$ [RGB]	7.5-10.5	5.0-7.0	2.5-3.5	0.0	2.5-3.5	5.0-7.0	10.0-14.0	12.5-17.5

The standard deviation of the method could reach a range of ±5 [RGB], which means that, for an MC range of ±4% from the reference value, the influence of moisture can be ignored.

4.3 Summary

The *in-situ* density measurement assessment was applied and verified on two timber specimens of different thickness. An average accuracy of ~97% could be established from this study and this has to be regarded as satisfactory and successful for use in *in-situ* assessments.

Assessment of* in-situ *density in timber using X-ray equipment [Paper I]

Based on the results of the experiments in **Paper I**, the following conclusions were drawn.

- It was possible to obtain very accurate estimates of timber density and a strong correlation between the density of structural timber components and X-rays in combination with digital image processing. The proposed procedure can be used *in situ*.
- The correlation is linear for a range from 250 kg/m^3 to 1,000 kg/m^3. As common wood species for structural use range from 300 kg/m^3 to about 800 kg/m^3, the linear correlation produces a better approximation.
- The thickness of the investigated component is of major importance and needs to be adapted for in the analysis by a correction factor (Δ_{RGB}), whereas the moisture was of minor importance for the range between 8%-16% MC.
- As a general conclusion, digital radioscopy provides good opportunities for the development of a successful future tool for the *in-situ* assessment of timber structures and it is as easy or difficult to use as any other non-destructive method. It also contributes to the detection of failures and deterioration in the material in the early stages, which in turn increases the service life and durability of the structure.
- As commonly stated for timber engineering purposes, the density governs the stiffness and to some extent also the strength properties. The procedure can therefore be used in the analysis of structural behaviour. The density properties of timber components are also relevant for the examination and evaluation of mechanical connections.

5 Assessment and evaluation of the material stiffness of the oak from the *Vasa* warship

This chapter spotlights and summarises the aspects and difficulties involved in the *in-situ* evaluation of the material stiffness (MOE) of the *Vasa* warship for future structural assessment and the development of a methodology which enables the rapid assessment and prediction of the stiffness in terms of MOE in the three principal directions of wood (**Papers II-IV**).

The *Vasa* warship is one of the most important national treasures of Sweden. After being launched in Stockholm Harbour in 1628, the warship experienced difficulties in stability and manoeuvrability and sank on her maiden voyage. In 1956, the jewel of the Swedish navy was located on the seabed, before being raised in 1961. It was at that point that the resurrection of the warship began. Since 1990, the ship has been on display to the public at the *Vasa* Museum.

In order to maintain the integrity of the ship after salvage, conservation treatment with polyethylene glycol (PEG) was carried out for a period of 17 years (Håfors, 1989, Håfors, 2010). The treatment prevented the *Vasa* warship from serious shrinkage and distortion that would otherwise have caused the collapse of the cell walls when the wood dried. However, a certain level of physical and chemical modification and degradation occurred (Capretti et al., 2008, Bjurhager, 2011).

These degradation processes have had a diminishing effect on the strength and stiffness of the warship structure, such as reducing bearing capacity, loss of cross-sectional area and global deformations, which has been reported by different authors (Mühlethaler, 1973, Schniewind, 1990, Ljungdahl et al., 2006, Bjurhager et al., 2010). This loss of wood substance causes higher porosity and permeability, which results in lower density and makes the wood bulk water (Hedges, 1990). A decrease in strength of at least 40% must therefore be expected (Mühlethaler, 1973, Schniewind, 1990, Ljungdahl, 2007). The strength and stiffness loss in archaeological wood is generally not directly proportional to the loss of mass and also depends in many cases on the degradation and quality of the remaining substance in the wood (Mühlethaler, 1973). In spite of this, the MOE in the longitudinal direction was only affected by a loss of 20% for high PEG content (Stamm, 1959).

Structural investigations of the warship were not initiated until the beginning of the 21st century, when data on on-going deformation were collected. At about the same time, an investigation of different reinforcement concepts for the ship and/or its support cradle was undertaken and different simple finite element (FE) models were also constructed for single cross-sections of the hull to predict future deformation and structural behaviour for different support scenarios (Sörenson, 1999, Ljungdahl, 2004). No final decisions have as yet been made about how to support the hull and prevent further movement and deformation. However, research has focused increasingly on the mechanical properties of *Vasa* oak and the way they are influenced by chemical degradation and PEG content, in particular the compression strength in the radial direction and the tensile strength and the stiffness of PEG-impregnated oak samples in the longitudinal direction (Ljungdahl et al., 2006, Bjurhager et al., 2010).

In 2013, a new support structure project was initiated with the aim of modelling the structural behaviour of the entire ship. For this reason, a holistic approach is recommended and parameters such as geometry, joints, load transfer within the warship and load transfer from the warship to the existing support cradle have to be thoroughly explored (**Paper II**). Material parameters such as MOE and strength need to be investigated in more detail than before, which is a difficult task in itself. Due to both natural variation in the *Vasa* oak and chemical degradation and softening due to PEG content in the *Vasa* timbers, the MOE and strength properties are expected to vary considerably at different positions. It is therefore desirable to develop a methodology (**Papers II-IV**) which enables the quick and easy measurement of geometry, damage and predictions of the stiffness of the structure. Due to the unique nature of the material, the measurements should preferably be as non-invasive and non-destructive as possible. The prediction of the mechanical properties of waterlogged wood and the influence of conservation treatment lead to larger expected variations and greater uncertainty in the evaluation process.

For more detailed information on the problem areas of a general nature for the *Vasa* warship, see **Paper II**.

5.1 Scope and methodology of the study

The overall aim of this study was to develop an on-site assessment strategy to predict the mechanical properties of the *Vasa* oak material at structural level (**Papers III & IV**) and to propose a strategy for developing a new support system that distributes the loads from the hull structure to the cradle (**Paper II**) and serves as a foundation for future decision-making. In a support system of this kind, the distribution of the acting loads should be easy to monitor and the movement and deformation should be prevented.

So, in order to create an even more accurate model for the more precise prediction of the deformation over time, the material characteristics should be investigated globally on site using non-destructive testing, i.e. in a large number of positions, on the warship. In order to achieve this, essential material parameters, such as radial, tangential and longitudinal MOE, can be estimated on the basis of *Vasa* oak density. Generally, the mechanical performance of timber is strongly related to density (Kollmann et al., 1968, Dinwoodie, 2000).

In the case of the *Vasa*, however, this is complicated by the impregnation agent, PEG. PEG is known to increase the density, while at the same time also reducing the mechanical properties, in particular stiffness and strength properties.

Establishing a relationship between mechanical properties and density in the *Vasa* wood is, as mentioned previously, difficult due to the fact that the PEG treatment has increased the density but at the same time reduced the strength and stiffness properties by up to 50% (Mühlethaler, 1973). It might, however, be possible to overcome this problem. The following general approach to linking density data to the mechanical properties of PEG-impregnated *Vasa* oak was suggested.

(1) Mechanical testing of clear-wood specimens from *Vasa* oak in all three fibre directions (R, T, L) for the determination of MOE, which was of primary interest as an input parameter in an FE model. Determination of specimen density using both X-ray measurements and weight-volume measurements to validate the X-ray method (**Paper I**) as an accurate way of determining density. Determining the PEG content with commonly used extraction methods, such as Soxhlet extraction.

(2) Establishing relationships, first between density and PEG content and then between PEG content and MOE, to link the density and the stiffness in terms of MOE in the PEG-impregnated *Vasa* oak, assuming the homogeneous distribution of PEG content in the clear-wood specimens. At that point, data from both previous studies and the present study were used in order to increase the amount of data for analysis.
(3) Non-destructive density measurements with the X-ray technique only on structural elements in the *Vasa* warship for the prediction and verification of the mechanical properties from the relationships established in Step 2. The PEG content, however, varies in depth (Björdal et al., 1999, Bjurhager et al., 2010). As it was impossible to monitor the depth of the PEG visually or by X-ray, a general PEG profile, based on previous measurements from different locations on the *Vasa* warship and at different depths, served as a further link to estimate the MOE and, as a consequence, the stiffness of structural elements.

For detailed information regarding the methodology used to assess the density and MOE of the *Vasa* oak and the experimental testing procedure, see **Papers III & IV**.

5.2 Evaluation of the relationship between density and MOE

The main results from **Paper III & Paper IV** are summarised in the following section.

Results of the density determination using X-ray

The density of small specimens of both *Vasa* oak and reference oak (*European oak, Quercus robur*) was measured from conventional volume-weight measurements along with X-ray measurements. Satisfactory agreement between the conventional density measurements and the X-rayed density was achieved for both the clear-wood specimens (**Paper III**) and the elements at structural level (**Paper IV**). Most importantly for the structural elements, the X-ray results showed good agreement with the mean density obtained from the adopted PEG profile (**Paper IV**, Figure 3), in combination with the density-to-PEG-content relationship already established for small samples (**Paper III**). The density of *Vasa* oak in this study, but also in general, ranges from 800 kg/m^3 to 1,000 kg/m^3. For the reference specimens, the ratio between the X-rayed density and the conventionally measured density was 1.03 (0.02), while, for the *Vasa* samples, the corresponding value was slightly higher, 1.04 (0.04), (standard deviation in parentheses). Similar results were obtained from the on-site measurements of full-scale elements. The X-ray technique produced a slight overestimation for both the *Vasa* oak and the reference specimens and this was also confirmed for the structural elements on the *Vasa* warship. The overestimation might be due to some uncertainty related to the sensitivity of the X-ray equipment. However, as the overestimation is small and within the uncertainty range of the method, the X-ray technique is considered to be well suited to the non-destructive estimation of density in both (PEG-treated) archaeological and recent wood (**Paper I**).

When it comes to the influence of PEG concentrations on density properties, a study from 2010 of the PEG-content-to-density relationship in recent European oak showed that there is a strong linear relationship (R^2=0.84), obtained from a least-squares-method fitting, between increases in density and increases in PEG content (Bjurhager et al., 2010). A linear relationship (R^2=0.63), obtained from the same curve-fitting technique, was therefore chosen for the adaptation of a curve by arranging the results from previous studies (Ljungdahl, 2007, Ljungdahl et al., 2007, Bjurhager et al., 2008), together with data from this study, see **Paper III**, Figure 2 and Eq. 1. This relationship was regarded as satisfactory and was used to obtain the average density of structural elements from the adopted PEG profile. The reliability of the fitted function could be evaluated by comparing the estimated PEG content (38.2%; by fitting) and the actual PEG content (34.2%; from NMR experiments), cf. **Paper III**, Table 2.

Results for stiffness parameters

Density is commonly used as an indicator of the expected mechanical performance of wood (Kollmann et al., 1968, Dinwoodie, 2000). The reduced stiffness in the *Vasa* oak probably has an important influence on the time-dependent deformation of the ship's structure. The *Vasa* samples (**Paper III**), with a relatively high average density of 916 (39) kg/m^3 (**Paper III**, Figure 2), showed reduced MOE in all three directions. It is therefore preferable to estimate the MOE of different members of the ship using a non-invasive X-ray method, together with data from previous destructive measurements.

An MOE-to-PEG-content relationship was established in order to estimate the MOE and to test the applicability of testing the MOE non-destructively using an X-ray calibration technique (**Paper III**). The relationship between MOE and PEG content is expected to be non-linear (Mühlethaler, 1973, Ljungdahl, 2007), except for the MOE-to-PEG content in the longitudinal direction, where the relationship is expected to be linear (Stamm, 1959, Bjurhager et al., 2010). In order to relate the PEG content to the MOE in the radial (R) and tangential (T) directions, a logarithmic function was chosen for adaptation to the data and a linear function was adapted for the relationship in the longitudinal (L) direction.

The difference in MOE between the *Vasa* specimens and the reference specimens from the compression tests was highly significant in all three directions. In the R direction, the average MOE for the tested *Vasa* samples was 54% compared with the references, whereas the corresponding value in the T and L directions was 58% and 78% respectively. The MOE and therefore also the stiffness of *Vasa* oak is therefore significantly reduced in all three directions compared with recent European oak (**Paper III**). The reduction was also more marked in the R and T directions compared with the L direction.

The average MOE reduction in the structural components is, however, much less due to the exponential distribution of the PEG content from the surface, which results in a considerably lower average PEG content compared with the homogeneous distribution in clear-wood samples. The corresponding reduction of the average MOE in the structural components compared to PEG-free specimens is 32% (1334 MPa) in the R direction, 31% (672 MPa) in the T direction and less than 10% (10371 MPa) in the L direction (**Paper IV**).

The fitted data (**Paper III**, Figure 3) according to the least-squares method of the radial MOE for the *Vasa* oak with a coefficient of determination (R^2) of 0.49 shows that the stiffness is highly affected, even at a low PEG content, while the effect declines at a high PEG content. The radial MOE has been found to be reduced by 50%, with an increase in PEG from 0% to only 10% (Ljungdahl, 2007, Bjurhager, 2011). These previous results agree well with the findings in this study, see **Paper III**.

In all the principal directions (R, T, L), a tendency towards a decreasing MOE with increasing density was seen. These results illustrate that there is a clear diminishing effect on the stiffness. In the longitudinal direction, the approximate loss of stiffness might be expected to be about 20% for high PEG contents (>30%), whereas the stiffness loss in the tangential and the radial directions showed larger variations and might reveal losses from 30% to about 55%, even for low PEG content (<10%). The PEG content had a great influence on the density properties that were measured, as PEG might be bulked in the areas of decomposed wood substance. For this reason, knowledge of the PEG content is of great importance in the future evaluation of the stiffness and strength properties of the *Vasa* oak. The *Vasa* samples display fairly large scatter in stiffness in terms of MOE, which can be ascribed to variations in other parameters apart from PEG content (e.g. bacterial and/or chemical degradation).

A comparison between the estimated and measured MOE of the clear-wood samples in **Paper III** showed fairly good agreement with one another. The MOE in both the radial and tangential directions was slightly underestimated using this method. The average MOE in the radial direction was underestimated by 3% and in the tangential direction by 14%, whereas a slight overestimation of the MOE in the longitudinal direction of 6.8% was found. In this context, it must be remembered that the shape of the curve for the PEG-content-to-MOE relationship in the tangential direction was simply assumed to be identical (apart from a shift of 50% in magnitude) to that in the radial direction, due to the limited number of data points. Moreover, as for the tangential direction, the data describing the PEG-content-to-MOE relationship in the longitudinal direction were extremely limited. Further mechanical tests therefore need to be carried out in both the longitudinal and tangential directions in order to refine the functions for MOE prediction in these directions.

In **Paper IV**, the MOE in the principal directions was estimated from X-ray measurements in combination with the density-to-PEG-content and PEG-content-to-MOE relationships previously established in **Paper III**. To compare the estimated MOE from the X-ray measurements, the MOE was determined from the adopted PEG-content-to-thickness profile in combination with the PEG-content-to-MOE relationships. In general, the MOE results from the two methods showed relatively good agreement with one another (cf. **Paper IV**, Table 2). As the relationships used for stiffness estimation in terms of MOE were initially based on actual mechanical tests on (small) *Vasa* oak samples, it is also likely that the X-ray investigation procedure is able to produce reliable estimates of the structural performance of the individual elements. This kind of data can in turn then serve as valuable input data for the computer modelling of the ship.

To summarise, the differences between the predicted values and the MOE values determined by mechanical tests on small-scale specimens or by an adopted PEG profile for the structural components of the *Vasa* warship did not show any statistical significance.

5.3 Summary and key findings

The main findings and conclusions from the evaluation and applicability of the proposed methodology in **Papers II-IV** are summarised in this section.

- The mechanical complexity of the *Vasa* warship in general can be partly attributed to large variations in the oak in the ship in terms of the natural variability of the wood, biological degradation localised at the surface, chemical treatment and the disintegration of the cell-wall structure originating from centuries of waterlogged conditions. This might cause difficulty in the assessment and evaluation of the mechanical and physical properties at structural level. A well-defined investigation procedure must therefore be applied in the evaluation of the mechanical properties.
- X-ray investigations are of great importance in the evaluation of the mechanical and physical properties of the *Vasa* warship, as the great advantage of X-rays over other methods is the non-destructive nature of this technique, which enables a virtually unlimited number of measurements without any material destruction. It was possible to obtain accurate estimates of density and a strong correlation with the density of both structural components of *Vasa* oak up to about 400 mm in thickness/depth and small-scale specimens using X-rays in combination with digital image processing. Based on the results, it is likely that the average density of large elements in the ship was also accurately estimated by X-ray (although this could not be verified by conventional density measurements). The method appears to lead to only a slight overestimation of density within the uncertainty of the method.
- The increase in density comes from the chemical treatment for stabilising the ship's structure. Due to the PEG concentrations, the stiffness in terms of MOE in all principal directions is substantially reduced, but principally in the radial and tangential directions. In general, the stiffness results show relatively good agreement with one another. As the relationships used for MOE estimation are initially based on actual mechanical tests on (small) *Vasa* oak samples, it is also likely that the X-ray investigation procedure will produce reliable estimates of the structural performance of the individual elements. This kind of data, in turn, can then serve as valuable input data for the computer modelling of the ship.
- Based on this methodology, it was possible to estimate MOE in the R, T and L directions. Good agreement was also found for the estimated stiffness in terms of MOE in all three directions, compared with the measured ones. However, sufficient data need to be obtained for the tangential and longitudinal directions in order to produce a more reliable estimate of the MOE profile based on X-ray density measurements, as the MOE relationships are based on the mechanical testing of small-scale elements.
- Finally, the procedure presented in this study can also be applied to other PEG-impregnated oak objects around the world with biological/chemical degradation similar to that of the *Vasa* ship.

6 Non-destructive evaluation of the timber floor structure in the *Skansen Lejonet* fortification

This chapter gives a general summary of the *in-situ* evaluation of material properties and the structural analysis of the floor structure in the *Skansen Lejonet* fortification. The assessment methodology and the experimental approach for the assessment of the material properties have previously been mentioned and described in Section 2 and Section 3 and can also be found in **Paper V**.

Skansen Lejonet was built in the late 17th century by Erik Dahlbergh, a soldier and architect, and is one of the few remaining traces of the original defence structures with walls up to 4 m thick that made Gothenburg one of the most heavily fortified cities in Sweden at that time. The core of the structure is divided into two major vertical cells by a circumferential masonry arch and an upper cell divided by timber floors for the artillery. Although *Skansen Lejonet* has never been attacked, it has been exposed to environmental impact over the centuries. During the 19th century, the fortification served as a storage facility for an ammunition factory and infantry. During the first part of the 20th century, there were some requests to repair and refurbish the roof structure and windows, but no attention was paid to the timber structures. Nowadays, the building as a whole and the investigated floor structures in particular serve as a location for weddings and dinners for up to 130 people, referred to as ceremonial events (second load case).

6.1 Scope of the study

The structural investigation procedure used in this study is based on adapting a general assessment methodology to evaluate the structural condition and the mechanical performance of the floor structures in *Skansen Lejonet* in an efficient manner. The methodology has already been mentioned and described in Section 2 and **Paper V**.

The aim of the study was firstly to examine the structural health of timber floor structures and their performance by using various NDT and quasi-NDT methods and by evaluating strength and stiffness in the floor structures in the fortification known as *Skansen Lejonet* in Gothenburg, western Sweden.

The second aim was to evaluate whether the floor structures fulfil the structural requirements for two load-case scenarios according to Eurocode standards; the original intended load scenario, using the floor structure as armament with cannons and the infantry of the 17th century, and the present use, where the structural use was regarded as an imposed load (location for ceremonial events), according to the EN 1991-1-1 European Standard (CEN, 2002).

6.2 Evaluation of the structural element properties

The properties that were tested were the density (ρ), the modulus of elasticity (MOE) and the cross-sectional properties, as well as the strength properties according to the literature. The test methods to assign and quantify the parameters were stress-wave timing (microsecond timer), X-ray equipment and resistance drilling. A detailed investigation of the properties was carried out after the preliminary investigation, where the geometry and load path of the floor structures were thoroughly studied to create the most accurate model possible.

The stress-wave-based assessment of the structure is a simple and efficient measurement technique to identify the internal soundness and condition of structural elements but also to determine stiffness parameters in terms of MOE for structural analysis. The structural performance of the *in-situ* elements and the internal damage were successfully determined using an appropriate measurement strategy. The quantitative results were subsequently used to assign stiffness and strength properties for the structural evaluation (**Paper V**).

The main use of the X-ray equipment was firstly to investigate the quantitative (density) parameters using a calibration procedure described in **Paper I** and, secondly, as a complement, to inspect qualitative parameters such as the interior condition of critical and/or deteriorated sections and accessible structural details. The results are, however, only based on a total of nine measurements, justified by and based on the structural soundness of the beams that was investigated at an earlier stage using stress-wave timing.

The drilling resistance measurements served mainly as a complement in the qualitative investigation, where stress-wave timing and X-raying lacked access, especially in the support regions. Furthermore, this technique was used in the detailed investigation as part of the determination of an effective cross-section. A total of 51 resistance-drilling measurements in selected locations on the timber members in both floors were made to identify reduction in the cross-section. The reduced cross-sectional properties affected the second moment of area by 12% to 20%, compared with the global measured cross-sectional properties.

The floor structure was generally in very good condition at the inspected critical sections, as were the joints, although in some positions deterioration and surface deterioration could be detected using the assessment techniques. These signs of degradation were taken into account in the structural evaluation (**Paper V**).

6.3 Structural analysis

The timber floor structures were modelled in the RSTAB® 5.16 frame analysis software and the elements were modelled as beam elements. The structural elements were modelled as simply supported beams and, in the regions of the columns, the affected beams are mainly continuous beams. The decision to model the supports as simply supported was made as it could be seen that the beams were mainly free to rotate at their ends, even though they might be partly fixed at some points due to their support length into the wall. The mechanical and material properties were assigned from the *in-situ* measurements of the individual elements. Nine different models were created to compare the effect of different input parameters with respect to the measured and reduced cross-sectional properties, the measured and generalised density properties and the individual inserted MOE properties from both the literature and the measured properties. Two load-case scenarios were taken into account and the requirements according to existing design standards were fulfilled for both load-case scenarios. The redundancy of the structures also allows for the failure of some primary members, before the estimated capacities at some points were exceeded.

6.4 Summary and key findings

- Preparing a systematic approach to and documentation of the in-situ inspection and testing is crucial for an accurate, efficient assessment process.
- The extent and sequence of measurements should be adjusted to match the structural condition and existing information relating to the structure. It is therefore preferable initially to identify members requiring further investigation using global measurements, before applying methods such as resistance drilling and X-ray that require more effort and time.
- The quantitative evaluation of the mechanical properties and the density using stress-wave timing and radiographic measurements provided both good agreement and reasonable input for the structural analysis.
- Reliable results can be obtained, thereby increasing the ability to minimise interventions and prolong the service life as a part of sustainable development.
- The effect of local interior deterioration, which was only found in a few structural elements close to support regions, was not taken into account, but it should be remedied.
- In the event of severe damage to large parts of the members, the members would have been disregarded in the structural analysis and it was also shown to be possible that, due to the redundancy in the design of the floor structure, the removal of some structural members would still produce sufficient capacity.
- This study shows that the current structural capacity fulfils the requirements for the load combination according to EN 1991-1-1. Since none of the models produces excessive design stresses, a detailed analysis taking local defects into consideration was not deemed necessary.

7 Assessment of stresses in loaded structures using resonance frequency analysis

The structural integrity due to problems in the uncertainties relating to load and the load-bearing capacity of timber structures is highly important, since peaks caused by increased loads might occur. One solution to these problems lies in the evaluation of timber structures using non-destructive testing (NDT) methods and, in this specific case, a frequency-based identification method (**Paper VI**). This method allows an estimation of actual stress levels at any time and without the need for a reference state, thereby enabling a realistic assessment of the structural behaviour and the detection of the most loaded and vulnerable members.

The tension machine used in this research is similar to the vertical one used in (Livingston et al., 1995). Equal boundary conditions were assumed. The static system is consequently a simply supported beam with identical rotational springs at both ends. This leads to two unknown parameters, namely the axial force, S, and the rotational stiffness, k, see Figure 7.1. This means that at least two bending frequencies are needed to determine the parameters. It is necessary to keep the number of unknown parameters to a minimum in order to ensure that not too much accuracy is lost, even if it would be theoretically possible to include more parameters, such as material properties.

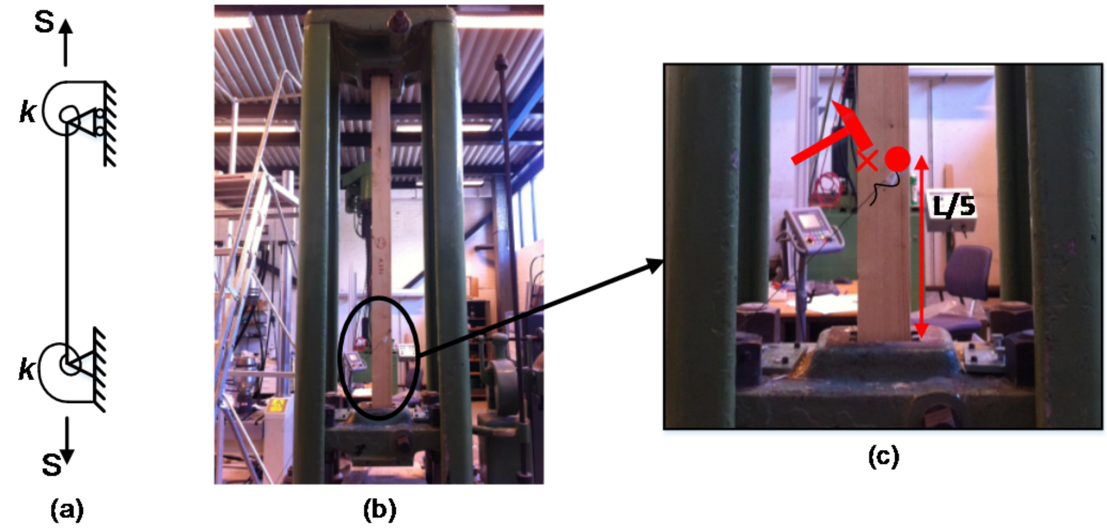

Figure 7.1 (a) Simply-supported beam under axial load with rotational spring stiffness, (b) tensile testing machine and (c) positions for the accelerometer and excitation are illustrated (Livingston et al., 1995).

7.1 Experimental procedure

The test set-up for the non-destructive determination of the axial forces on the specimen was based on the literature study of frequency analysis. Transverse vibration tests to determine the E- and G-moduli were performed on small-scale specimens of Norway spruce (*Picea abies*). A total of 32 timber specimens, with the following final measurements of the samples: L×H×B = 1500×75×35 mm^3, were used in this study. The same tests were carried out on an aluminium bar serving as a reference specimen with L×H×B = 1,500×50×10 mm^3.

Finally, transverse frequency measurements were made on the specimen under different load levels, ranging from 2 MPa to 11 MPa for timber specimens and 4 MPa to 32 MPa for the aluminium reference bar. The collected data were then evaluated using Timoshenko's beam theory to estimate boundary conditions and axial load.

For the actual tests, the use of a single accelerometer appeared to be appropriate, as the vibration modes are well known for the given system. The accelerometers were prevented from being placed at modal nodes to enable the desired frequencies to be recorded. A distance of 20% of the length was chosen as the most appropriate position to enable measurements up to the first five frequencies. The beams were excited on the weak axis, since the lower moment of inertia causes a higher variation in frequency for a change in axial force. As the results appear to be sensitive to the stress level, the specimen was tested for a wide range of axial loads.

7.2 Results

Figure 7.2 shows an example of the FRF plots for the aluminium bar and one timber specimen for different load levels. It can be seen that the geometry of the aluminium bar was chosen in such a way that the frequency increase to a higher load is of a comparable magnitude to that of a timber specimen. This is important for the comparison of parameter estimation results, as the sensitivity study showed that the axial load is highly sensitive to errors in frequency. It can be seen that the peaks are much clearer for the aluminium specimen than for the timber specimen, which is mainly due to the differences in material homogeneity.

Table 7.1 lists the first three bending frequencies of the above specimen for the different load levels.

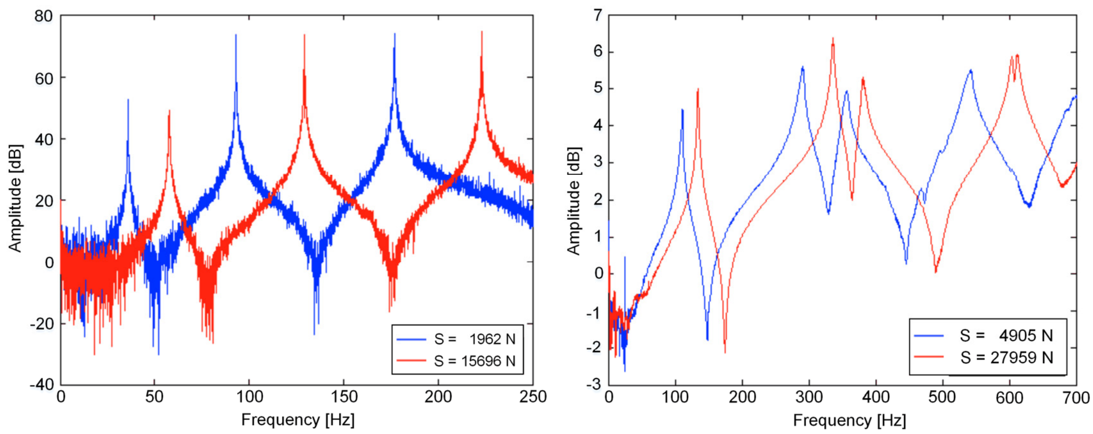

Figure 7.2 Comparison of frequency plots for aluminium (left) and timber (right).

Table 7.1 Comparison of measured frequencies for aluminium (left) and timber (right).

Applied load S [N]	f_{1b} [Hz]	f_{2b} [Hz]	f_{3b} [Hz]
1960	36.0	93.1	177.0
4020	40.0	98.9	184.0
6670	44.5	106.6	193.9
7750	46.4	109.6	197.6
9810	49.5	114.9	204.4
11580	52.2	119.6	210.0
13540	55.0	124.3	216.6
15700	57.8	129.4	223.3

Applied load S [N]	f_{1b} [Hz]	f_{2b} [Hz]	f_{3b} [Hz]
4900	111.3	291.3	542.3
9220	118.2	307.8	569.1
13930	123.6	319.0	584.7
19030	128.1	327.1	596.2
23640	131.6	331.9	600.8
27960	134.2	336.6	604.2

Figure 7.3 shows plots of the squares of the first three measured frequencies, f_i^2, against the applied load, S, under the assumption of equal boundary conditions, k, at both ends of the beams. Since different friction grips were used for timber and aluminium, the respective restraint lengths are also different, namely 1,260 mm and 1,245 mm respectively. For the aluminium bar, the measured frequencies, f_i, are all more or less arranged in a line, which shows that the boundary conditions remain almost constant for different load levels. The assumption of equal restraints at both ends is valid for the aluminium bar, as the friction grips are identical and the aluminium is homogeneous. For the timber specimen, only the frequencies of the three highest loads are situated in a line. The main reason for this is that the clear length, L, changes over different load levels. This can be taken into account by setting different lengths for the lower load levels. Already during data acquisition, it became clear that the peak of the third frequency was not clear enough to fulfil the precision requirements, at least not for the applied measurement method. The higher the frequency modes, the lower are their accuracies and thereby their use for parameter estimation.

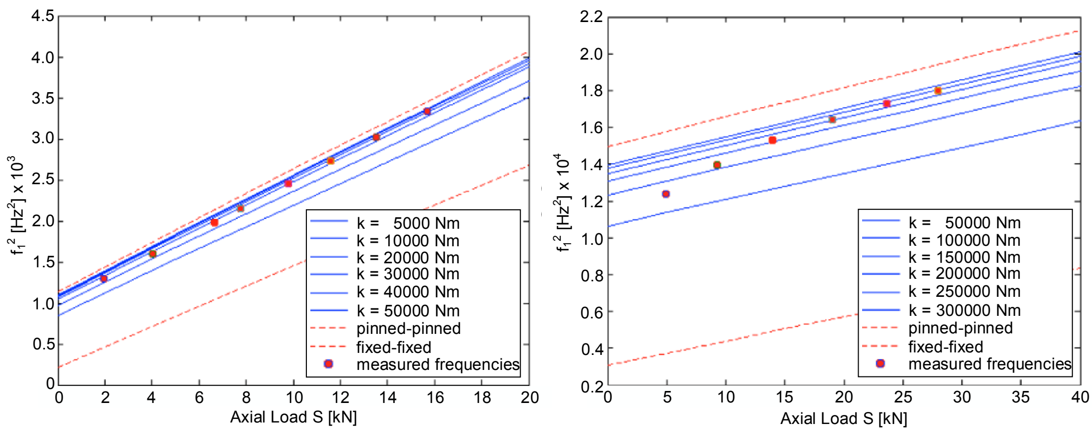

Figure 7.3 Plots of axial load against the square of the calculated first frequency for different boundary conditions together with measured first frequencies for different load levels for aluminium (left) and timber (right).

7.3 Summary and discussion

In what follows, the bending frequencies resulting from the data processing are used to estimate the axial load, *S,* and the boundary conditions at the restraints. In the first step, this was done using only the first two frequencies under the assumption of equal boundary conditions. In the second step, an attempt is also made to use the third frequency either for error minimisation or to expand the model by a third parameter by dropping the assumption of equal boundary conditions. Since the stiffness of the timber specimen is much smaller compared with the steel grips, the rotational stiffness at the supports is mainly influenced by the E-modulus of the specimen. For the inhomogeneous timber, the E-modulus is, however, not constant over the whole specimen length and this can consequently lead to a difference in boundary conditions.

After all the input parameters had been determined, the parameter estimation could be initiated. The use of two frequencies produced reasonable results for the axial load, S, for both materials. The parameter estimation was limited to the first two frequencies, which makes the assumption of equal boundary conditions indispensable and therefore excludes the expansion of the model to a third parameter.

The results in Table 7.2 show that the estimation of the axial load, *S,* improves for higher load levels. Again, the best results could be obtained using the transverse E-modulus. It can be seen that the differences for the two E-moduli decrease for higher loads. The axial loads are generally overestimated, with mean errors ranging from 7.6% to 46.6%. The standard deviations are of the same order, which results in a very large spread for the results. The main reason is probably the clear length, *L,* which was chosen to be the same for every specimen, even though there might be differences caused by varying material properties. This parameter was the most difficult to assess, as the restraint length cannot be visually determined but has a large influence on the results.

Table 7.2 Mean errors of the estimated axial load, S_{est}, for all the timber specimens using the transverse E-moduli.

Applied load S [N]	% of yield [%]	S/S_E [-]	Mean error on S [%]	Std. dev. on error [%]
4900	**7.4**	**0.25**	**46.6**	**89.5**
9220	**14.7**	**0.48**	**34.3**	**45.0**
13930	**22.1**	**0.70**	**27.8**	**39.9**
19030	**29.4**	**0.94**	**16.2**	**26.9**
23640	**36.8**	**1.17**	**9.4**	**23.7**
27960	**44.1**	**1.40**	**7.6**	**20.2**

Considering model uncertainties, such as equal boundary conditions and constant properties over the length of the specimen, the estimated axial loads appear to be fairly reasonable and provide an incentive for further research.

8 Conclusions and suggestions for future research

The main research objectives for this entire project were to improve advanced assessment methods and verify the efficiency of guidelines and recommendations on how to perform assessments of existing timber structures with reference to their condition and structural capability. The thesis was divided into two main parts, where four main aspects were analysed. The first part contained a development of a calibration procedure for the *in-situ* assessment of density properties, as well as an investigation of the opportunities to use X-ray equipment in the evaluation of the performance and condition of timber structures, which was applied throughout the project in the different applications. The second part of this work comprised a final verification and evaluation of the proposed procedure through two case studies. Furthermore, the assessment strategy, the use of NDT methods and the difficulties involved in the evaluation process were studied.

The outcome of and general conclusions from the four main aspects of the project, described in the introduction, are summarised in this section. Future research on these aspects is also suggested. For the detailed discussions and conclusions, see **Papers I-VI** and the summary section of the chapters in this thesis. The following general conclusions (including some suggestions for future work) could be drawn.

I Determination of density of wood with portable X-ray (Paper I)

- It was possible to obtain accurate and reliable estimates of timber density and demonstrate a strong correlation between the density of structural timber components and X-rays, in combination with digital image processing.
- The proposed procedure can be used *in situ,* as shown in the case studies.
- One clear disadvantage of the method is, however, that the density data produced by the image represent the average density of the member through the thickness, which makes the evaluation of radiographic elements more difficult.
- Digital radioscopy provides good opportunities for the development of a successful future tool for the *in-situ* assessment of timber structures and it is as easy to use as any other non-destructive method.
- X-ray investigations also contribute to the detection of failures and deterioration in the material in the early stages, which in turn increases the service life and durability of the structure.
- Further development of the density calibration procedure is, however, needed to apply the procedure to composite materials or wall elements with several different layers.

II Property assessment of oak from the Vasa warship (Papers III & IV)

- The mechanical complexity of the *Vasa* warship causes difficulty in the assessment and evaluation of the mechanical and physical properties at structural level, due to chemical treatment and the disintegration of the cell-wall structure originating from centuries of waterlogged conditions.
- Due to its non-destructive nature, the developed and well-defined X-ray investigation procedure for evaluating the mechanical and physical properties of the *Vasa* warship enabled a virtually unlimited number of measurements without any material destruction.

- It was possible to obtain good estimates of density from X-ray density measurements and a strong correlation with the density of both structural components made of *Vasa* oak and small-scale specimens. Based on the results, it is likely that the average density of large elements in the ship was also well estimated by X-ray (although this could not be verified by conventional density measurements).
- The stiffness in terms of MOE in all the principal directions decreased to a large extent due to the PEG concentrations.
- Based on this methodology, good agreement was obtained for the estimated stiffness in terms of MOE in all three directions, compared with the measured ones.
- The procedure presented in this study can also be applied to other PEG-impregnated oak objects with biological/chemical degradation similar to that of the *Vasa* warship. However, sufficient data need to be obtained for the tangential and longitudinal directions in order to produce a more reliable estimation of the MOE profile based on X-ray density measurements.
- This kind of data can in turn serve as valuable input data for the computer modelling of the ship, as a complete three-dimensional model of the warship would be of great help when it comes to creating a new support system using advanced technology in order to protect the *Vasa* warship in the future and prevent further deformation in the ship structure.

III In-situ assessment of historical timber structures (Papers II & V)

- The framework of the existing standards and procedures itself is an efficient tool for the evaluation and investigation of structures and does not necessarily need improvement.
- Preparing a systematic approach to and documentation of *in-situ* inspection and testing is crucial for an accurate, effective assessment process. So, studies taking a holistic approach into account should be further focused on.
- Each structure has its individual and unique characteristics and needs to be judged and investigated separately, adapting the assessment strategy to all the existing information that is documented.
- The guidelines for the assessment of *in-situ* material and mechanical properties from non-destructive testing need to be further developed and improved to increase the accuracy of the investigated parameters.
- The quantitative evaluation of the mechanical properties and density using non-destructive measurements provides good agreement and reasonable input for the structural analysis. Reliable results can be obtained, thereby increasing the ability to minimise interventions and prolong the service life as a part of sustainable development.
- The extent and sequence of measurements should be adjusted to match the structural condition and existing information relating to the structure. It is therefore preferable initially to identify members requiring further investigation using global measurements, before applying methods such as resistance drilling and X-ray that require more effort and time.
- Future work should focus on the evaluation of joint behaviour and stiffness in timber structures, as well as on the static model, in order better to predict the actual and detailed behaviour and load transfer to and through connections and joints.

IV Pilot study of the assessment of stresses in loaded structures (Paper VI)

- The use of two frequencies produced reasonable results relating to the stress levels for both materials. The parameter estimation was limited to the first two frequencies, which makes the assumption of equal boundary conditions indispensable.
- The results show that the estimation of the axial stresses is generally overestimated, but it improves for higher load levels which are of interest when structural members are overloaded.
- Considering model uncertainties, such as equal boundary conditions and constant properties over the length of the specimen, the estimated axial loads appear reasonable and provide an incentive for further research.
- The study in **Paper VI** was limited to basic knowledge of frequency analysis. The development of this procedure is in its starting phase and more in-depth knowledge and understanding of the frequency analysis of complex members is needed. Further experimental testing relating to geometric parameters, boundary conditions and large-scale validation is therefore necessary.

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