CHALMERS

On-site assessment of timber structures

Master's Thesis in the Master's programme Structural Engineering and Building Performance Design

SVEN LÖWENMARK

Department of Civil and Environmental Engineering
Division of Structural Engineering
Timber Structures
CHALMERS UNIVERSITY OF TECHNOLOGY
Göteborg, Sweden 2009
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Department of Civil and Environmental Engineering
Division of Structural Engineering
Structural Engineering
Timber Structures
Chalmers University of Technology
SE-412 96 Göteborg
Sweden
Telephone: + 46 (0)31-772 1000

Cover:
Figure illustrate a radiograph of wood with different densities and conditions. In the lower log, dowels and a nail is also visible, see Section 5.4.

Chalmers Reproservice/ Department of Civil and Environmental Engineering
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ABSTRACT

Primitive methods are often used today in order to assess timber structures on-site. If more modern technologies would be developed, a more accurate assessment of timber structures could be carried out in terms of preserving structures and to reduce unnecessary remedial work. The technologies which have been developed in this field are known as non-destructive and semi-destructive testing methods and some of those seem very promising. In this report general on-site assessment is described, but also assessment of the strength of individual members. Some of the more commonly non-destructive testing methods have been described and critically analysed and one of those, digital radiography, has also been used in laboratory and in the field, in order to ascertain its capability to detect deterioration in members. Digital radiography, as one of the non-destructive methods, would absolutely be beneficial in the on-site assessment of timber structures, according to this Master's thesis. One of the more promising markets is listed buildings, where it often is required to have as small interventions as possible. According to a survey carried out, a market for this type of technology would exist in Sweden. The biggest drawback would however be the high investment cost. Closely related to the on-site assessment is the remedial work necessary to be carried out. This has also been described in the report including description of remedial work in listed buildings, where additional precaution has to be taken.

According to earlier research, as for example Cruz et al. (2008), there is a need to complement the research concerning estimation of strength in deteriorated members. In order to contribute to this research, a load test was carried out on a deteriorated timber joint from a roof truss. The conclusion from the test was that the deterioration of one timber member in a joint will have minimal impact on the strength of an entire joint with the same design as the one used in the test.

Key words:

In-situ assessment, timber structures, x-ray, listed buildings, digital radiography, decay, remedial work, non-destructive testing methods

Bedömning på plats av träkonstruktioner
Examensarbete inom Konstruktionsteknik och Byggnadsfysik
SVEN LÖWENMARK
Institutionen för bygg- och miljöteknik
Avdelningen för Stål och Träteknik
Chalmers tekniska högskola

SAMMANFATTNING

I dagens bedömningar på plats av träkonstruktioner används ofta primitiva metoder. Om istället mer moderna teknologier skulle bli utvecklade, skulle en bättre bedömning av träkonstruktioner göras med hänsyn till att bevara mer av konstruktionen och minska onödigt reparationsarbete. Teknologier som idag har utvecklats inom detta område är kända såsom icke-förstörande och halv-förstörande metoder och några av dessa verkar vara riktigt lovande. I denna rapport har generell bedömning på plats av träkonstruktioner beskrivits, men också bedömning av hållfastheten på enstaka konstruktionsdelar. Några av de mer vanliga icke-förstörande testmetoderna har beskrivits samt kritiskt granskade. En av dessa, digital röntgenfotografering, har också använts i laboratoriet samt i fält för att bekräfta dess förmåga att upptäcka röt- och insektsskada i konstruktionsdelar. Digital röntgenfotografering skulle, som en utav de icke-förstörande metoderna, absolut kunna användas med fördel enligt detta examensarbete. En av de mer lovande marknaderna är kulturminnesmärkta (K-märkta) byggnader, där man oftast eftersträvar så lite förstörande av konstruktionen under reparation som möjligt. Enligt en utförd undersökning skall det finnas en marknad för denna teknik i Sverige. Den största nackdelen är den höga investeringskostnaden av utrustningen. Nära förankrat till bedömningen på plats är åtgärdande arbete följt av bedömningen. Detta har också beskrivits i rapporten inklusive åtgärdande arbete i kulturminnesmärkta byggnader, där extra försiktighet fordras.

Enligt tidigare publicerad forskning såsom till exempel Cruz et al. (2008), så finns det ett behov att utöka forskning runt uppskattning av hållfastheten i röt- och insektsskadade konstruktionsdelar. I avsikt att bidra till denna forskning, utfördes ett lasttest på ett rötskadat förband tillhörande en takstol. Slutsatsen från detta test var att rötskada i en trädel som är en del av en knut med samma uppbyggnad som den testade knuten i detta arbete inte påverkar dess hållfasthet nämnvärt.

Nyckelord:

Bedömning på plats, träkonstruktioner, k-märkta byggnader, digital röntgenfotografering, röta, reparation, icke-förstörande testmetoder

Contents

ABSTRACT I

SAMMANFATTNING II

CONTENTS III

PREFACE VI

1 INTRODUCTION 1

1.1 Background 1

1.2 Aim and methodology 1

1.3 Limitations 1

1.4 Outlines 2

2 ASSESSMENT OF TIMBER MATERIALS AND STRUCTURES 3

2.1 What causes the need of assessment 3

2.2 General assessment 3

2.2.1 Load-bearing capacity of overall structure 5

2.2.2 Load-bearing capacity of connections 6

2.3 Estimation of timber characteristic 6

2.3.1 Sampling 7

2.3.2 Load tests 7

2.3.3 The grading approach 8

2.4 Swedish design codes 9

2.5 Biological damage 10

2.6 Non-destructive testing methods 10

2.6.1 Stress waves 11

2.6.2 Resistance drilling 12

2.6.3 Digital Radiography 13

3 REMEDIAL WORK 18

3.1 Choice of remedial work 18

3.2 Examples of remedial work 19

3.2.1 Member replacement 19

3.2.2 Scarf repairs 20

3.2.3 Reinforce by using metal 23

3.2.4 Adhesives 25

3.3 Remedial work on historical structures 25

3.4 Upgrading structures 26

4 METHODOLOGY AND EVALUATION OF PERFORMED INTERVIEWS 29

4.1 Background and aim 29

4.2 Evaluation process and results 29
4.2.1 Governing factors whether existing buildings are repaired or demolished 30
4.2.2 Replacement of damaged members 31
4.2.3 Cost-effective ways to repair timber structures 32
4.2.4 Parts most frequently repaired in the structure 33
4.2.5 Methods used today to determine the capacity of the structure 34
4.2.6 Market for restoration of older timber structure 35
4.2.7 Remedial work in listed buildings 36
4.2.8 Potential market for digital radiography 36

5 USE OF DIGITAL RADIOGRAPHY IN LABORATORY 38

5.1 Aim and background 38

5.2 Material 38

5.3 Methodology 39

5.4 Results 40

5.5 Conclusion 45

6 USE OF DIGITAL RADIOGRAPHY IN FIELD 46

6.1 Aim and background 46

6.2 Methodology 46

6.3 Results 47

6.4 Conclusion 53

7 TESTS ON THE DAMAGED PART OF A TRUSS 54

7.1 Aim and background 54

7.2 Methodology 54

7.3 Truss design 55

7.4 Results 57
7.4.1 Comparison between test values and calculations 58
7.4.2 Detection of failure mode with the means of radiographs 60

7.5 Conclusion 61

8 CONCLUSIONS 62

9 SUMMARY AND FUTURE RESEARCH 63

10 REFERENCES 64

APPENDIX A 66

APPENDIX B 67

APPENDIX C 80

APPENDIX D 81

Preface

This Master's thesis concerns the on-site assessment of timber structures and included literature studies and practical studies both in the laboratory and on-site. In order to complement guidelines, a survey, testing of the capability of digital radiography and testing of a deteriorated timber joint has been carried out. The research has been carried out from February to November 2009. The work is a part of a research project concerning on-site assessment of timber structures and is carried out at the Department of Civil and Environmental Engineering, Division of Structural Engineering, Chalmers University of Technology, Sweden. The foundation Nils and Dorthi Troëdsson is acknowledged for their support to obtain digital radiography equipment for scanning of timber structures.

The application of digital radiography in field was carried out in a log house, situated in Trollhättan. Mats Rönnevik, antiquarian in Trollhättan, is highly appreciated for his assistance in the assessment of the log house and so also Mattias Hallgren, who both lent me a timber joint for use of digital radiography in the laboratory and also helped me find a field object where to use the technique. Thomas Kruglowa is highly appreciated for assistance in the thesis, particularly with the planning and evaluation of the load test and the laboratory staff for carrying through the test. The load test was carried out in the laboratory of the Department of Civil and Environmental Engineering and so also the first application of digital radiography. Professor Robert Kliger is acknowledged for supervision and examination of the thesis.

Göteborg November 2009

Sven Löwenmark

1 Introduction

1.1 Background

The on-site assessment of timber structures is today discussed among many researchers all around the world. The knowledge of timber, which through the history of mankind has been the number one construction material, is today more limited than other man-made materials as steel and concrete. More research has been carried out concerning steel and concrete and now more research is also needed concerning timber. The need concern the on-site assessment of both older and newer buildings. However, older buildings can sometimes be more valuable than newer buildings and, as a result; the knowledge of on-site assessment of those buildings are of more significance. In order to improve the on-site assessment, non-destructive testing methods have been developed, and are particularly appreciated when assessing listed buildings, as it decrease the interventions made on the structure.

1.2 Aim and methodology

The main aim of the Master's thesis is to contribute to the guidelines concerning on-site assessment of the condition and structural capability of timber structures and individual members. In the state-of-the-art carried out in the first phase of the thesis, it was found that extensive research recently had been carried out; see Kasal et al. (2009). Therefore it was decided to focus on the requirement related to the condition in western Sweden. The requirements where founded through a survey carried out, where the assessment of location and extent of decay in the structure seemed to be the main requirements. Contribution to the guidelines concerning this type of assessment was carried out partly through testing the means of using the non-destructive test method digital radiography in laboratory and in field.

In the state-of-the-art it was also discovered that the strength of timber structures are often underestimated and as a result replaced, when they in reality are safe and within allowable values. This is particularly significant in listed buildings. In order to contribute to better understanding of the performance of a damage connection from a truss, a test of such a connection was carried out. In this test, digital radiography was also used in order to test its capability to diagnose decay and connection details. Closely related to on-site assessment of timber structures is the remedial work, such as repair, replicate, reinforce and replace. This has also been described in the report with some considerations taken to listed buildings.

1.3 Limitations

Non-destructive testing methods have been extensively described in the state-of-the-art report by Kasal et al. (2009). As a result, only a few of the methods are shortly described in this report. The main focus of the assessment described in this report concern local deterioration. The question how to calculate the loads more in detail in old buildings was not included in the thesis.

In the report “*Advances in digital radioscopy for use in historic preservation* ”written by Anthony (2005), a method how to quantify deterioration is described, see Section Image measurement for quantification of deterioration. However, this method was found later in the research process and has not been adopted in order to assess the extent of deterioration. The main aim of the thesis was to localize deterioration and not to assess the extent of it. In order to also assess the extent of deterioration, deeper studies have to be carried out.

1.4 Outlines

Chapter 2, Assessment of timber materials and structures is described and the assessment procedure is based upon literature studies, see references in the text.

Chapter 3, Remedial work is described which is necessary to be carried out as a result of an on-site assessment. This chapter is based upon literature studies and where Ross (2002) is the main reference.

Chapter 4, Methodology and evaluation of performed interviews are described of the survey carried out, in order to extend the understanding of the situation today regard to on-site assessment of timber structures.

Chapter 5 and 6, Use of digital radiography in laboratory and in field respectively is described and the capability of this technique is shown.

Chapter 7, Test on a damaged part of a truss is described and carried out in the thesis, in order to contribute to better understanding the influence of decay to the strength properties of a timber structure. Digital radiography was also used prior and after the test of the part of a truss.

2 Assessment of Timber Materials and Structures

2.1 What causes the need of assessment

Several different events can cause the need of an assessment of the load-carrying capability of a structure. Among those events are the following, found in ASCE (1982):

- *partial or complete collapse of the structure*
- *development of unallowable deflections, vibrations or cracks with regard to requirements in serviceability situation*
- *changes in the use of the building*
- *changes in the applicable building code, especially with respect to prescribed loads*
- *fire damage*
- *reduction of load-carrying capacity due to modifications in the structure, damage, partial failure, deformation, decay, insect attacks or settlement of the structure*

One should have in mind that structures not always are sound from the beginning when built. Back in time the structures where often built by improvisation. With structural knowledge and tools used nowadays, it is possible to ascertain errors often existing in the structural geometry, see also Cruz et al. (2008). This may appear in shape of missing bracing between trusses and sometimes the structure can be eccentric loaded due to for example rafters not totally joined. In case of floor systems, it is quite common with insufficient support length at the beam ends or lack or sloppy bracing between beams. It does happen also that alterations, such as removal of support walls and other elements or introducing of intermediate partition walls is being carried out during its service life not very considered.

Joints in timber structures frequently have some kind of damage. It might be metal corrosion, timber splitting or crushing. Initial defects are quite common as well, and may consist of missing plates or fasteners, to short end or edge distances of fasteners, too small washers or gaps between elements that should be in contact. It is therefore important for the engineer to inspect the joints and identify possible failures.

2.2 General assessment

An overall assessment of the load-bearing structure may be divided into four distinct phases, according to ASCE (1982):

- *inspection of the condition of the members, the connections and the structural environment*

- *determination of the loads acting on the structure*

- *structural analysis to determine the effects of loads on individual members and connections*

- *assessment of the ability of the members and connections to sustain the applied load*

These evaluation steps may be followed by some sort of remedial work on the structure or restrictions regarding use, or possibly regarding the occupancy if the structure proves to be unsafe or unserviceable.

In order to assess the condition of timber trusses the manual *"Inspection of wood beams and trusses"* has been carried out, see Naval Facilities Engineering Command (1985). In this, a rating system is established for typical deficiencies, rated according to urgency of action required.

However, before any structural assessment takes place, a visual assessment is performed. In this, it is possible to detect first of all outer defects which may consist of knots, fungal attack, insect damage, wrong slope of grain and seasoning checks. A more specific list of what should be considered in the visual analysis is presented below; see also ASCE (1982). This is also a list to prepare for further structural analysis when this is expected to be necessary.

- *The condition of the members and connections must be ascertained to be able to determine if they are as sound or good as new material*

- *The quality of wood and other elements must be determined in order to assure stress magnitudes within the allowable range. In the case of timber, species normally must be stated and the individual members graded in accordance with applicable stress grading rules.*

- *In order to perform a structural analysis the dimensions of the members must be known. In the case of available drawings, the dimensions and layout can be checked according to these. If drawings are not available, a survey must be performed in order to determine relevant dimensions.*

- *The service environment around the structure must be noted in order to assure correct stresses. Where environments are severe with regard to moisture, acidity, temperature or closeness to ground, consideration also must be taken to type and degree of protection which been taken for the structure or which has to be taken.*

- *Magnitude and distribution of loads have to be checked during inspection. A listing of building materials to calculate dead weight including features affecting magnitude and distribution of superimposed loads. Example of affecting features may be adjacent structures or forest shelter which may influence the snow load, or the terrain in the surrounding area which may affect the wind load*

To obtain a more comprehensive view, it is also a good idea to talk to people with knowledge about the history and maintenance of the structure. This may give information about earlier reparations, loading history and modifications which help in determine structural problem areas.

In the evaluation of a structure, a structural analysis is often required. The purpose is to determine applied forces on the structure and resulting stresses and deflections. For the structural analysis to be useful, a careful made model is necessary. As connections often not are totally rigid, this may be a challenge. The designer then has to decide whether the model will handle the connection as rigid, as pin-connected or with rotation capacity.

The final step in the assessment of the structure is to evaluate the load-carrying capacity. The stresses and deflections shall be checked to be within the allowable range, including a reasonable safety factor. If loading history is not known or if the structure will be exposed to new loading conditions not originally designed for, it is recommended to not use more than 90 percent of original design stresses, according to ASCE (1982). It is also important to consider the fact that design values given for the material at the time of designing and building of the structure not have to be the same as at the time of assessment. Therefore the inspector has to find out when the structure was designed and built.

During a site inspection it is important to determine the extent of decay and thereafter consider if it is enough to replace a part of the member, or if the whole member has to be replaced. The moisture content may be checked during an inspection which also can give equilibrium moisture content. This can in some cases be an important factor to consider, for example, if steel details are added to the structure. Subsequently, the distance between the bolts across the grain cannot be too long, as wood material increase in dimension with higher equilibrium moisture content and shrinks with lower. This may result in splitting in grain direction if not considered in the design of the bolted steel plate.

2.2.1 Load-bearing capacity of overall structure

It is equally important to evaluate the load-bearing capacity of the overall structure as it is for the individual members. If the structure shall perform in a satisfactory way, rotational resistance, sufficient strength and stiffness must be developed in order to resist applied loads. Some details to look for when assessing the whole structure are, according to ASCE (1982), the following:

- *anchorage of foundation walls to footings*
- *anchorages of sole plates and header joists to foundation wall or flat slab*
- *anchorage of corners of shear walls to foundation by providing a tie between studs and foundation*
- *fastening of studs to sole plates or floor framing*

- *fastening of rafters, ceiling joists and trussed rafters to wall studs*
- *tying the two sides of a gable roof together at the ridge beam*
- *that adequate strength is provided in roof, floors and walls so that they can act as diaphragms and shear walls*
- *that continuous chords are provided for flanges of diaphragms and shear walls*
- *that transverse and longitudinal bracing is provided for trusses and trussed-rafter roof systems*
- *that adequate x-bracing is provided if diaphragms and shear walls are not provided*

2.2.2 Load-bearing capacity of connections

Several different fasteners have been used throughout the years to join wood members. Among those are machine bolts, lag bolts, shear plates and split ring, connectors, dowels, toothed and pronged plates, clamping plates, spike grids and speciality items. The allowable load for a fastener or connector is dependent on the specific gravity of the wood being joined, the moisture content of the wood, its physical dimensions and the arrangement. The allowable load is dependent on the moisture content throughout the history of the member, but at least should the conditions when the structure was built be determined in calculations. Changes in the equilibrium moisture content may lead to shrinkage, which loosen the fastener or connector and reduce the effectiveness. Deterioration like corrosion may happen to fastener or connector which can be hard to detect with primitive tools.

Other signs showing a weak structure can be a sagged, twisted or rotated connection. It can also be that the capacity of the connection is gone, even if it is not visible. An example is failure in purlin-to-beam connection, where the deck starts to take the load instead. But this may result in overloading another connection instead.

According to the study *"Nailed Joints in Wood Structures"*, referred to in ASCE (1982), is an all-embracing formula to calculate the capacity of a connection not feasible. Thus, it is not possible to evaluate a joint only by calculating ultimate load-carrying capacity. Furthermore, it is not appropriate to design joints on the basis on joint-slip limitations. The evaluation demands more consideration.

2.3 Estimation of timber characteristic

As mentioned in the list concerning visual analysis in Section 2.2, one part of the assessment is to evaluate quality of the timber members, which include strength and stiffness properties. This can be done with several methods, and one of those is the stress grading method. This method and load test and sampling, which is the two other methods most commonly adopted by building contractors will be shortly presented and analysed in following sub-chapters.

2.3.1 Sampling

Building contractors are often tempted to take samples from the timber in order to determine the characteristics or to assess the state of conservation. This is done by taking some member, which for some reason should be replaced, or by taken small pieces of the timber at different places, exactly as the procedure is when assessing other materials.

The problem is that timber consists to a large extent of natural variability like knots and different slope of grain. Therefore it is not possible to obtain the strength of the timber with reasonable accuracy by using only a few samples. In order to achieve reasonable accuracy, several samples have to be taken with 40 timber pieces each, see also Cruz et al. (2008). This is obviously not possible during an assessment. Also, a few samples would not be able to represent possible biological damage in the structure like decay or insect attack.

However, samples may be used to evaluate moisture content, species and density. They can also be used to assign that the clear wood strength fall within the expected range, but then complemented with evaluation of strength with another method.

2.3.2 Load tests

A load test is performed either by using hydraulic jacks or, more commonly, by putting dead weight such as water tanks or cement bags on the structure of interest. Subsequently, resulting deformations are measured and used to adjust a predicted model (commonly a final element model), which in turn gives the mechanical properties of the elements and joints.

Vibration tests are also used occasionally. The structure is then exposed to an instantaneous load (excitation), and following vibration is measured with an accelerometer. This gives the frequency, which is used to determine the modulus of elasticity which also predict the strength through correlation.

Both tests are expensive and time consuming and results tend to be affected by moisture content and how well the support conditions and the load paths are understood and modelled. Further on, the correlation used to determine the material properties are based on the whole species and may differ for individual members. The values are also established on new timber which may not represent older in the same way, where load and environmental history may affect the correlation.

2.3.3 The grading approach

This is the most commonly adopted approach in assessing the timber quality and involves the determination of species. The timber is evaluated in order to identify a specific grade, which correspond to specific material properties like strength. This can be performed by report the assessment to an existing stress grading standard, used to industrially grade timber for structural uses. In the evaluation process regard is taken to defects like knots, slope of grain, fissures and density. At first an average stress grading level is applied to the members and after that possibly more specific to members exposed to large loads or of importance for the structure in some way.

Stress grading rules used in the structural evaluation are written at a national level, but typically coordinated at an international level, like CEN in Europe. When species and stress grade are known, corresponding design values can be found in the national or international design codes. Those design values are based upon extensive research, including tests on both small pieces of material and full-scale tests. However, the use of those design values has some drawbacks. The tests are performed on timber which origin from newly grown trees, which belong to what is called the second generation growth and has grown fast. This result in timber with lower density and mechanical properties compared to that of the first generation growth, which grew slowly. Older buildings are often built of the first generation growth, which mean that the design values do not totally match the reality, as the strength is higher compared to what is tabulated in the codes. This may result in underestimation of the capacity of the timber.

Moreover, the design values are often constructed based on average properties of an entire species. To not make an underestimation of the strength, 95% of the timber will predict higher strength than tabulated in the design values and only 5% lower. When using those design values in the assessment of individual members, the strength will often be much underestimated.

Not only does the method used today with existing design values and visual assessment with primitive tools run the risk of underestimate the properties of individual members, but may also overestimate member capacities due to deteriorated areas hard or even impossible to detect at an visual inspection. A study has shown that mechanical properties can be reduced with up to 10% before any visual indicators appear and at 5-10% weight loss due to decay, the mechanical properties of a member can be reduced with as much as 80%, Kasal et al. (2009).

To improve the on-site assessment of timber structures both better methods to determine the strength of individual members could be developed and more modern techniques to evaluate the localisation and extent of deterioration in members. An additional interest is to be able to assess historical structures without too large interventions than necessary. This has result in the development of modern non-destructive and semi-destructive techniques which can be of help in a structural evaluation without, in the first case, cause any interventions on the structure and in the second case, small interventions on the structure. It can also be a tool to retain as much material as possible or even complete structures, which otherwise would have been replaced due to underestimation of strength. This can conserve the cultural and architectural significance and may be of help to engineers in order to learn from historical building techniques.

2.4 Swedish design codes

In general there exist very little recommendations regarding assessment of existing timber structures both nationally and internationally, according to a state-of-the-art report, carried out by Kasal et al. (2009), and this is also the case in Sweden. Boverket, the Swedish national board of housing, building and planning, is the Swedish organisation publishing the national design codes and recommendations. According to Lars Göransson (Boverket), little research has been carried out and published in the recommendations. The information published by Boverket concerning on-site assessment of timber structures can be found in *"BKR 2003"* in the Section 5.3; *"Design by calculating and testing"* and guidelines concerning on-site assessment in general in Section 2.12; *"Requirements in the serviceability limit state"*, see Boverket (2003). What else can be found are references in the guidelines *"Allmänna råd om ändring av byggnad, BÄR"* (Boverket, 2006) to the guideline *"Design by testing"*, published by Boverket and ISO -13822, which is a European international standard (ISO, 2001).

In BKR 2003, in Section 5.3, some valuable information may be founded, as for example; "*In determining section properties, the effect due to reduction of the cross section shall be taken into consideration. Holes due to bolts, screws and nails need not however be taken into consideration if the lateral dimensions of the connectors are not greater than 6 mm*". What can be found in this Section is certainly valuable, but needs to be complemented with even more specific information of how to know and assess the condition of the timber structure. In Section 2.12, one may for example read that *"calculation of deformations and oscillations may be performed in accordance with the elastic theory using an analytical model which gives a reasonable description of the stiffness, mass, damping and boundary conditions of the construction"* and further that *"cracking in elements of structure shall be limited in view of their function and durability"*. This information is good, but not specific for wood.

ISO-13822 concerns all materials and is as a whole very general, which means it is not very useful in common practise to assess timber structures. What is left is the guideline "Design by testing", where it is specified how to assess the strength of existing structures, see Boverket (1994). However, as can be read in the beginning of the guideline, the main application of it is by testing in laboratory, thus, not for use in on-site assessment. The testing is carried out on a model of the member or joint interested, made in the laboratory or on samples taken from the timber of interest. Accordingly, with a model it would first of all be very hard to simulate deterioration, if not impossible, and with samples the problem still exists of natural variations in the timber and interventions made on the members. In the guideline is however the test procedure described including how to load the samples in order to evaluate the strength property.

Beside Boverket has the Publisher T-virkesföreningen published the *"Instruktion för sortering av T-virke"* (T-virkesföreningen, 1981). In this short guideline recommendation is given which strength class the timber has with regard to knots.

Another national guideline found in the literature survey was the "*Guideline for structural condition assessment of existing buildings*" published by American Society of Civil Engineers, see ASCE 11-99 (2000). Also this guideline was found to be too general for practical use in on-site assessment.

2.5 Biological damage

Biological damage is a frequent justification for complete replacement of structures which would otherwise been kept in service, according to Cruz et al. (2008). This may partly depend on difficulties with the assessment of extent and localisation. Models to predict strength have been tried, but to obtain corresponding values on-site include several factors of uncertainty. As a result, decayed members are commonly assessed to not have any strength at all and are therefore replaced or strengthened as if they were already lost. An exception is when the decay seems to be in its initial phase and only affect the surface and when the member in addition is over designed.

When the timber is attacked by beetles, the damage is often only in the surface layers of sapwood and can be assessed with simple tools as a knife for example. The capacity of the member is subsequently reduced with the reduced cross section. As a safety this cross section is implemented on all other members as well, with exception for members with higher importance or higher stress levels. This may although be too conservative, as even the insect damaged layer can be able to resist load.

Other insects may leave holes in the structural components which result in a new calculated reduced cross section. In some cases it has been shown that insects have deteriorated the structure itself in the member. In those cases it is not possible to calculate with a reduced cross section, but rather to use a reduced quality due to lower density. Much research related to validation of the influence insect attacks have on the strength and stiffness properties has not yet been carried out, according to Cruz et al. (2008). However, according to Brozovsky et al. (2008), if cross section is known, the severity of the damage may be classified as:

- mild failure: cross-section reduction < 5 %
- medium failure: cross-section reduction 5 to 15 %
- hard failure: cross-section reduction > 15 %.

The severity of damage of wood borer, which is the most dangerous insect for the structural condition of timber may, according to Brozovsky et al. (2008) be assessed as:

Table 2.1 Criteria for assessment of elements affected by wood borers

Kind of wood-borers	∅ of surface output opening	number of output openings in relation to 1 m^2 for particular failure type		
	[mm]	mild	medium	hard
sawyer beetle	4 to 9	2 to 4	5 to 16	more than 16
woodworm	1 to 3	6 to 10	11 to 24	more than 24

2.6 Non-destructive testing methods

Various non-destructive testing (NDT) methods have been tested and developed in order to simplify the assessment of timber structures on-site. This is, as mentioned, particularly required in historic timber structures, where the aim is to cause as small interventions on the structure as possible. Three of the more usual techniques are shortly described in the following sub-chapters. As digital radiography have been tested in the report and studied more in detail than other NDT methods, it is also described more in detail. For more information about described methods and additional techniques, see Kasal et al. (2009).

2.6.1 Stress waves

Stress waves is a wide spread method to assess timber structures. There can be different shapes of the waves and the most common one used to assess timber on-site is the long wave. In this wave form the particles in the material oscillate in the same direction as the wave propagate.

The parameters used to detect voids and internal defects in wood are the velocity of the sound waves and attenuation. Attenuation results from scattering at material interfaces and absorption.

One form of stress wave inspection is sounding. It means to simply strike the object with a blunt tool, like a hammer and then listen to following sound, in order to differentiate sound and decayed material. The limitation with the method is that only serious decay will be detected and even if the inspector is very experienced, the inspection is subjective and may differ for different inspectors. Another factor to consider is other mechanical properties, which may affect the sound to sound like decayed material.

Sonic stress waves are waves with frequencies within the audible range and are usually only called stress waves. There are two ways how to perform the test; to measure the velocity or to carry out a frequency spectrum analysis. Velocity is measured in a different way in the longitudinal direction in a member, compared to the transverse. In the transverse direction a timer is connected directly to a hammer and an accelerometer is placed at opposite side of the member, see Figure 2.1. By measure the width of the member and the time for the sound wave to travel from one side to the other, it is possible to determine velocity. When measuring the velocity in the longitudinal direction instead of connecting the hammer directly to the timer, two accelerometers are placed on the member with a specific distance in between.

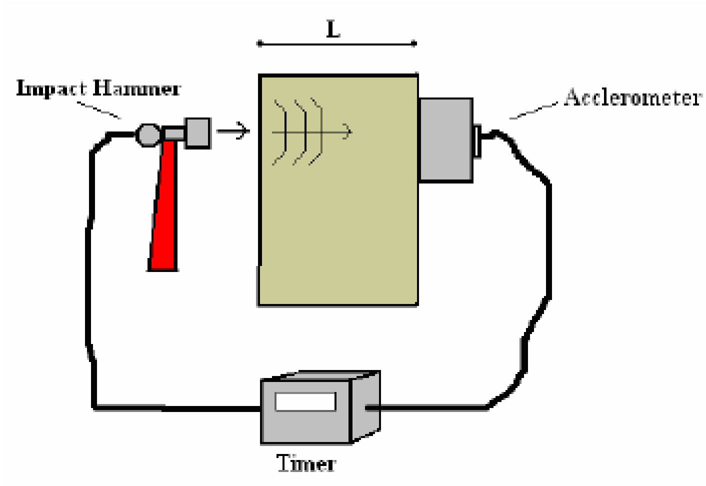


Figure 2.1 Test with a stress wave system (Lear, 2005)

An alternative to traditional measurement is frequency spectrum analysis. This method has the advantage that it only needs accessibility to one side of the member due to a specially designed probe. The probe contains an accelerometer and is connected to an oscilloscope, which convert the sound waves from a strike with a hammer, to frequency. The frequency is dependent on the condition in the timber, which make it possible to determine different degrees of deterioration.

2.6.2 Resistance drilling

Resistance drilling is a semi-destructive but near to non-destructive method. The interventions consist of drill holes of 1.5-3.0mm in diameter. Resistance drilling has also, according to Kasal et al. (2009), been used in other areas as tree growth and health surveys, bridge and building surveys and in the termite and pest control industry.

The drill consists of a sensitive bets which is connected to an instrument recording the resistance during drilling. The emerged torque required to maintain the constant cutting speed corresponds to the resistance in the timber and the correlation to the penetration length is what will be recorded on a graph, see Figure 2.2. Peaks correspond to higher density and dips to lower and total decay will exhibit as a straight line and is marked with red in the Figure. In the sound wood the different densities due to late and early wood can be seen.

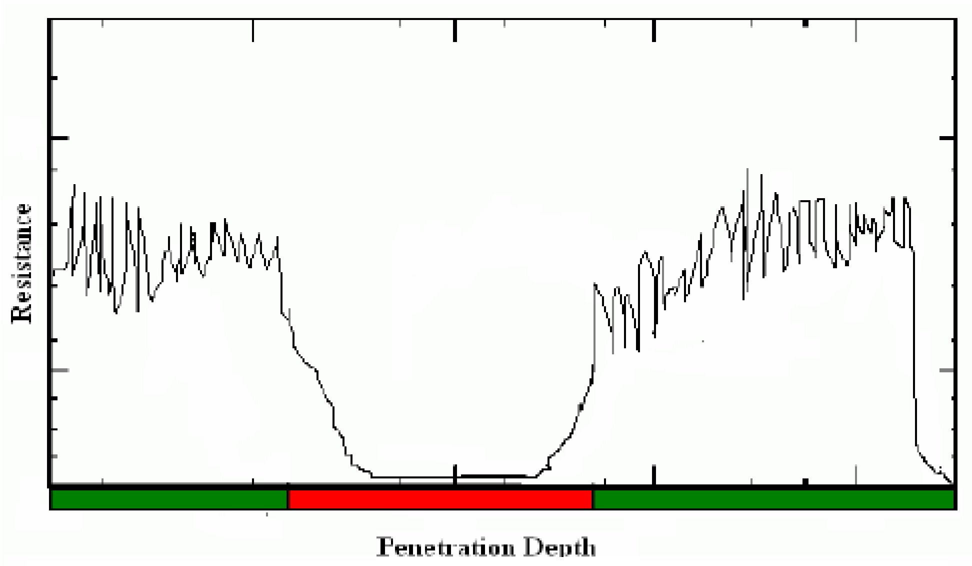


Figure 2.2 *Graph visualizing result from resistance drilling (Lear, 2005)*

Beside wrong use of the resistance drilling it will deliver proper result. One has to think of where to make the drilling holes and what speed to use. If the speed is too low, the different densities will be hard to distinguish in the graph, and if it is to high the drilling may break. To interpret the results in a satisfactory way may also be a challenge. One has for example to think about that conifers naturally are softer in the inner core and to not take this for being decayed material and also that the curve will have different shape depending on in what direction the drill cross the annular rings.

As with many other investigative techniques, a limitation is the accessibility. The drilling equipment is rather big and may therefore be hard to place in desired position. The length of the drills may also be a problem, as they might be shorter than the member width in case of thick member. To receive a complete map over the member a number of holes often have to be carried out. The problem is when the structure is of significance, as in historical buildings, where as small interventions as possible are required. Another uncertainty when using the technique is that the needle, according to Kasal et al. (2009), tends to deviate from its original line. This is related to the flexibility of the thin needle causing inability to resist natural variability in the member.

The technique is however beneficial as a complement to detect rot, but not very appropriate in order to determine the strength of the member, as knots, fibre deviations and other aspects are not covered in the analysis.

2.6.3 Digital Radiography

Digital radiography has not been spread earlier as a method to assess timber structures due to safety issues and images necessary to be produced analogous. However, those limitations do not exist today, as the technique has been developed in other areas like food and safety industry. This development has resulted in a highly user friendly and portable equipment.

Digital radiography exists of a radiation source and a radiation sensitive film. When using the equipment, the source is placed at a specific distance in front of the object of interest and the radiation sensitive film is placed closely behind the object, see Figure 2.3. During operation radiation is emitted through the object and the film receives the data about the object. When the film is depicted digitally through a scanner, what can be seen shows different densities of the material emitted. Darker areas correspond to lower density and lighter areas to higher density. When the image has been digitally scanned, it is also possible to work with different programs to make it clearer, or to focus on a smaller part of the object.

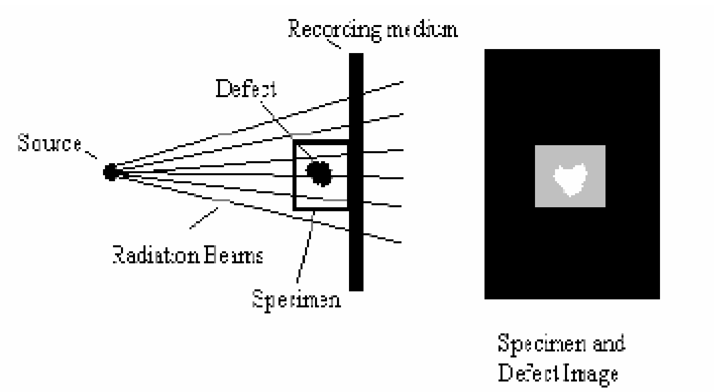


Figure 2.3 General arrangement for radiographic imaging (Lear, 2005)

Background and technology

Two commonly used sources in radiography are gamma rays and X-rays. The gamma rays have the advantage to be more portable than the X-rays, due to its nature, and do not need any cooling system. The drawback is that the image quality gets poorer during time and the contrast lower compared to X-ray.

X-rays are a sort of ionizing electromagnetic radiation with short wavelengths, widely used in the medical area due to its ability to penetrate organic material. X-rays characterises of energy and wavelength where shorter wavelengths correspond to higher energy and the correlation is known in the formula:

$$E = \frac{hc}{\lambda} = \frac{1{,}24}{\lambda} \qquad (2.1)$$

In the formula E correspond to radiation energy; h to Plank's constant, c to velocity of light and λ to the radiation wavelength. Typical X-ray equipment has a range from 50kV up to 320kV, or up to 200kV if portable.

When radiation beam pass through a material it is attenuated and depending on density and thickness of the material the magnitude of the attenuation differ. This difference is what is recorded on the image behind the object. With lower energy input the difference in attenuation in different materials will be larger, but the problem may be that the energy is not enough for the radiation to pass the complete object until the film where it is to be recorded. When the beam reach the film, the intensity of the radiation can be calculated as:

$$I_x = I_0 \cdot e^{-\mu \cdot t} \qquad (2.2)$$

In Equation 2.2, I_x is the emergent intensity, I_0 the initial intensity, t the thickness of the material and μ the linear absorption coefficient per unit thickness. The only material specific parameter independent of the thickness is μ, which can sometimes result in difficulties. As can be seen in Figure 2.4, the value of μ at some points correlates between the materials at specific photon energy levels. At the point of 1 MkV where the steel and concrete coincide, will, as a matter of fact all materials coincide. This may result in images where it is hard to distinguish between the different materials.

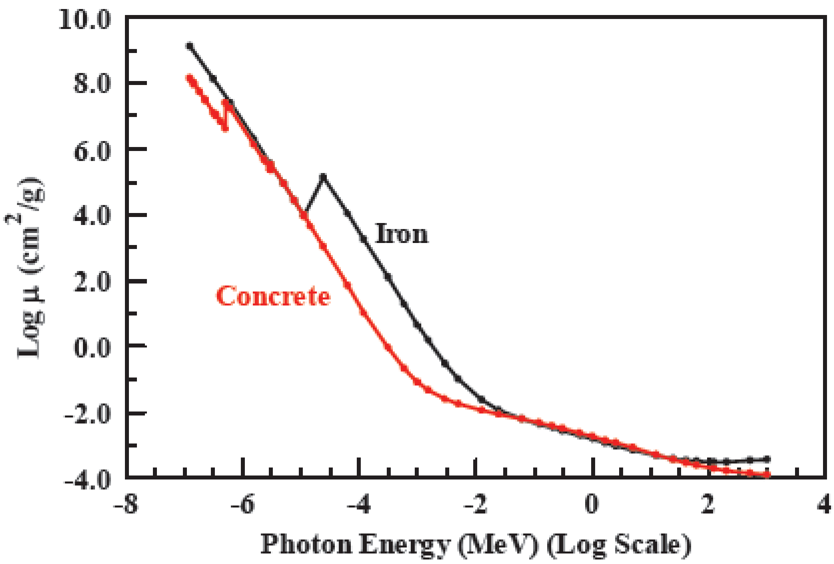


Figure 2.4 Correlation between the linear absorption coefficient and the photon energy level for iron and concrete (Kasal et al., 2009)

Imaging

Back in time film radiographs have been used to capture the image. They have an emulsion which is sensitive to radiation and changes with different intensity. The drawback with this technique is related to safety concerns and the expensive costs at operation in field.

During past decade digital radioscopy has been developed, which offers images in real time to a lower cost and with higher safety. Thanks to the storage feasibility in a computer, it is also possible to work with the quality of the images in different programs.

Imaging quality

Imaging quality is greatly affected by how the equipment is arranged during operation. To receive as good sharpness and contrast as possible, it is important to have the film as close to the object as possible. However, it is also possible to have it at a specific distance from the object, if smaller details are of interest, but have to be done carefully to not exceed an accepted level of unsharpness.

In order to avoid distortions, the image plate should be placed perpendicular to the source. This is however not always possible due to accessibility and as a result the images may be a bit harder to interpret. To make the interpretation easier it is beneficial to place a material easy to detect and distinguish at the border on the film in order to help the orientation. It is also necessary to consider how to put the source in order to detect deteriorations and cracks. To detect a crack for example, the source often has to be put parallel to it, if it not is large enough to be detected anyway.

Powerful programs can be used on a laptop to enhance image produced on site. The programs may be able to invert the image, adjust the contrast, the brightness or the colour etc. Another function sometimes able to use is a grid to overlay the image in order to be able to measure different distances. This may be done on site in order to evaluate the image and consider how to proceed with the inspection.

Application

In a structural analysis radiography may be used to evaluate deterioration in members, the condition and existence of metal fasteners or answer questions of internal or hidden construction techniques. In this report discussion will concern deterioration.

Decay can be detected by recognize the difference in density in the object. Due to the resulting breakdown of the material when a member decays, it loses density. If the member is sound the annular rings can be clearly visible and the structure is homogenous. At moderate decay the annular rings may still be seen, but more unclear and different densities of the member start to be seen in form of lighter and darker areas. When the decay has advanced even more it more obviously seen like darker areas clearly separated from the lighter ones and the annular rings totally disappear.

It is also possible to observe disruptions in the grain structure like grain deviations, knots or mechanical distortions like fractures, drill holes, cuts or natural cavities. Damage by insects can be detected in the same way, often like holes through the structure.

Limitations

Although there are plenty of advantages with the use of radiography there are also some limitations. First of all, the resulting image produced is two-dimensional. This means that what is seen on the image is the average density over the depth of the object. If it is not known how deep the decay is; it means it is not possible to determine the extent of the decay. In order to overcome this limitation access both from aside and from above of the object is necessary, but this is in many cases not possible due to limited accessibility. With only one view it can also be hard to detect internal features like cracks or other defects oriented perpendicular to the radiation. To detect internal cracks, they have to be at least 2% of the thickness of the object and oriented parallel to the radiation.

In most of the portable radiography equipment available access to both sides of the object is necessary. This can in some situations limit the ability to investigate due to inaccessibility. Other structural elements may also obscure the survey.

Even if the newer radiography equipment is safer compared to the older one due to use of lower energy, some consideration about the safety must be taken. It is recommended to inform the people in an area near the equipment before operating the equipment. This is particularly important when using higher energy needed to penetrate thicker objects or objects with high density.

The fact that portable radiography often has a lower maximum of energy level compared to stationary radiography may restrict the possibility to penetrate very thick members and produce images sharp enough to be useful.

3 Remedial work

In the case of assessment showing that the structure does not seem to fulfil the requirements for the remaining service life, it has to be decided what remedial work to be done on the structure. There are four types of measures possible to perform, see Ross (2002):

- *repair (locally to a member, or a joint)*
- *reinforce (add material to reduce the loading on the original frame)*
- *replicate (new material in the original form)*
- *replace (a new, different structure)*

3.1 Choice of remedial work

What alternative to choose may also be expressed as; if one should seek to upgrade the existing structural arrangement to work, if one should seek to change the existing structure in order to work better or if one should introduce new structure, see Yeomans (2003).

Remedial work is often not included in any budget and the governing factor when choosing what remedial work to perform is therefore often the economical question. Another factor to consider is structural integrity, which includes enough strength capacity. The ideal operation is to restore the strength to the original design, but is not always possible.

The durability of the remedial work differs. Some require service after a couple of years and other will stand for indefinite time. Other factors to consider are physical configuration and the associated environment. For example, the repair method may differ completely if it is a check or a bigger crack that is to be repaired. And the same consideration must, according to ASCE (1982), be done if the member is placed outdoors or indoors.

Further consideration must be done regarding activities or loads acting on the structure during repair work. The activities may require as little disturbance as possible, which may affect the choice of remedial work. The structure may also sustain other significant loads during repair work.

When choosing sort of remedial work it is also important to consider the entire expected lifetime of the structure. In the past, it has happened that the structure was repaired only to sustain a couple of more years and after this time it was decided that the structure should be used for more years, but at that time the structure was in a very bad condition. The functional use may also change during the time in use.

The sort of remedial work also depends on the availability of craftsmen, equipment and material. The craftsman may have different experience and may feel more comfortable with special solutions. In different places and countries, the availability and the price of material vary. In Sweden for example, the availability of softwood is great and it is also cheap and it can therefore be preferred to use this material. At some occasions specialized methods are used, but those may also be patented. More advanced solutions may require more advanced equipment and in this case this may be a limitation if not available.

The last two factors to consider are safety concern and aesthetic. The structure needs to be safe both during service and during repair activities. During repair activities enough bracing and proper supports therefore must be used. It is also specially recommended to not use welded steel details in contact with wood, see ASCE (1982). In most cases the structural elements are not visible and following the aesthetic is not of paramount interest. However, sometimes the structural timber elements are constructed visible, especially in historic structures, due to aesthetic issues. In this case it becomes more important which sort of remedial work that is chosen with regard to aesthetic. Fulfilling the aesthetic requirements may in this case be the most challenging part.

3.2 Examples of remedial work

3.2.1 Member replacement

According to both Ross (2002) and the survey, see Section 4.2.4, the complete member most usually replaced is the sill plates. Those often come in contact with ground which results in decay. If the distortion is not too severe and if the building is a simple framed structure, it is possible to use jacking and propping to adjust this problem, see Figure 3.1. The ground may be lowered around the sill plate and additional support inserted.

Now and then other members have to be replaced as well due to rot, beetle attack or damage. Often the original joint has to be modified in those cases to be able to fasten the new member.

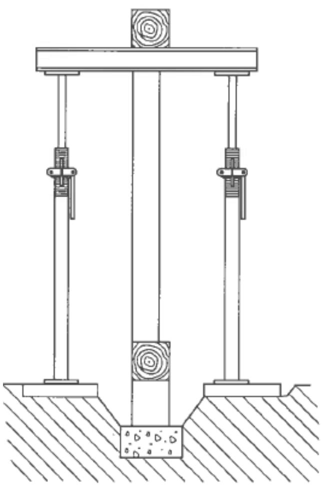


Figure 3.1 Jacking and propping (Ross, 2002)

3.2.2 Scarf repairs

It is often required to replace the end of a beam, which requires some sort of scarf. The scarf can be made of timber alone, or with additional material like metal. The scarves made completely of timber is generally weaker than the beam was initially, which has to be considered with regard to existing loads on the structure. A quantitative assessment of the joint loading with regard to moments and forces therefore has to be done. Common for all scarves, according to Ross (2002), is that they require:

- *An adequate overlap scarf length*
- *End connections to the blades*
- *Some reserve of strength for moments on the other axis*
- *A mechanical lock to prevent slip failure (for tapered scarves)*

Scarves in bending

The scarves must sustain applied moment, see example in Figure 3.2 and can therefore be sawed as in Figure 3.3. The angle of the sawn anchorage will have local failure. The optimal angle, which will give the maximum moment resistance without local failure, is approximately 70°. For the two parts to not separate, they also have to be joined with dowels. Those types of scarves will achieve one third of the strength of the unjointed section and one third of the stiffness.

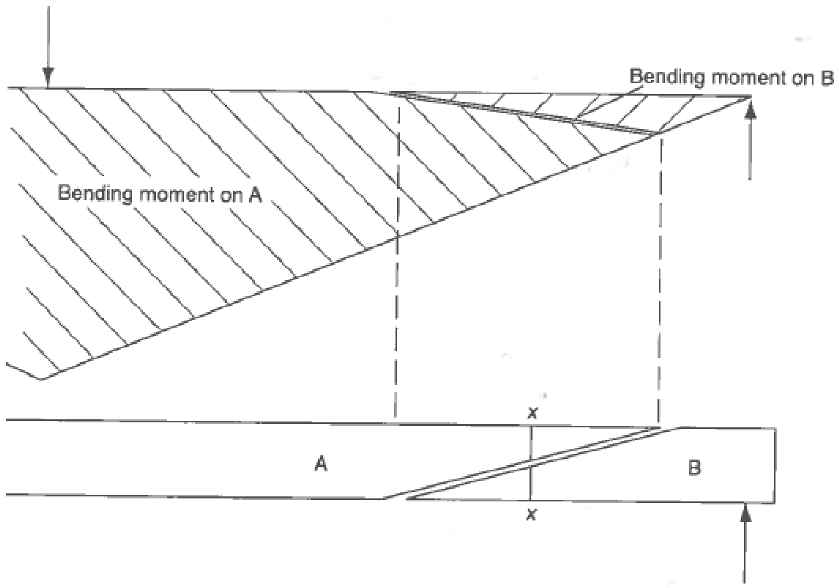


Figure 3.2 Moment on scarf in bending (Ross, 2002)

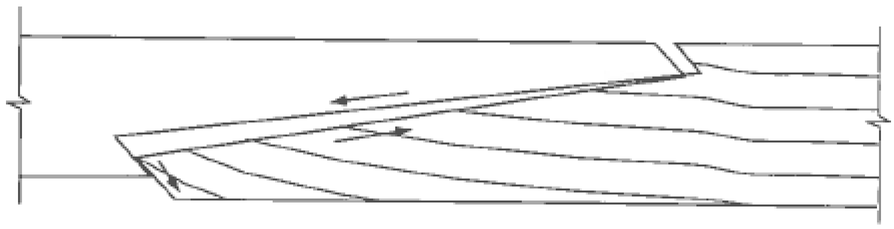


Figure 3.3 Scarf in bending (Ross, 2002)

It is also possible to use metal fasteners to increase the strength further. The metal fasteners have higher shear strength compared to dowels and can also develop tensile forces by using washers. To increase the strength even more, steel plates may be fasted with bolts at the sides of the timber.

Scarves in compression

The simplest scarf in compression is the one where the two parts is butted towards each other; see Figure 3.4(a). However, in most cases the compressed members are also prone to buckling, which mean lateral moment exists as well and therefore some lateral resistance is needed also. To resist lateral moment it is possible to build a tenon and mortice joint, as seen in (b). If the secondary lateral load is more significant, it is better to construct it like in (c). These types of scarf are however stronger on one side and weaker on the other, and to make this difference smaller it is better to use squints as in (b). The more experienced carpenter may also be able to build the so called scissors scarf (e). This one has a high resistance to buckling; however, some strength is reduced in compression.

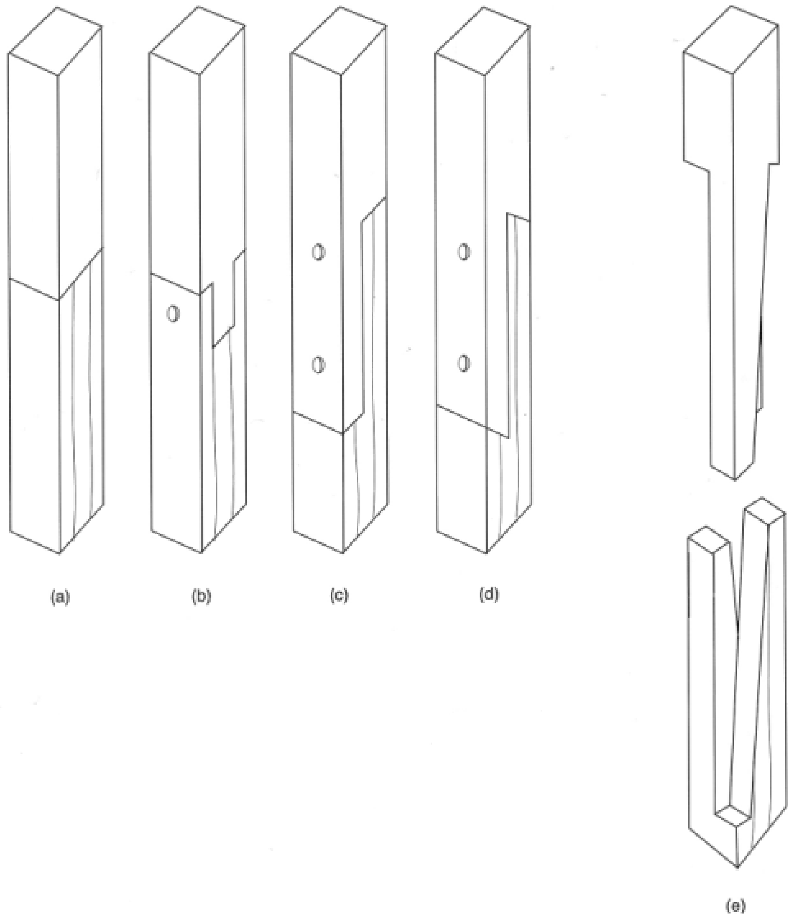


Figure 3.4 Scarves in compression (Ross, 2002)

Scarves in shear

At smaller loads a scarf well used to resist shear is the face-halved scarf, Figure 3.5(a), with pegs to hold it together. At higher loads it may be prudent to taper the scarf sides, in order to minimize the risk of fissures at the scarf base (b). However, this scarf needs more pegs to be hold together.

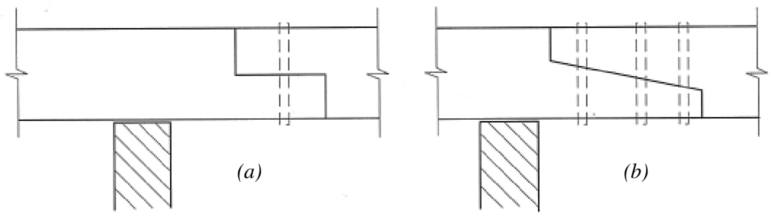


Figure 3.5 Scarves in shear (Ross, 2002)

Scarves in tension

When constructing a scarf in tension the optimal solution would be to taper the scarf side and to make a hole in the middle where pins can be stacked in, in order to tighten the scarf, see Figure 3.6. "The design aims to balance the residual tension capacity of the scarf at section x, against the shear capacity of the potential failure line y_1" (Ross, 2002). The y-line shows where the shear force is resisted and if the grain is inclined, like y_2, the shear strength as a result will be considerably decreased. This scarf will achieve approximately one quarter of the unjointed member.

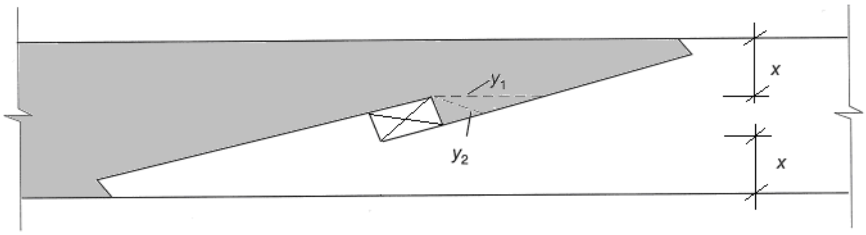


Figure 3.6 Scarf in tension

The reduced strength in most joints is however not a big problem, as the beams, as a rule, have been designed very generously in the medieval and later buildings. The scarves are also in general made near supports where the moment are lower than maximum. Despite this in mind, it is important to estimate and assess whether the strength is enough and to consider local defects.

3.2.3 Reinforce by using metal

Particularly when the member subjected to reparation is not visible, the possibility exists to choose among a range of repair methods including metal. This type of repair may be called to reinforce, because the metal can be seen as added to the original material, and lies partly outside. The most significant benefits with the use of additional metal are:

- In general, they require less original timber to be removed
- Member strengths can be increased
- Some estimate of strength can be made using Code rules

Splice plates

One method probably more used than anyone else mentioned in this chapter, is to use splice plates. This involves plates fastened at the sides of the member to be reinforced, shown in Figure 3.7(a). The fastening may be done with nails, screws, bolts or bolts with connectors. This method is appropriate when a beam end has to be replaced due to rot and lengthened to reach support (b).

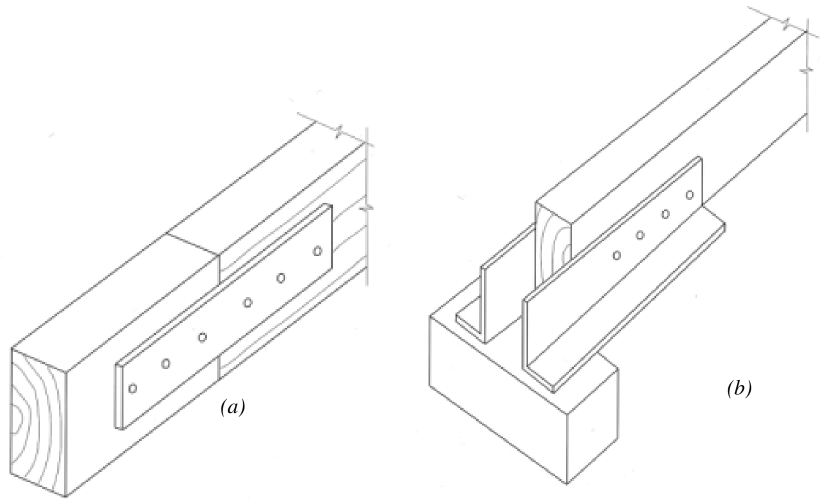


Figure 3.7 Scarves made with splice plates (a) and splice angels (b) (Ross, 2002)

Flitch plates

For beams heavily loaded flitch plates may be an appropriate repair method. In contrast to splice plates, flitch plates are placed inside the member, see Figure 3.8. Holes in the plates to fasten it with bolts may be carried out before application, but preferably after to make the fitting better.

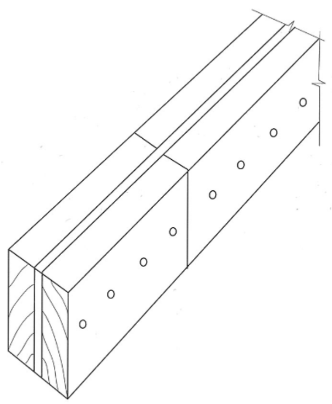


Figure 3.8 Scarf made with flitch plate (Ross, 2002)

Frame reinforcement

In some situations there might be no other possibility but to reinforce timber frame with steel details. Two examples are the reinforcement of a roof truss, where lateral support is missing, see Figure 3.9(a), and the reinforcement of a beam in order to convert it into a bowstring (b). In the first example a steel rod is used to tie the two walls together. In the second, a strut and a steel rod is used in order to develop additional resistance to vertical loads.

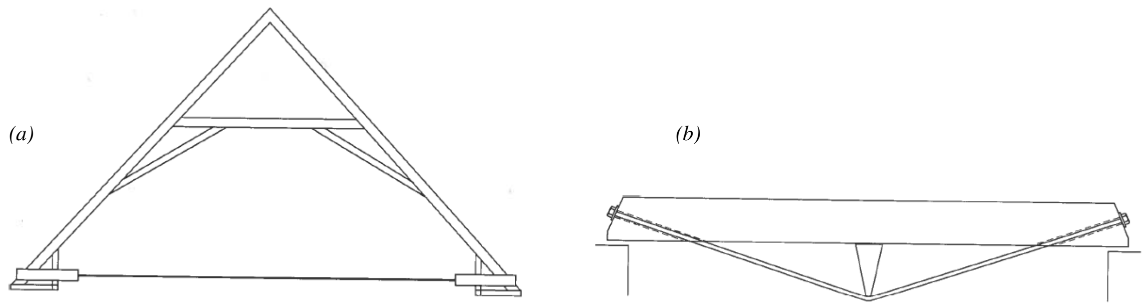


Figure 3.9 Frame reinforcement by use of steel details (Ross, 2002)

3.2.4 Adhesives

There are relatively few situations when adhesives are used in in-situ repair of timber. This is due to the demanding requirements regarding surrounding conditions.

The two broad classes of adhesives are the formaldehyde adhesives and epoxy resins. The formaldehyde adhesives were specifically developed for timber and have existed on the market for 50 years. When used in a correctly made joint, it is often stronger than the timber itself. The problem is to meet all requirements in the surrounding environment. For the bond to have maximal strength the moisture content should be 8-12%. Above 20% there is an increasing risk of bond failure. Ideally, the timber should be within 5% of their equilibrium moisture content. During curing, the surrounding temperature should in general not be more than 20°C, which may be hard to fulfil in many countries during a long period of the year, see Ross (2002).

Epoxy was, according to Larsen K. E., Marstein N. (2000), introduced in 1946 by a Swiss chemical company and has since then been used extensively in Europe, Japan and North America in reparation of decayed timber structures. The adhesive is not as sensitive to the environment as the formaldehyde, which makes it useful. However, it is expensive and is therefore often mixed with different fillers. It is today most used to replace decayed parts in the middle of beams, with embedded steel rods, which then are joined in a sound new beam member. I historic timber structures one should consider that the experience of the reparation method during 40 year could be too little for use on a building built 1000 years ago.

3.3 Remedial work on historical structures

After an inspection of a historical building has been performed and the significance is known, it is necessary to consider how to retain as much as possible of the original structure in the following remedial work, without affecting safety and durability above requirements. In order to fulfil this, some general guidelines has been developed, see Ross (2002):

- *Maximise the retention of original material*

- *Allow the original form to be seen*: the repair method should be chosen and performed in order to let the original structural form 'come through'

- *Do the minimum*: all remedial work have to have a reason. Remember to not think like a new building will be built, but to make the existing building sound.

- *Consider 'reversible' remedial work*: reversibility has become a well known concept among conservators, but require some additional consideration. A well used repair method in medieval buildings is timber-to-timber. Though, this may not always be reversible. When using timber-to-timber connections larger interventions often have to be done. A more reversible work would instead be to use for example steel plates at the sides to strengthen a timber connection. It is not the steel itself which make it reversible, but the way it is used. For example, if some of the material inside would be carved out in order to install a steel plate embedded of epoxy resin, it would not be reversible. Because the aim of reversible remedial work is to make it easy to change the work in the future, in case of ability to make it even better, but to still retain the original structure and its material as much as possible.

See also the *"Principles for the preservation of historic timber structures"*, published by ICOMOS, the international council on monuments and sites, where the principles Ross develop is to be found.

When assessing the structure, before any remedial work is done, it is further on important to consider the difference between the old timber in historical buildings and the newer timber in modern buildings. In modern buildings the timber members often have a smaller size, which seldom result in visible fissures. In historical buildings the timber members used is often larger and older, which often may result in inevitable, larger fissures, particularly seen in oak. However, this does only affect the shear strength and therefore seldom becomes a reason to remedial work. To fill the gap with some incompressible material is not a good idea, as the fissures then may grow when MC in the timber increases.

3.4 Upgrading structures

Often a building is subjected to upgrading as a result of most commonly change of use or economy. The aspects of concern are following:

- strength

- thermal insulation

- fire resistance

Upgrading is in general more intrusive than remedial work (Ross, 2002) and may therefore result in less significance of a historic structure.

When there is a change of use, like very often, to convert a domestic area to offices, the floor structure often has to be strengthened. Following suggestions of how to do this will cause large interventions, but may be used when the significance is of less value or priority.

The first example describes how to strengthen a floor structure consisting of principal beams and joists, see Figure 3.10. First a slot is made through the principal beam in the middle. Thereafter U-beams are put in place against the timber ends and supported on their ends in order to decrease the stresses in the principal beams. As the U-beams divide the principle beams in the middle, moment is transferred to those, which result in principal beams loaded with half the load, and thus double the floor's capacity.

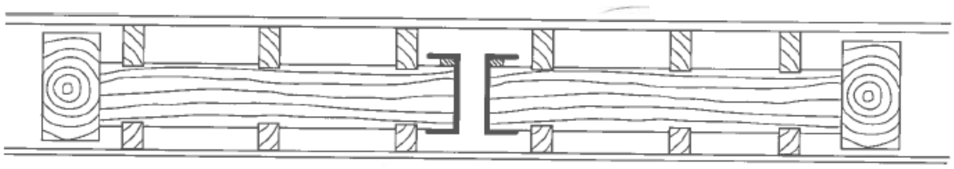


Figure 3.10 Strengthening of floor structure consisting of joists and beams (Ross, 2002)

The most critical member in old timber floor structures is usually the principle beams. Therefore, those must be strengthened in order to strengthen the whole floor structure. One alternative how to do this is to fasten U-beams with bolts on each side of the principal beams, if the joists are not too deep, see Figure 3.11(a). Another alternative is to make a slot in the principal beam from above and then fasten a T-beam with screws against the beam (b). However, large interventions on the floor will in this case be performed.

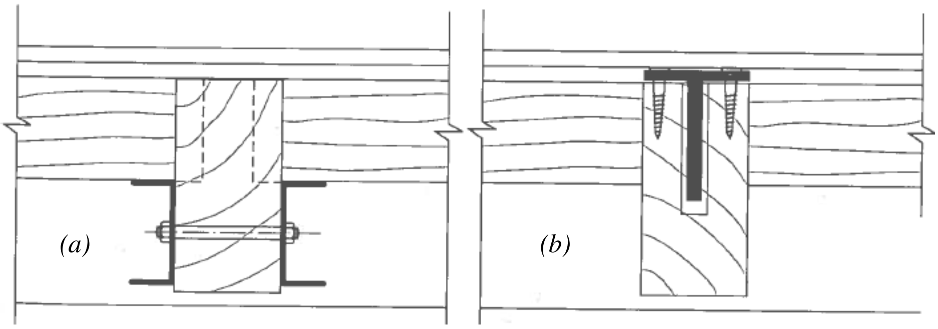


Figure 3.10 Strengthening of principle beams in floor structures (Ross, 2002)

To generate more effective buildings, additional insulation may be required as well. This does not only save energy, but may also contribute to better moisture conditions. To install additional insulation in the walls can often be problematic, unless a total renovation of the walls is to be done. The easiest and most effective place to install new insulation is in the roof. There are several different ways to do this, depending on if the rafters are asked to be visible, if there is a ceiling below the trusses or depending on how easy a dismantling of the roof covering would be.

Sometimes the period of fire resistance have to be upgraded. A common example is when a framed building is taken into public use. The timber may either be protected by a fire board or it is also possible to complement a floor structure with steel construction to extend the period of fire resistance.

4 Methodology and Evaluation of Performed Interviews

4.1 Background and aim

To receive a more comprehensive view over the on–site assessment in Sweden, a survey was performed. The aim was to find out if more research was needed about the on-site assessment according to the survey participants, and if so, what area that would be of most interest. The survey was performed through interviews, which were carried out over telephone and the answers to the questions were directly written down and complemented when necessary directly after the interviews. A large quantity of information was also given beside asked questions and some of it can be found in the answers to the questions in Section 4.2.

In total, 30 people from the industry where interviewed. A vast majority of them worked in the western part of Sweden, except one in the north, two in the east and two in the south. However, one of the participants seemed a little bit uncomfortable with the questions asked. Structural engineers, specialised consultants, antiquarian, owners of listed buildings and renovation companies were among the participants. The majority of people interviewed were not able to answer all questions, as they were specialised more in one particular area. However, some of them had a more comprehensive view and were able to answer all questions. Examples of questions asked were like; what governs whether older timber structures are repaired or demolished and what methods are used to determine the capacity of the structure. To see all questions, see Appendix A.

4.2 Evaluation process and results

After all answers to questions were analysed, some important information was concluded, see Section 4.2.1-4.2.8. As mentioned, this section also includes information obtained beside asked questions. The number of answers on each question varied, and the results from question 1 and 2, are presented in Table 4.1 and 4.2 as an example.

Table 4.1 What governs whether older timber structures are repaired or demolished?

Causes to repair:	*Number*
Listed building	5
More economical	1
Causes to demolish:	
The land may be used for a purpose with higher rate of return	5

The building may be exposed to decay fungus	1
Extensive construction error	1

Table 4.2 When timber structures are repaired, are individual members repaired or replaced and what cause the kind of remedial work carried out?

Repaired:	*Number*
More economical	6
Listed building	5
Less intervention on surrounding material and impact on living environment	2
Replaced:	
High costs related to craftsmanship and social fees in Sweden	4
When most part of beams seem deteriorated	5
Difficulty with assessing the timber quality	1

4.2.1 Governing factors whether existing buildings are repaired or demolished

There are many buildings classified as listed buildings. Among listed buildings are notable buildings, which mean that the building is not allowed to be demolished and any remedial work shall be carried out with supervision of antiquarian. Beside notable buildings, there are also other kinds of listed buildings. A building may also be listed with regard to the local plan for example. The framework is then often listed as well due to restrictions in the constructional plan. In the Västra Götaland region there can be found 250-300 notable buildings. This includes churches built before the year 1940, as according to law, automatically are classified as notable buildings.

Use of land which results in higher rate of return is a common reason for demolition. As a result, the demolition is not caused by the condition of the building, but may be demolished due to a new type of activity. If it is possible to use existing buildings it is usually more economic to repair than to demolish. If the building is not listed, the whole responsibility is in Sweden laid upon the owner, in contrast to Norway for example, where all buildings older than 1527 automatically are listed.

The probability that demolition is considered due to problems with renovation will be higher if decay fungus is founded. The drawback with decay fungi is its ability to reach water several metres away from the damaged place and may therefore sustain even in dry parts of the building.

Major construction errors may result in demolition. Measures are often costly and may also result in follow-up costs during residual lifetime. The large quantity of foreign manpower which is hired in the construction sector is nowadays a contributory factor to major construction errors in Sweden, according to some of the participants in the interviews. The manpower is often skilled, but is not always aware of the Swedish standard and qualified leadership able to mediate this is often missed.

4.2.2 Replacement of damaged members

It is often more economic to repair a member than to replace it. However, replacement of members is often the alternative chosen if the craftsman's knowledge about repair is limited. This alternative also results in being on the safe side considering the strength requirement and possible uncertainty about the extent of rot. However, a problem occurs when the customer, or antiquarian, when such is involved, has interest in preserve as much as possible of existing structure.

Some members in the structure can be more difficult to assess, which may be a reason for replacement. A structural member often hard to assess is the sill on log houses. It is placed close to ground, often supported on stone and will therefore easily be exposed to high moisture content, which result in rot.

In case of listed building, the antiquarian authorities will be involved in the decision process concerning remedial work. Those normally follow the so called Precautionary Principle, which means, as much as possible of existing structure is preserved. This often results in a dialog between antiquarian and designer, or between antiquarian and the carpenter, whether it is justified to preserve the framework considering structural condition and cost. The responsibility of the designer is a durable framework and this has to be considered.

A problem related to the replacement of a structural member as a unit, is the intervention it causes on the adjacent material when, for example, a floor has to be demolished. This may be valuable material which preferably would be preserved. In this case reparation is to be preferred due to less intervention on surrounding material.

To replace large members, as a complete beam for example, may also result in huge impact on the living environment. It is always the aim to cause as little impact on this as possible and this is an additional reason to choose to repair.

In case of complicated structures it can be almost impossible to replace a complete member. To replace a complete member would result in advanced bracing of remaining structure and in cases as for example church towers this is near to impossible, according to an experienced craftsman.

Before choosing repair, the strength of possible part which is to be repaired also has to be considered. Sometimes there can be difficult to reach required strength, which may instead result in replacement. For example this may happen when there is a damage part in the middle of the beam, where maximum span moment appears, or which is more common; the beam is damaged over the support where the maximum shear force is present.

It is not that unusual, according to some interviewed people, that there are clients who have lack of knowledge or interest in preservation of existing structure. This is a reason which may result in replacement of complete members, instead of repair. This is often also connected to carpenters who believe it is a more economic alternative to replace a member.

4.2.3 Cost-effective ways to repair timber structures

A common view is that there are cost-effective ways to repair timber structures. However, it seems like mostly traditional methods are used and not a large number of innovative repair methods, which are to be found in other countries. Some usual repair methods are the following:

- Strengthening of beam by attach boards at the damaged part
- Strengthening of rafter by fasten it to the walls with bolts
- Sealing of the moisture source causing the damage, as for example a leaking roof
- Repair of visible structure by using halved joint, see Figure 4.1 and Section 3.2.2
- Strengthening of walls by using ironwork

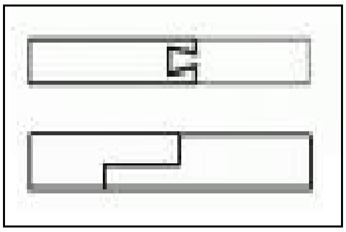


Figure 4.1 Halved joints

In other countries, as for example England, an innovative method to strengthen beams has been developed. First the decayed material is taken away and, if it is a valuable beam, it can be carved out. Thereafter steel rods are fasted in existing beam by filling the empty space in the beam with resin and thereafter the steel rods are fastened in the new timber into drilled holes, see Figure 4.2. However, in Sweden there exist scepticism, according to the survey, considering the mix of different material like timber and steel and therefore one choose to repair timber with timber. But a limitation with these methods, is that they cannot be used everywhere. A halved joint for example, which is a common repair method, cannot always be used in the middle of the beam at maximum moment. This may result in replacement of a larger part of the beam and is not optimal in a preservation point of view considering historic structures.

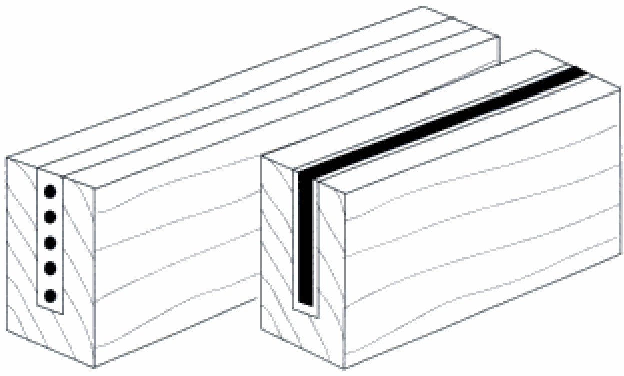


Figure 4.2 Repair by use of steel rods and epoxy resin (Ross, 2002)

4.2.4 Parts most frequently repaired in the structure

Ground plates, as the sills, are placed close to ground and as a result they often decay. It may be caused due to that the building was built too close to the ground from the beginning, or sometimes it happens because the ground level is rising approximately 10cm/100 years, according to a craftsman specialized in antique craftsmanship. To a middle age building this rise will be of great significance for the moisture conditions in the sills.

Sills situated towards the south are the most exposed members. Below the panel at the outer walls, a board drains water coming down the walls and operates as a shelter for the sills, see Figure 4.3. Unfortunately, those boards sometimes are to short, which result in water blowing into the sills.

Figure 4.3 Board draining water coming down the wall (http://hvilaro.blogspot.com/2008/07/byte-av-syllstockar.html, 2009)

It is common with damage in suspended foundations. In those cases it is often the bottom floor structure which is damaged by rot.

Insect attack occurs mostly close to ground. Insects that are harmful and cause deterioration of the strength of the structure are wood borers, which eat the earlier wood. Wood borers like timber with high moisture content and that is why they mainly can be founded close to ground. The insect which mainly attack at a higher level in the building, as for example in the roof truss, only attack at the surface and is not as dangerous for the strength of the structure.

Beams near support, in particular near outer walls, may easily decay if design with respect to durability was poor. Presence of both limestone and moisture are excellent condition for fungus and the timber will decay as a result of this condition.

In newer buildings one has usually learnt how to protect the building from damage by damp. What are most exposed in newer buildings are the outer walls.

Roof leakages are usually formed on buildings equipped with a gutter on the roof, which can be found mostly on churches with slate roof or a roof with steel plate covering. The leakages originate from leaves and other organic materials assembled in the gutters. As a result, the roof may be prevented from drainage, and after some time the water may find its way to the roof truss.

Low ventilation is a favourable condition for damp and a base for accumulation. Therefore problems related to damp will be more serious in a sealed building. If the building is ventilated, like for example in cowsheds, problems related to damp will be rare due to the vapour transport in the air.

A common construction technique used back in time was the construction of joints on the roof trusses outside the roof panel. This is a co-occurrence place where rot is detected.

Those were the parts most frequently repaired according to the survey. For further reading about typical mechanical failures in the timber structural system, see Tampone (2007).

4.2.5 Methods used today to determine the capacity of the structure

Visual inspection is important and probably the most common type of inspection of the structure. Much can be discovered in the structure by visual inspection only, as for example rot, which can be discovered due to discolouration. It can also be seen whether any settlements have taken place, which can give a hint of what could possibly be damaged. Furthermore it is possible to by experience understand how the forces in the structure act.

If the member is attacked by insects, the insect species can be determined by measuring the diameter of the holes. By knowing what kind of insect that have attacked the timber one is also able to determine the severity of the damage.

The knife is a common tool used to detect rot in timber. It is inserted in the material to determine if there is rot or not. If it is possible to insert it, it is probably decayed (unless it is a crack) and if it is not possible to insert it, it is probably sound. It is also possible to cut off a piece of the material in order to detect if there is any rot in the outer parts of the timber. However, access to the complete member may be limited, which is a limitation with the method.

Another method used is to strike the member with a hammer, also called sounding, see Section 2.6.1. The following sound will then differ, depending if the member is decayed or sound. For example, this can be used to determine if house fungus has eaten the timber from the inside. However, the method demands experience and give only an approximate estimation of the condition.

To detect whether a joint is left with a dowel or not, it is possible to use a hacksaw blade. To check rot in joints, it is possible to use a special drill, also used by power producing companies when testing their posts. Although, some thinks it is tough to make a good estimation of the material quality and this results in some cases in guesses.

Trial drilling is another method used. In this method, the structural member is inspected by several outspread trial drills. Rot is then discovered by sense the resistance during drilling and by observe the colour of the drilling core coming out. This evaluation may operate as an indication of the actual strength in the member. As all knots in the member is not included in the analysis of the strength, a lower strength class than obtained result is often used. But this may also result in being very much on the safe side, resulting in replacement of the member, when in fact it would not have been necessary. Difficulty to obtain a comprehensive understanding of the rot and the extent of it is another limitation with this method. The drilled holes also contribute to some decrease in strength and are possible entrances for moisture further on, which may result in rot if it did not exist before.

Experience of timber structures is of importance during inspection. Large-scale construction errors may for example be discovered by an experienced inspector. A house, belonging to a farm built at the end of the 19th century, is possible to know that it would not suddenly collapse.

Some of the interviewed people are convinced that there is lack of knowledge related to structural calculations of older structures. There is strong believed that the quality of the timber, in terms of mechanical properties, used in the past was much higher compared to the quality of the timber used today. This would result in a structure which always sustain more load in reality than it does according to calculations. Others predict the performance capacity with the means of a load test, described in Section 2.3.2. In the load test deflections are measured and verified to not exceed acceptable values in the serviceability limit state. It is not possible to combine the load test with calculations in the ultimate limit state, as it is not possible to calculate the ultimate capacity of an existing timber structure as it would involve too many assumptions. Deflection is the only factor able to measure, which is directly related to the residual resistance of timber structures.

4.2.6 Market for restoration of older timber structure

Clearly a market for restoration of older timber structures exists today according to the survey. Signs have also pointed toward a growth during the last decades, according to Ulf Larsson, an antiquarian interviewed, see Larsson (2009). There is a possibility of a continuing growing market in the future, thanks to that ecological building currently is popular (renovation more ecological compared to demolish and build new) and renovation an alternative to save resources. However, the entrepreneur's attitude for the development is also vital.

4.2.7 Remedial work in listed buildings

The company chosen to do the remedial work in a building is chosen by purchasing. However, an antiquarian, when such is involved, usually suggests craftsman very skilled in antique repair methods. Craftsmen educated in antique repair methods are for example educated at the school called Dacapo, situated in Mariestad.

Recommendations on how to perform remedial work mostly consist of requirements given by the client. The designer or architect involved has the responsibility to make sure these requirements are followed. If antiquarian is involved, a discussion with the designer or craftsman what measures that should be taken and how and which method that should be used etc. are common. General recommendation is that beams built in the 20th century and later more easily is replaced compared to similar beams built before.

4.2.8 Potential market for digital radiography

Corroded nails and ironwork in load-bearing timber structures are unusual phenomena, according to the survey. What happens when a member is moisturized is that the wood decay before any metal corrodes. Therefore, the primary use of radiography would be to assess the condition of timber in members and connections. Sometimes the rot starts inside the timber and can be hard to detect. The extent is normally not determined until the connection is dismantled. In some cases, it is necessary to dismantle the connection anyway and the extent of rot will then not be a problem. However, in some situations it is desirable to not dismantle the connections, and then equipment capable to assess the condition of the material without dismantling could be useful.

When rot is suspected in the floor structure, test samples are taken in some beams and remaining beams are assumed to be in equal condition. In this case it would be desirable to instead be able to use radiography to inspect the beams. However, a limitation with this technique used for this purpose is normally the inaccessibility to all faces of the beams.

Further on, members may be very inaccessible in a visual inspection. At some places radiography could be beneficial, like braces in the church towers or joggle joints, which are difficult to access by other means.

A difficulty one has as a craftsman regarding decayed buildings is to estimate the cost of the remedial work. The rot do not only exists on the outer layer of the timber, but also at the inner layers, as mentioned. As a result, estimation of the extent of the rot at an early stage in the project may be hard. This may lead to several surprises during work further on and to apply for an extended budget normally takes quite a long time. Radiography has the potential to ease the estimation of the cost a lot.

That reparations in timber structures are performed much on the safe side seems like a common view. Compared to steel and concrete, quite little scientific research has been carried out regarding the strength in damaged timber structures. The result is reparation or replacement of the timber structure, when in reality it has more capacity than assumed. Sometimes a timber beam is replaced by a steel girder or concrete beam, as these are materials one nowadays has more knowledge about. Radiography has the possibility to assist both considering research and as equipment on-site, in order to carry out a more qualified assessment.

As a whole, most of the participants in the interview had the opinion that more modern technologies like digital radiography would be beneficial in the on-site assessment of timber structures. The price of the service will however be of much importance for how the technique will be spread. In some situations no other inspection method than digital radiography is possible in order to assess the condition of the timber and then this technology will be invaluable. In other situations other methods exist as well and then it is more an economic question which inspection method to use.

5 Use of Digital Radiography in Laboratory

5.1 Aim and background

A promising method among the NDT methods used for on-site assessment is the digital radiography. In order to confirm possible benefits of this technique, it was decided to use it in field. But in order to first gain some experience, the equipment was used in the laboratory. According to the performed survey, found in Chapter 4, possible use of radiography would first of all be in assessment of the condition of members. Therefore the capacity of the technique was tested on timber in different conditions, both in laboratory and in field. The equipment used for the analyses consisted of an XR200® x-ray source, manufactured by Golden Engineering, Inc, see Figure 5.1(a), and the Digital Image plate System by Logos Imaging, see (b). The imaging system uses a reusable plate which creates fluorescence if impacted by x-rays. The XR200® uses up to 150 kV and the number of pulses can be chosen from 1-99. The unit is battery driven by a DeWalt® battery, and therefore able to use even in condition with no access to power.

(a) The XR200® x-ray source

(b) The Digital Image plate System

Figure 5.1 The digital radiography equipment

5.2 Material

The materials to be x-rayed, seen in Figure 5.2, originated from pine and has once belonged to a log house, but had now been stored close to a sawmill for several years. They were found thanks to one of the craftsmen interviewed. Material 1 was stored without contact to ground and looked decayed when observed from outside, however, when knocking at it, the sound indicated a sound material. Material 2 was used as a brace to a tarpaulin and was in direct contact with ground. By looking at it, estimating the weight and by investigating the hardness of the material, it could clearly be stated that it was decayed. Material 3, placed under material 1 and 2, is sound gluelam beam and used as a reference to compare with decayed material.

Figure 5.2 Material to be x-rayed

Furthermore, a mortise and tenon joint was investigated, see Figure 5.3, in order to assess the capability of the equipment to separate different components. If feasible, it can be used, for example, to detect if any dowels exist in a joint or not. The joint to be x-rayed, which is also made of pine, has a high density and has been stored in dry conditions for 7 years. As wood ages, it changes some properties. It becomes darker and in equilibrium with the surrounding climate. The lowered moisture content causes wood to be harder.

a) Mounted, from the side *b) Dismounted*

Figure 5.3 Mortice and tenon joint to be x-rayed

5.3 Methodology

As a standard, the distance between the x-ray-generator and the object was set to 1m and the height of the x-ray-generator and the object was put on the same level above the floor. The image plate should, according to the manual, be put as close to the object as possible and was therefore fastened behind the object with contact to the material. The equipment was set up as described in Section 2.6.3 and seen in Figure 2.3. In order to fulfil safety issues it was checked that no one passed close to the operation area during operation, especially not in front of the x-ray-generator. The inspector took shelter behind a wall, with help of a lead from the x-ray-generator also equipped with a start button. After have sent, in all cases, 99 x-ray pulses through the material, the image plates where scanned. A recommendation was to not expose the plates in daylight and therefore the so called Precautionary principle was followed and the plates where taken out from their case in a dark room and after that put into the scanner. Directly after the plate was scanned, it was not possible to see almost anything in the digitally produced images. Therefore some enhancement where necessary before any analyse of the images could be carried out. The tools given in the program, which were included in the equipment, worked in a satisfactory manner in order to obtain understandable results.

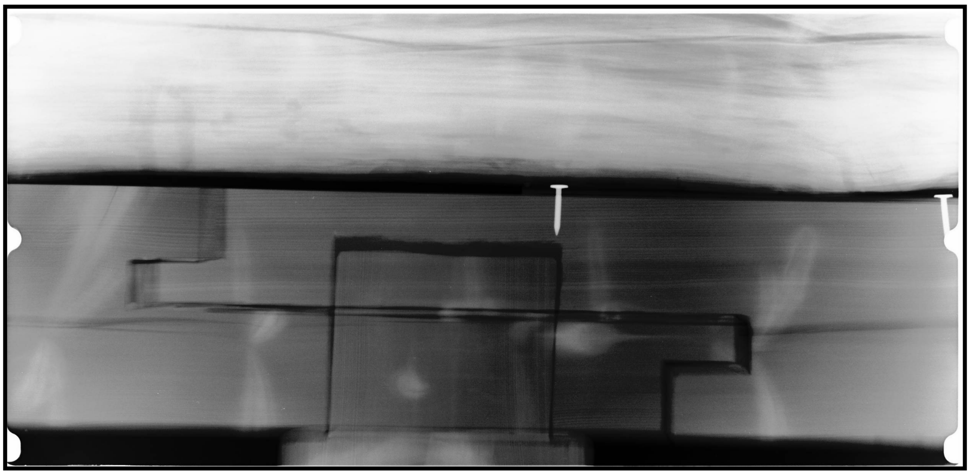
5.4 Results

In the first test carried out, material 2 was laid upon the gluelam beam, see Figure 5.4. In material 2 and between material 2 and the gluelam beam one may glimpse a dowel crossing the log. On each side of the dowel is a nail visible with high contrast to the rest of the log. The difference in density between the nails and the wood is large and therefore the contrast between them as well and the nails can easily be detected. The difference in density between the dowel and the log is not quite as clear and as a result, it is harder to detect the dowel. The image is in normal case brighter with higher density, but in this case, the image has been inverted and is as a result darker with higher density.

In Figure 5.4, a difference can also be observed in the structure between the materials. In the gluelam beam it is possible to glimpse the annual rings. What else can be clearly seen is the finger joint. The darker area at the left side of the gluelam beam is a result of that it is underexposed. In the log, compared to the gluelam beam, it is not possible to distinct the annual rings. Some type of structure can be seen, but it can clearly be seen that the original structure is deteriorated.

Figure 5.4 Radiograph of material 2 lay upon material 3

Material 2 is further more evaluated by comparison with the mortice and tenon joint, see Figure 5.5(b) and corresponding radiograph in Figure 5.5(a). The difference in grain structure can be noted similar to Figure 5.4, but now even more clearly. In the radiograph, the scarf between the mortice and tenon is visible. Some of the lighter spots correspond to knots visible in Figure 5.5(b) and other probably to inner knots not visible in the figure. However, the conclusion may be drawn that knots are clearly visible in radiographs. The two nails are nailed in the middle of the beam, but can be clearly seen. Very little of the grain structure is visible in the log.



a) Radiograph

b) Photo

Figure 5.5 Radiograph and photo of material 2 lay upon the joint

When inspecting other parts of material 2, it is clear that the log is decayed by looking at the grain structure, see Figure 5.6. As in Figure 5.5(a), only some grain structure is visible with a mottled appearance and no annual rings.

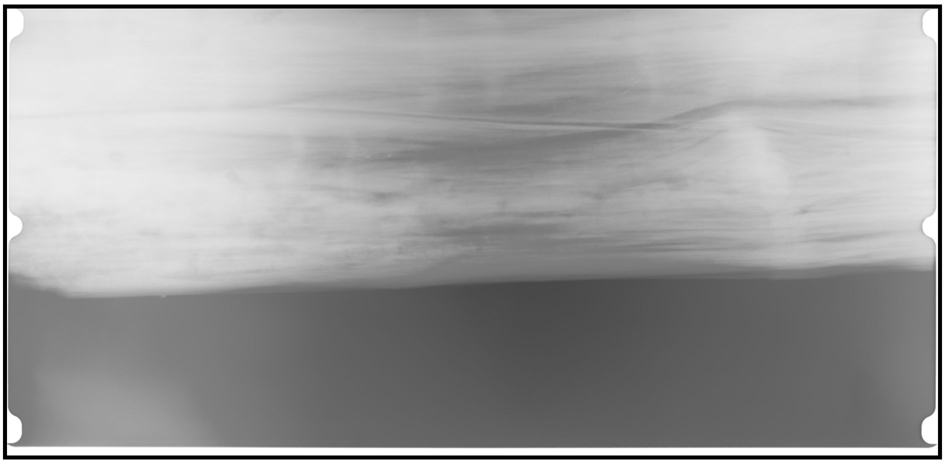
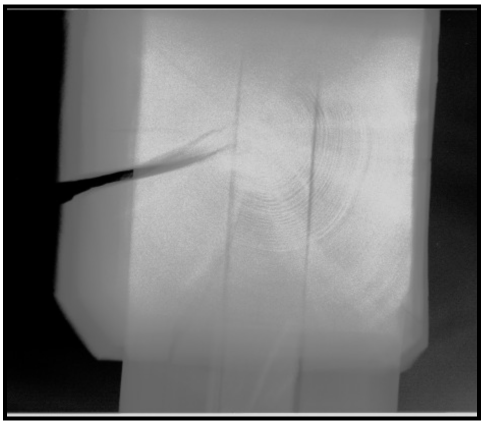


Figure 5.6 Radiograph of material 1

When studying the radiograph of the joint shown in Figure 5.3, it can be stated that distinction between different components in the joint is possible with x-ray equipment, see Figure 5.7. The scarf between the mortice and tenon can be seen in the lower part and looks like inclined splitting. The lock can be seen above the connection and it may be stated from the radiograph that the lock and the member inserted in have different thickness, as the structure of the lock is more transparent. The splitting in the vertical member can be seen as a darker line, and so also the splitting in the horizontal member, even if more unclear. It is possible to distinguish between the horizontal and vertical member where the tenon is inserted in the mortice due to the darker vertical lines, more easily seen above the horizontal member in the lock. In the horizontal member two inner knots are also visible as lighter spots with centre in the middle of the member and then directed toward the edges. Close to the vertical splitting another smaller knot is also visible. As the light from this is directed in the same direction as it is in the knots in the horizontal member, this knot has to be a part of this member as well. In the upper region a smaller knot is visible also but not any special direction of the lighter area and as a result it is not possible to be convinced if it belongs to the lock or the vertical member.

Figure 5.7 Radiograph of the joint (laterally reversed)

In order to evaluate the capability of the x-ray equipment to take images on the depth of a wooden member, an image was taken in line with the horizontal beam in the joint seen in Figure 5.3. In the radiograph in Figure 5.8(a), the mortise behind the horizontal beam can clearly be seen and so also the splitting at the side of the horizontal member. One may also glimpse fissures directed from the centre to the outer layer. The knot visible in the photo, see Figure 5.8(b), is not visible in the radiograph. This indicates that it is too little difference in density relative the depth of the object to be detected. The structure of the annual rings can be seen, which exhibit a sound member.

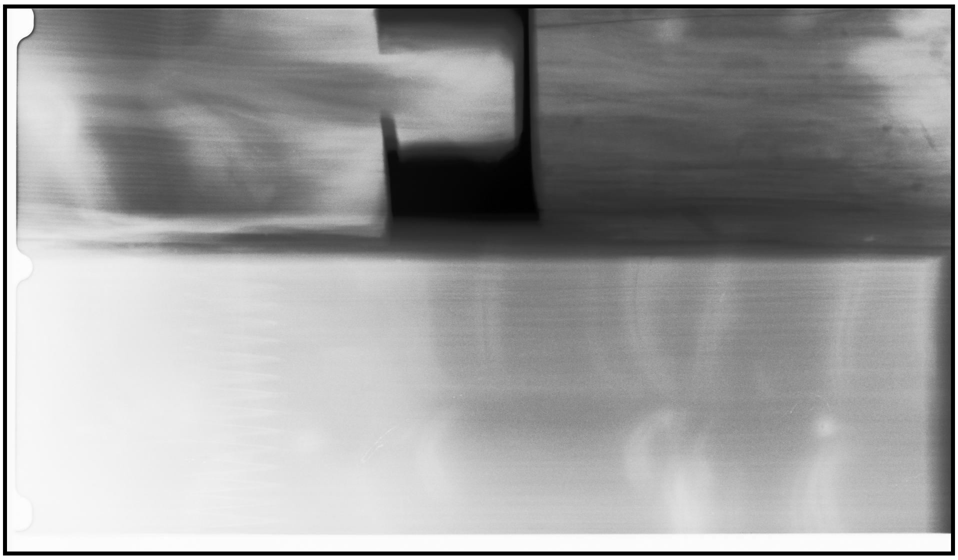


a) Radiograph

b) Photo

Figure 5.8 Radiograph and photo of the depth of the horizontal beam in the joint

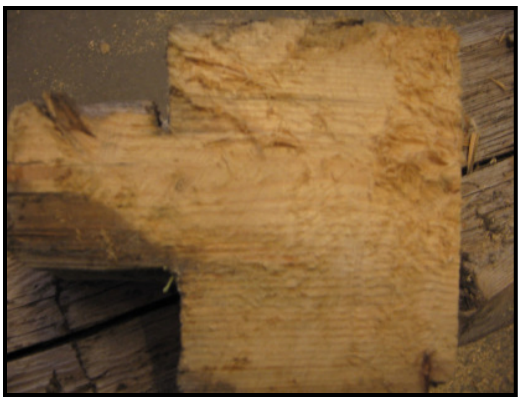
Furthermore, an end from material 1 and 2 respectively was compared, see Figure 5.9. They were laid on the gluelam beam as a support and the structure of this material can be seen exactly as before. According to the radiograph in Figure 5.9(a), the log to the right, material 1, seems to have the same grain structure as the rest of it, which means it is decayed. In the log to the left, i.e. material 2, the annual rings can be seen in most parts. However, in some parts, like in the middle of the beam and in the boundary to the outstanding part, a longer distance between the annual rings may be observed. To understand what this could mean, it was decided to cut up the end of material 2 in order to inspect it, see Figure 5.10.



a) Radiograph

b) Photo

Figure 5.9 Radiograph and photo of material 1, 2 and 3, as define in Figure 5.2



a) Outstanding part split in two

b) The end of material 2 after sawing

Figure 5.10 Inner face of the end of material 2

As can be seen in Figure 5.10, the cross section of the specimen seems sound, except some decay at the upper and lower edges. In the figure it can also be seen that the broader distance between the annual rings is a part of the original structure and does not indicate any rot. This is also verified by a physical examination of the material.

In the next radiograph, material 1 is laid below material 2, see Figure 5.11. When visually observed from outside, material 2 seemed decayed, but with this image the annual rings can clearly be seen which means it is sound. In the middle of the image there is a dark area which exhibits an even more decayed part of material 1. Furthermore, two dowels are seen in material 2, crossing the grain structure, with a nail at the side of one of those.

Figure 5.11 Radiograph of material 1 lay upon material 2

5.5 Conclusion

Through some different examples it has now been showed that digital radiography is able to localize rot, at least in the laboratory. Another feasibility sometimes required is to distinguish between different materials. The tests in laboratory verify the capability of this feasibility.

A test was also carried out in order to make clear what could be detected in the radiograph of a deeper timber member. In this test it could be stated that the grain structure was visible and so also the design of a member behind the deep beam. What could not be seen was a knot placed in the end closest to the x-ray-generator. The explanation would be that the difference in density in relation to the rest of the timber was too small, in relation to the deep of the beam.

6 Use of Digital Radiography in Field

6.1 Aim and background

The radiography was further on used in field and the capability of it tested on a log house in Trollhättan, see Figure 6.1, a city situated 100 km north of Gothenburg. The object was found thanks to one of the craftsmen interviewed. The aim of the project was to ascertain the benefits of digital radiography in the on-site assessment. In this on-site assessment it was the aim to localize decay in the members.

Figure 6.1 Log house inspected with digital radiography

The structure of the house is referred to as the central part, where the entrance and balcony is situated and two wing parts on both sides of the central part. The house had been damaged by damp in both an outer and inner wall. The main cause to the decay was a gutter, placed at the right side of the central part, which once was taken away. As a result, the rain water was led from the roof of the central part, down to the wall at the side of the central part. From there, the water passed on to the outer wall of the wing part, and this is where the panel has been taken away, see Figure 6.1.

6.2 Methodology

The method used in field was the same as the one used in the laboratory, described in Section 5.3. In Figure 6.2(a), it is possible to see an example of how the x-ray generator was set up. The backside of the wall was accessible in this case thanks to the attic, and there the image plate was fasten, see Figure 6.2(b). The geographic placement of the image plates on the wall was noted, in order for the antiquarian after the analysis to know where each image was taken.

a) Setup of x-ray generator *b) Setup of image plate*

Figure 6.2 Setup of the equipment

6.3 Results

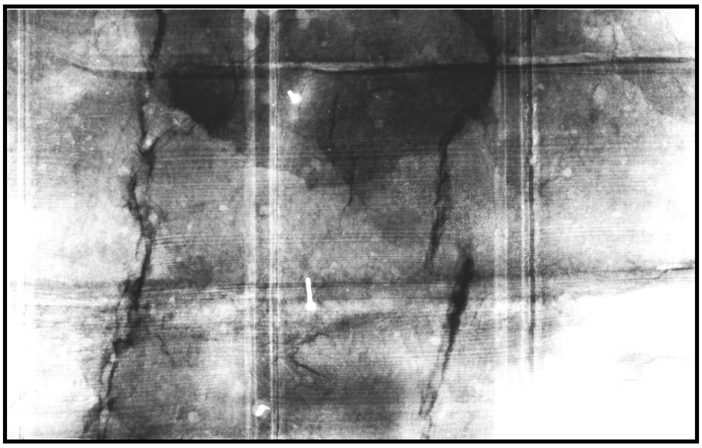
The panels on the outer wall had been dismantled by the craftsmen, in order to inspect the rot. It could then clearly be seen that the logs were decayed in this area. However, the antiquarian involved was confused whether the logs also where decayed closer to the window in the wing part of the house. In order to assess the condition of the logs, radiographs were taken.

The x-ray-generator was placed on the inside and the image plate was placed on the outside between the window and where the panels had been taken away, see Figure 6.3.

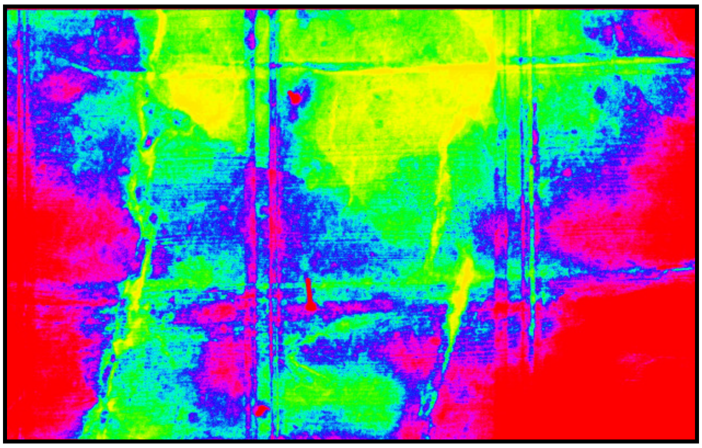
a) Interior wall to be x-rayed *b) Setup of image plate*

Figure 6.3 X-ray of outer wall

In the radiograph, shown in Figure 6.4(a), some vertical fissures can be seen, but also an upper region where the grain structure disappears into a dark area, which is expected to be rot. To extend the analysis, it is also possible to colourize respectively emboss the image, see Figure 6.4(b) and 6.5. In the embossed image it can be seen that the grain structure at some places disappears, which visualize the rot even more.



a) Radiograph



b) Colourized radiograph

Figure 6.4 Radiograph and colourized radiograph of the outer wall

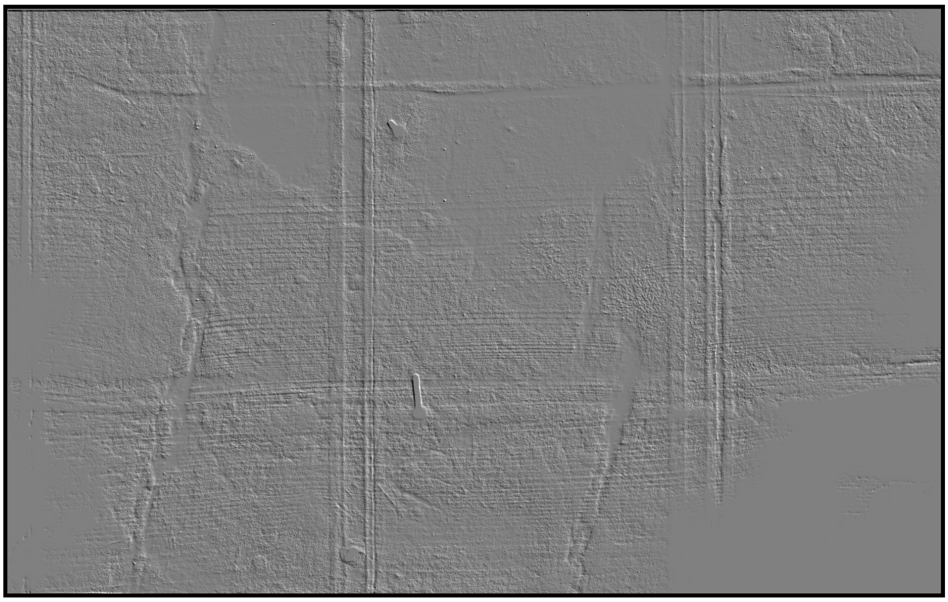
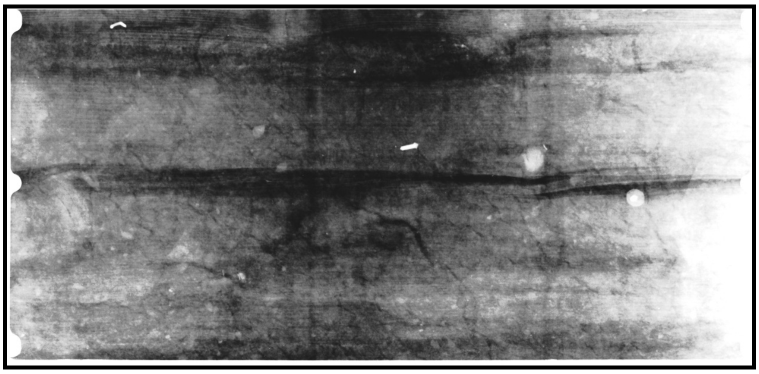


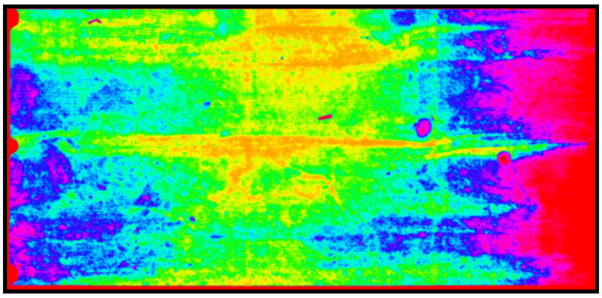
Figure 6.5 Embossed radiograph of the outer wall

After the outer wall had been inspected, the side wall of the central part was inspected. A visualized inspection had been carried out by the craftsmen, which resulted in some rot detected in the wall. However, the analysis of the wall was now asked to be extended. First, a radiograph was taken were rot were known to be, see Figure 6.6(a), which also were verified by the inspector.

In the image, and perhaps more easier in the enhanced images in Figure 6.6(b) and 6.7, the rot can be seen both in the middle, as a strip and in the middle at the upper part as a more concentrated spot. In the colourized image this is where the colour is orange first of all. The smaller lighter spots at some places in the radiograph, indicate smaller nails, see also Figure 6.7 where the contour of those are clearer. Similar images were obtained from other parts of the wall as well. It was not possible to take any radiograph on the upper face of the members, in order to determine whether the rot were continuous through the width of the logs or not.



a) Radiograph



b) Colourized radiograph

Figure 6.6 Radiograph and colourized radiograph of wall on the central part of the house

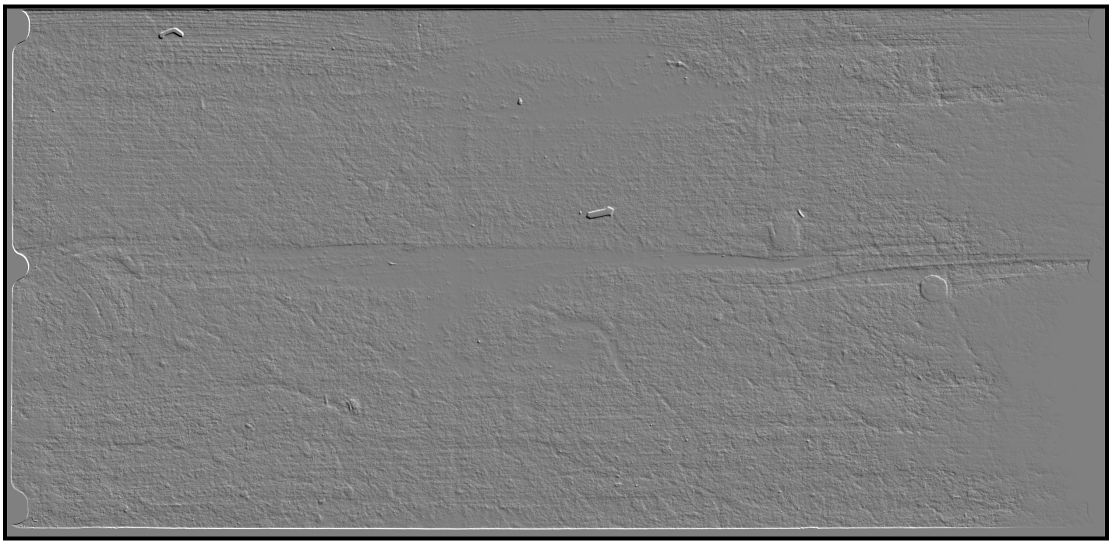


Figure 6.7 Embossed radiograph of wall on the central part

When it could be assured that the radiography detected the known rot, more radiographs were taken on the wall. First of all direct below the first radiograph, in the logs situated below the first one where it was not known whether rot existed or not. In the radiographs taken, more rot could be detected in a similar way.

According to Anthony (2005), the features exhibit decay in radiographs may be summarized as:

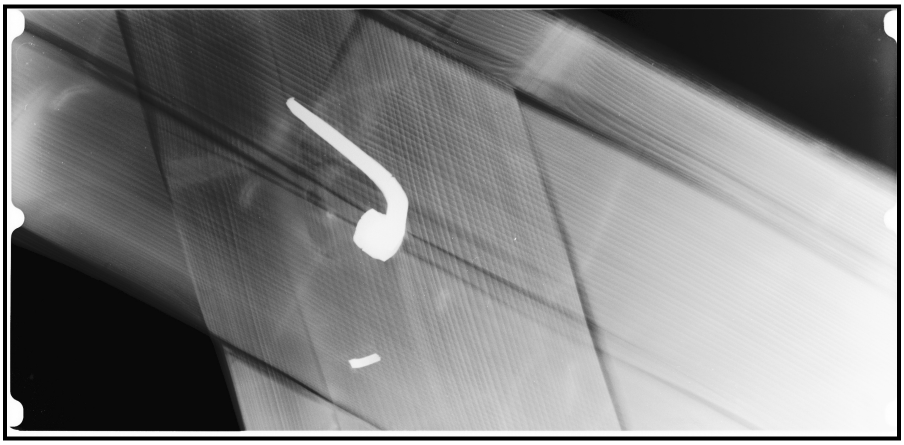
- *Darker colour(s) due to reduced cross section*

- *A transition from non-decayed wood with intact grain pattern visible on the radiograph to the lack of a visible grain pattern in the decayed area*

- *A generally mottled appearance in the darker decayed area*

In addition to the walls, a joint in the roof structure was inspected, see Figure 6.8(a), and was expected to be sound. This was also what the radiographs exhibited; see Figures 6.8(b) and 6.9(b). In the images it is also possible to see how the joint is mounted. In the area where the members are joined, the annual rings in two directions can be seen in Figure 6.8(b), which verify that there really are two members joined to each other. In the rafter, a line with the same width as the nails is visualized in the middle of the member. This indicates splitting, probably caused by stresses from the nailed connection. Where the more or less vertical post is fasted to the top chord, a slot can be seen, see Figure 6.9(b). It can be seen that the nail in this space has a reduced cross section, which mean it has been corroded. The bowed shape of the nail in Figure 6.8(b) is a result of a too long nail struck against the timber. In Figure 6.9(c) a drawing visualize the design of the joint from the front.

a) Photo



b) Radiograph

Figure 6.8 Radiograph and photo from the side of the joint inspected

a) Photo *b) Radiograph* *c) Drawing*

Figure 6.9 Photo, radiograph and a drawing of the joint from the front

6.4 Conclusion

As have been showed in some examples in this chapter digital radiography has proved capability to localize rot in members on-site. The limitation with the technique was found to be that it was not possible to access all faces of the members and as a result it could not be stated if rot were continuous through the members or not.

Thus, as a final conclusion from the use of digital radiography in field, it can also be stated that the technology has the capability to assess the condition of metal fasteners, even if this was not the aim of the analysis. When knowing the geometry of the setup and with help of a reference on the image plate it is also possible to measure corroded area in order to ascertain the capacity of metal fasteners (Kasal et al., 2008). For more analyses of metal fasteners, see Anthony (2003) and Anthony (2005).

7 Tests on the Damaged Part of a Truss

7.1 Aim and background

In order to better understand the capacity of a damaged part of a truss, a load test was carried out. The test was carried out on a joint made as two rafter pieces of sound timer of strength class 18 and the tie piece representing the horizontal part which was decayed and placed in between the two rafters, see Figure 7.5. As timber members often are estimated much on the safe side and as a result replaced, the test aimed to find out whether the strength of this joint would be much reduced due to a decayed member. The joint was a result of the design of a common roof truss, see Appendix B, and self-made by the author. In the analyse it was also the aim to use digital radiography, in order to analyse the joint and material properties. The timber were obtained from a sawmill in Kinna, specialised in taking care of decayed timber.

7.2 Methodology

The load-deformation test was carried out in the laboratory of the Division of Structural Engineering. The joint was placed according to Figure 7.2(a) with the load placed exactly above the support, also seen in Figure 7.1. Three sensors measuring the deflection called LVDT were used and were placed in the same point as the load, above the rotational centre and above the end of the truss, see Figure 7.1 and 7.2(b). During the test, the correlation between applied load and deflection could be observed on a graph, which corresponded to Figure 7.6. The joint was initially loaded with 0.016 mm/sec, but as the capacity of the joint was more than expected and in order to be able to follow the procedure on the graph, the speed was changed to 0.018 mm/sec after 67 min, 0.36 mm/sec after 78 min and to 1.4 mm after 91 min. Short after the last change, the test has been stopped. The results were digitally saved in a computer and thereafter analysed.

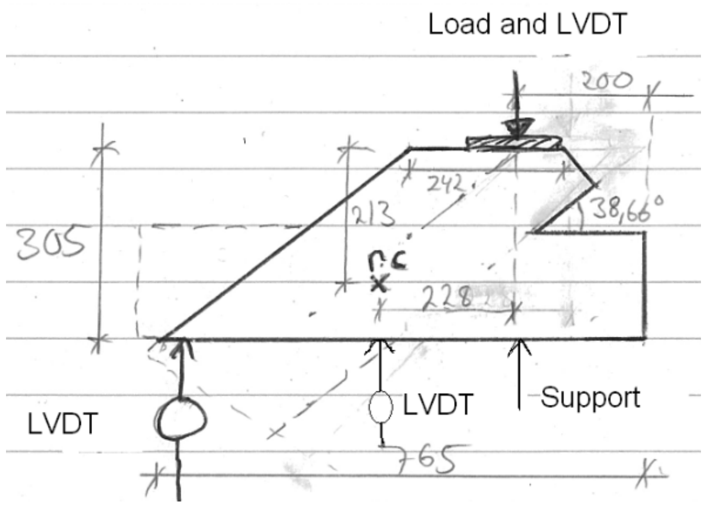
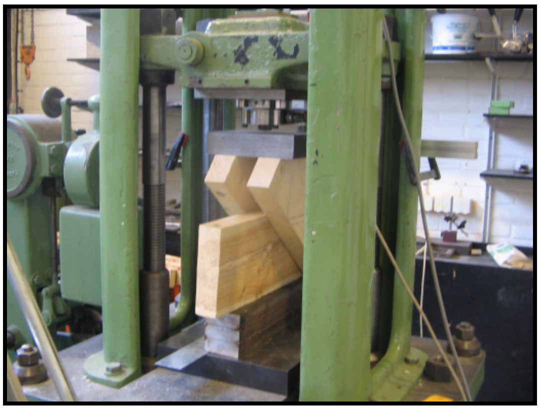


Figure 7.1 Model and planning of test setup



a) Test setup

b) Setup of LVDT above rotational centre and the end of the truss

Figure 7.2 Specimen and test setup

7.3 Truss design

The condition of the designed roof truss where set as:

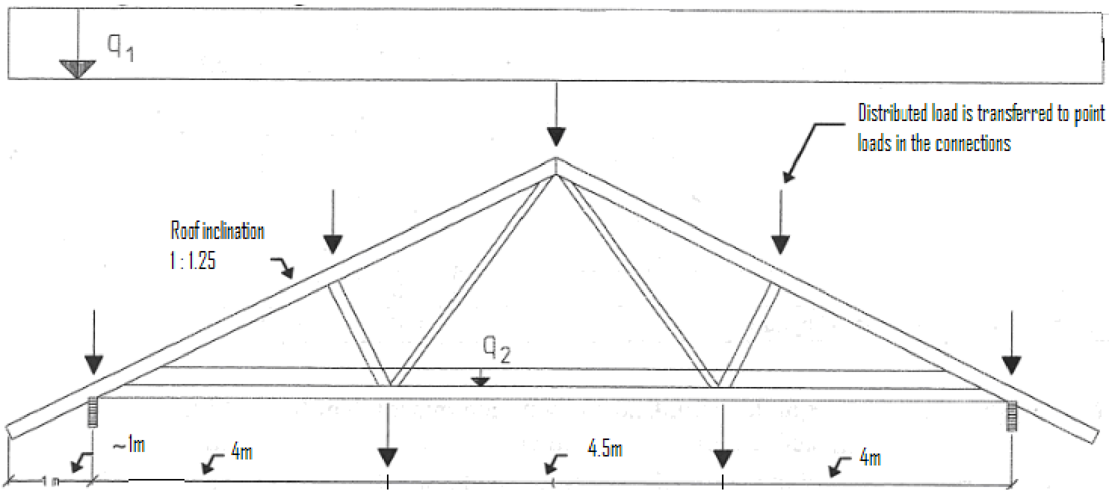


Figure 7.3 Design of roof truss

Bars in the roof truss were assumed to work as pin connected, see calculations in Appendix B. Calculations were performed according to Eurocodes and especially according to Eurocode 5. The building was assumed to be placed in Gothenburg.

Load combination in ULS:

$q = G*1.35+Q*1.5$

G = Selfweight

Q = Imposed load (Snow load)

This resulted in:

$q_1 = 2.58kN/m$

$q_2 = 0.58kN/m$

However, as all partial coefficients were used according to Eurocode 5 and as the roof truss was designed for long term load instead of instantaneous load, as the case is when testing a joint, the joint was overdesigned for testing. With those conditions, the design of the foot of the roof truss turned out to be according to Figure 7.4.

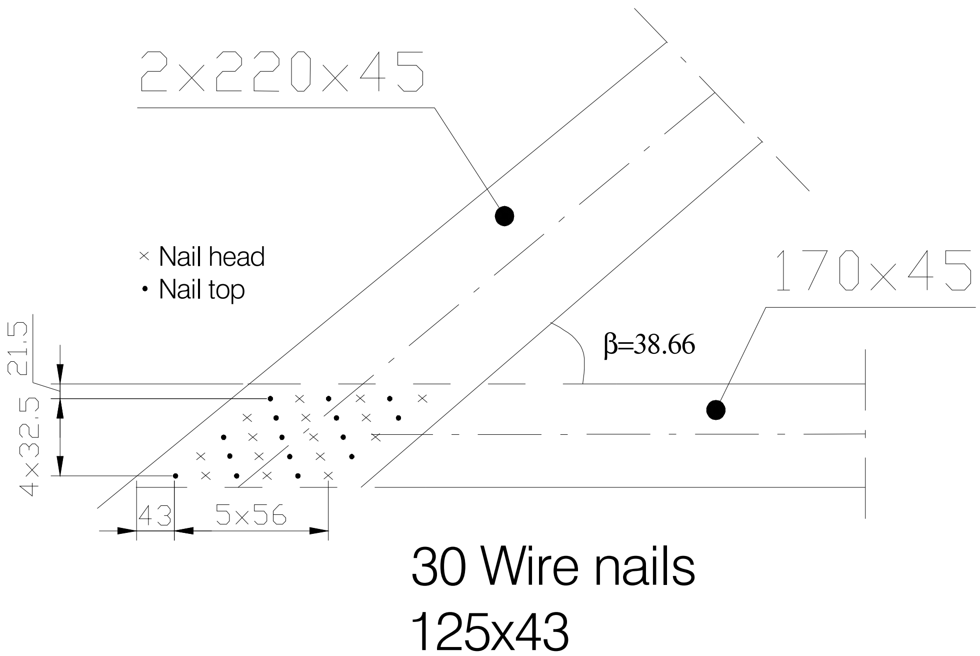


Figure 7.4 Drawing of the foot of the roof truss in mm

The timber joint was thereafter constructed by the author in the laboratory of the Division Structural Engineering. One may notice the difference in colour between the tie beam and the rafter, where the tie beam is darker, see Figure 7.5. This indicates the fact that the tie beam is decayed and the rafters are sound.

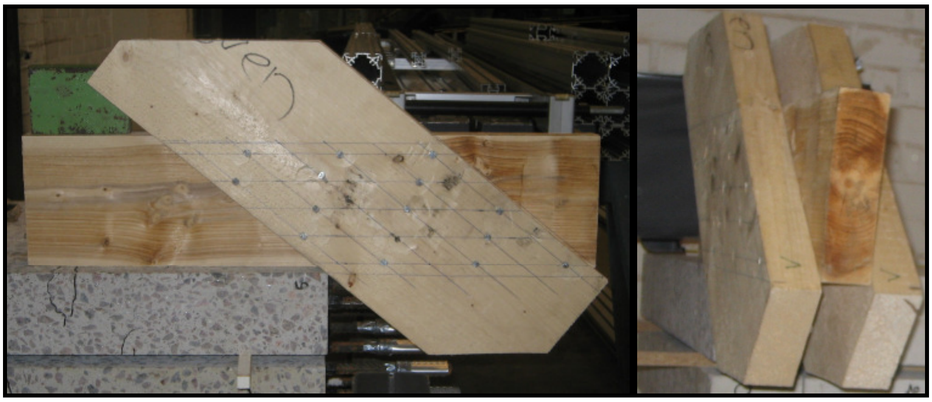


Figure 7.5 Joint from roof truss inspected

7.4 Results

In the load-displacement curve obtained from the test, see Figure 7.6, the result from the sensors, placed at three different places on the joint visualize displacement as a result of applied load. As input, maximum load was set to 53kN, as the calculated maximum load was not more than 9.6kN, see Appendix C. However, the joint sustained this entire load and the test had to be stopped at 53kN. In the diagram one may see that the curves turn at 53kN and then stop. Corresponding maximum deflection was 19mm. As the LVDTs started to produce deflections before the load cell started to load the joint, it resulted in different start values on the displacement axis.

The most characteristic values for the test are the ones from the sensor situated where the load was applied. The curve has two main inclinations and may therefore be called bi-linear. The two parts of the curve are near to linear with a correlation value (R) of 0.98 on the first part and 0.99 on the second part. One may say that correlation values over 0.89 mean very good correlation. The first inclination, which goes to approximately 23kN, corresponds to elastic response according to Johansens equations. In this part, the outer nails probably transfer the rotational moment themselves. The second inclination is established at approximately 27kN. In this phase all nails in the nail connection probably have been load-bearing, which result in bearing stress from all fasteners. Even if rupture was not achieved in the test, the rupture can be assumed to be ductile, compared to timber alone which has a brittle rupture. The reason is that many nails are used to fasten the joint, Blass H.J et al. (1995).

The result from the sensor under rotational centre exhibits displacement opposite the one placed where the load was applied. This phenomenon exhibits a joint which works more as fixed than pin-connected. Even if the end of the joint in reality is not fixed, this behaviour is related to that a very long support is used, compared to the distance between rotational centre and applied load.

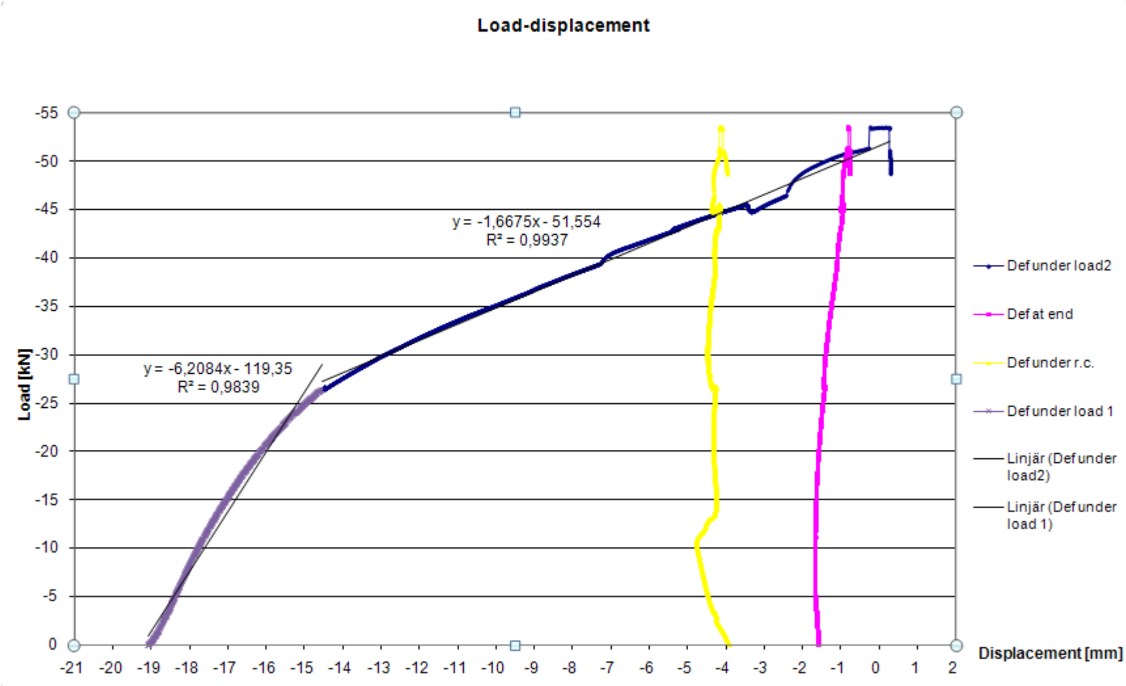


Figure 7.6 Load-displacement curves at three points on the joint

According to the results, the capacity of the joint was much higher than expected. The conclusion is that the geometry of the joint; two rafters with a decayed member in between and fastened with nails through all tree materials, results in a decayed member which does not reduce the strength of the joint. The lower density will therefore not be of importance to the structure.

7.4.1 Comparison between test values and calculations

An approximate moment capacity of the nail group was calculated according to Equation 7.1, a formula presented in the Australian Standard, Timber Structures Code and also cited in *"Connections for timber-framed structures"*, Engström (1997):

$$M_n = Q \cdot r_{\max} \cdot \sum_{i=1}^{n} \left(\frac{r_i}{r_{\max}} \right)^{3/2} \qquad \text{Equation 7.1}$$

where M_n = *permissible moment capacity of the nail group*

Q = *permissible load capacity of a single fastener*

r_i = *distance of the i:th nail to the centre of the nail group*

r_{max} = *the maximum value of* r_i

This resulted in $M_n = 2193\ Nm$, which corresponds to the load $F_n = 9618\ kN \sim 9.6\ kN$ (see Appendix C for all calculations). According to Engström, "permissible" consider when some nails have started to yield. As a result this calculated permissible load is comparable to approximately F = 27 kN, where yielding starts to occur in the nail group. However, the joint may carry at least 26 kN further after the nails have start to yield and probably more. This result shows that the formula probably is too conservative.

In order to model the joint, assumptions have to be made whether the joint should be modelled as rigid, simply supported or semi-rigid. If the angel α between applied moment and Δθ is close to 90°, the joint should be modelled as rigid. If α is close to 0° it should be modelled as simply supported and when α is not close to either 0° or 90°, it is often modelled as semi-rigid. Equation 7.2 is used to calculate α:

$$\alpha = \arctan \frac{M}{\theta} \qquad \text{Equation 7.2}$$

For the first part of the curve up to approximately 6 kNm in Figure , which exhibit an elastic behaviour this gives α = 89.99°. As a result, the joint may be modelled as rigid in the elastic region.

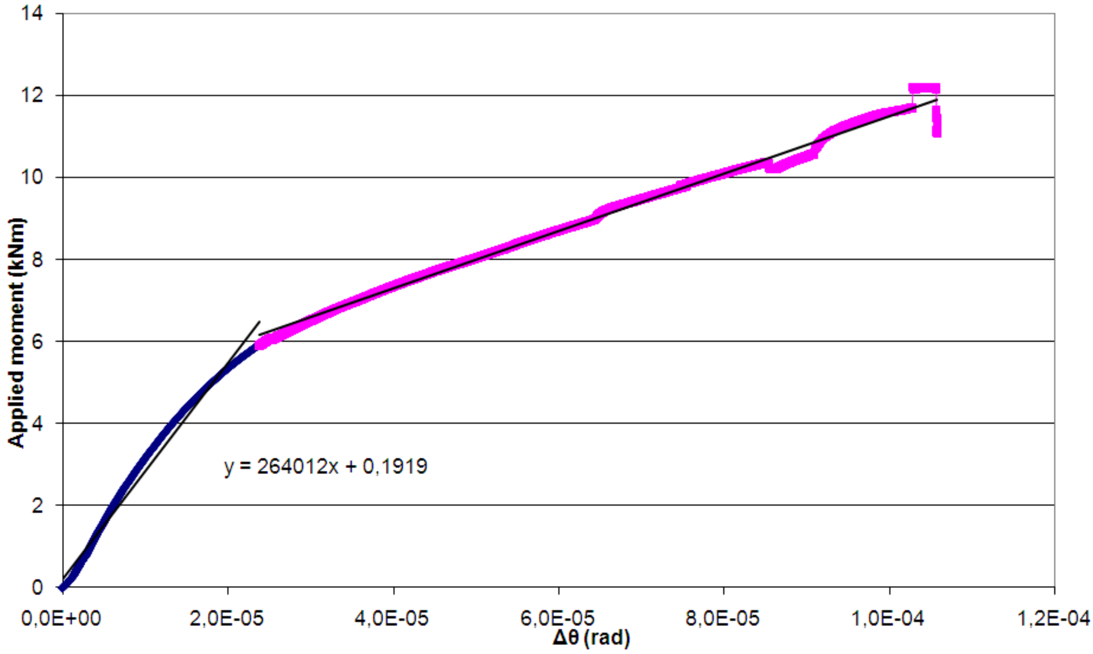


Figure 7.7 Moment-Δθ curve from the sensor placed at loading point

The rotational stiffness, $k_s = M/\theta$, is the inclination of the elastic part of the moment-$\Delta\theta$ curve in Figure 7.7, which according to the equation in the diagram corresponds to:

$k = 264012$ *kNm/rad.*

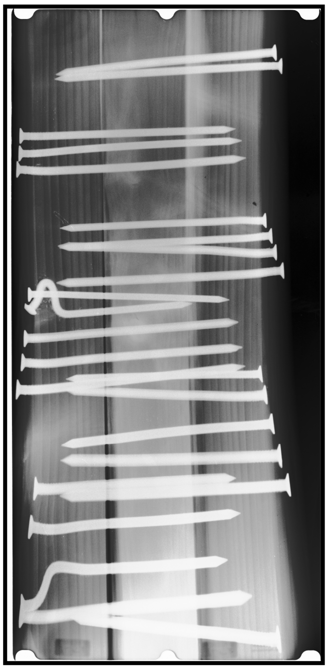
7.4.2 Detection of failure mode with the means of radiographs

In order to better describe the failure mode of the test, radiographs were taken before and after the test. The joint was x-rayed from five different angels, and one of the setups and corresponding radiographs are showed in Figure 7.8 and 7.9. To see the remaining radiographs, see Appendix D. In this setup, the image plate was bowed, in order to be placed as close to the object as possible. This resulted in a bowed radiograph, see Figure 7.9.

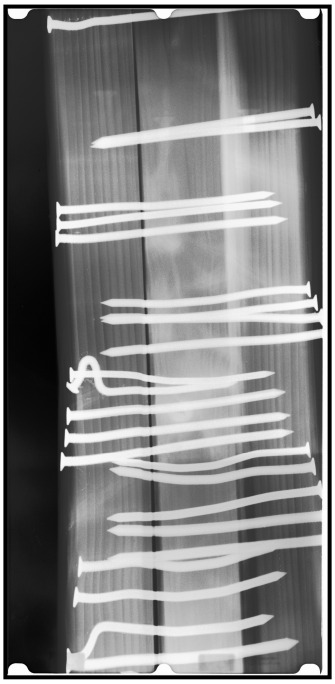
In the radiograph before the test, it can be seen that two of the nails could not be put in correctly, but where bowed close to the nail head. As the images not show exactly the same view, those may operate as references when comparing the radiographs. In (b) it can be seen that many nails have yielded which subsequently was the failure of the test. As the design is double shear, yielding occurred at two points in the nails. Many nails have also changed position. In the radiographs it can be seen that the nails between the end against the outer wall and the rotational centre have carried most of the load as they are most deformed.

a) Setup of joint *b) Fastening of image plate (bowed)*

Figure 7.8 Setup of joint and the image plate



a) Before the test



b) After the test

Figure 7.9 Radiographs of the joint before and after the test

7.5 Conclusion

In order to estimate the impact a deteriorated member has on the resistance of a timber structure in terms of embedding strength, the conclusion can be drawn that another design would have been more appropriate than the one used in this thesis. To better estimate the impact on embedding strength, fewer nails should be used and longer members. However, the conclusion can be drawn that a roof truss with a deteriorated member as a tie beam placed between two sound rafters would sustain the design load without any remedial work to be carried out as long as the decayed piece did not contaminate the sound rafters, i.e. the connection was kept dry.

8 Conclusions

After the state-of-the-art it could be stated that much research had been carried out recently concerning the on-site assessment of timber structures. However, very little was produced in Sweden and very limited guidelines has been published in the Swedish recommendations. Therefore Ms Thesis is carried out and still much more research is needed.

One area needed to be complemented with additional research concerning the on-site assessment of timber structures was the use of digital radiography. As a result, the capability of the technique was tested in field and laboratory and the results have been presented in the report. The conclusion can be drawn that digital radiography is useful in the detection of decay and metal fasteners in timber connections. The extent of decay could possibly be evaluated as well, but may however be more difficult. In order to quantify the extent of decay, the method described by Anthony could be used, see Section 1.3. In addition to the aim of the research carried out, it could also be stated that the technique is able to reflect the condition of metal fasteners and also to quantify the corrosion by measuring the corroded area on the images. Beside results presented in this report, digital radiography has also proven to successively detect fractures in the structure, see Anthony and Meade (2007).

One of the questions raised in the interview was if the remedial work nowadays performed in Sweden is cost-effective. In the report several alternatives on how to perform remedial work in a cost-effective way have been described, see Section 4.2.3 and also Chapter 3, where some of those are described more in detail. According to the survey, a demand exists for remedial work to be carried out in order to repair and upgrade structures, both due to economic questions and due to particular significance of structures.

Furthermore, conclusions can be drawn from the survey that very simple methods in general are used today in the on-site assessment performed by craftsmen, structural engineers, antiquarians etc. A general view among the participants was that more modern technology, like digital radiography, absolutely would be beneficial in the assessment and some suggestions on future use of the technique has also been noted, see Section 4.2.8. One reason for replacement of members instead of repairing them, according to the survey, can sometimes be the limitation of possibility to assess the member with technologies available. With more modern technology this would probably not be necessary and in some cases would be an invaluable tool.

In order to evaluate how the material properties in terms of density and E-modulus are affected by decay in a member another type of design has to be tested than the one tested in this thesis. The distance of the members probably has to be longer and fewer fasteners should be used. However, it may be stated that a decayed member fasted between two sound members with fasteners through all three members will have minimal influence on the strength of the joint.

9 Summary and future research

Accordingly, the conclusion drawn from the survey, the state-of-the-art, the use of digital radiography and the load test carried out on a decayed joint is that digital radiography is useful in the detection of decay and has the capability required.

In order to develop the on-site assessment further, additional research has to be carried out concerning non-destructive methods. Digital radiography and resistance drilling, would preferably be developed in order to better estimate the extent and different stages of the deterioration. The research carried out concerning resistance drilling has proved that deviation in the drilling path tend to exhibit deceptive plots of the condition of the cross section. For more reliable results, more research is needed to be carried out in this area. Digital radiography could be further developed in order to identify and quantify deterioration in different stages, related to different densities.

More tests on deteriorated members and joints also have to be carried out in order to better estimate residual strength and to not underestimate the strength of the structures. This today often results in remedial work carried out like replacement of existing timber structure, which would not been necessary with better assessment possibilities and guidelines as a result of tests and research.

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Appendix A

Questions asked in the interview

1. What governs whether older timber structures are repaired or demolished?

2. Are individual members repaired or replaced when timber structures are repaired and what cause what kind of remedial work that is chosen? *(Is the member for example too damaged, is it difficult to assess the quality or is it simply cheaper?)*

3. Are there cost-effective ways to repair timber structures?

4. Which part of the building does most frequently have to be repaired?
    a. Any typical damages related to a certain epoch?

5. What methods are used in order to determine the capacity of the structure?
    a. Do they have any limitations?
    b. Would they like to develop any method?

6. Is there a market for restoration of older timber structures?
    a. Do you believe the circumstances will change in the future?

7. Are there many listed buildings and is the structure included as listed?
    a. Who is able or allowed to repair those buildings?
    b. Do they have any guidelines for how to repair?

Appendix B

Design of roof truss according to EC

Place: Gothenburg

Snow load

Snow zone: 1 S_k=1kN/m^2

$s=\mu_i*c_e*c_t*s_k$ $c_e=c_t=1$

$s=\mu_i*s_k$

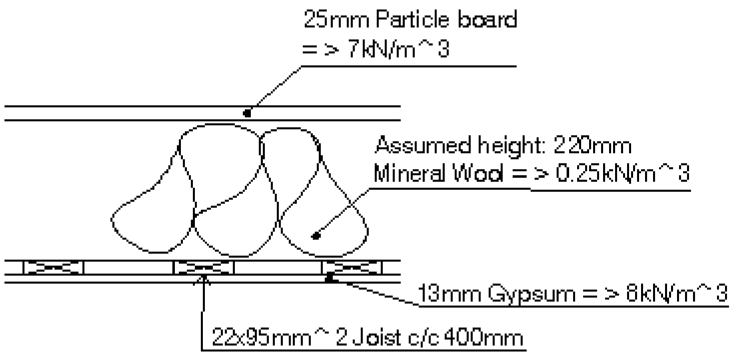
Roof inclination: 1:1.25 angel β=arctan (1/1.25)=38.66°

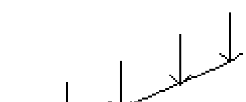
μ=0.8*(60-38.66)/30=0.57

s=0.57*1=0.57kN/m^2

Selfweight

Assumed design of floor structure:



Assumed roof cover: Brick: 

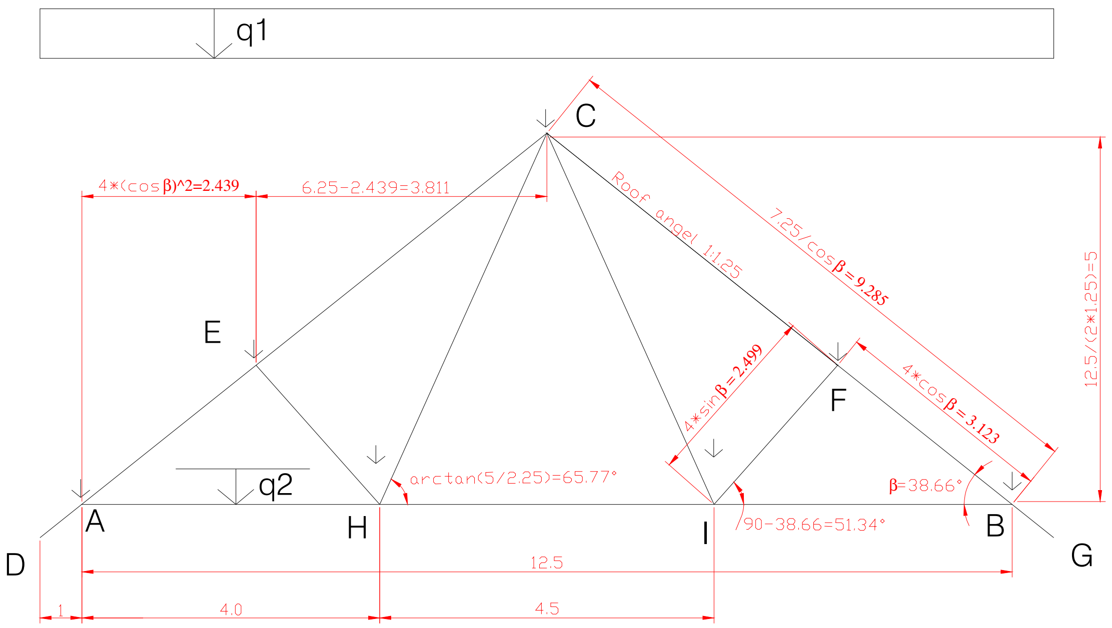
75kg/m^2=0.75kN/m

Horizontal: $0.75\cdot\frac{l}{l\cdot\cos\beta}=\frac{0.75}{\cos 38.66}=0.96kN/m^2$

Selfweight of attic structure:

Assume c18 ρ=320kg/m^3

$$0.025 \cdot 7 + 0.22 \cdot 0.25 + 0.013 \cdot 8 + \frac{0.022 \cdot 0.095}{0.4} \cdot 4.8 = 0.36 kN/m^2$$



[m]

Load in ULS:

q_1=(0.96*1.35+0.57*1.5)*1.2=2.58kN/m

q_2=0.36*1.35*1.2=0.58kN/m

Check moment at span E-C

$$M_{\max} = \frac{q \cdot l \cdot \cos\beta}{\frac{l}{\cos\beta}} \cdot \frac{(\frac{l}{\cos\beta})^2}{8} = \frac{q \cdot l \cdot \cos^2\beta}{l \cdot 8} \cdot \frac{l^2}{\cos^2\beta} = \frac{q \cdot l^2}{8}$$

$$M_{\max} = \frac{q \cdot l^2}{8} = \frac{2.58 \cdot 3.811^2}{8} = 4.68 kNm$$

$$\sigma_{\max} = \frac{M_{\max}}{W} \leq f_{md}$$

$$W \geq \frac{M_{\max}}{f_{md}} = \frac{4.68 \cdot 10^6}{9.69} = 0.48 \cdot 10^6 mm^3$$

Needed height with b=45mm:

$$\frac{h_n^{\ 2} \cdot 45}{6} \geq 0.48 \cdot 10^6 \Rightarrow h_n = 253mm$$

$$b = 2 \cdot 45 \Rightarrow h_n = 179mm \Rightarrow Try : 2 \cdot 45x220$$

Service class 2 (snow main load) => k_{mod}=0.9 γ_m=1.3

Strength class c18:

$$f_{md} = 0.9 \cdot \frac{18}{1.3} = 12.46 MPa$$

$$f_{cd} = 0.9 \cdot \frac{17}{1.3} = 11.77 MPa$$

$$f_{td} = 0.9 \cdot \frac{11}{1.3} = 7.62 MPa$$

$$E_{0.05} = 6GPa$$

Strength class c14:

$$f_{md} = 0.9 \cdot \frac{14}{1.3} = 9.69 MPa$$

$$f_{cd} = 0.9 \cdot \frac{16}{1.3} = 11.08 MPa$$

$$f_{td} = 0.9 \cdot \frac{8}{1.3} = 5.54 MPa$$

Tie beam

$$M_{max} = \frac{0.58 \cdot 4500^2}{8} = 1.468 \cdot 10^6 \, Nmm$$

$$\sigma_{my} = \frac{M_{max}}{W} \leq f_{md}$$

$$W_{need} = \frac{M_{max}}{f_{md}} = \frac{1.468 \cdot 10^6}{9.69} = 151.5 \cdot 10^3 \, mm^3$$

Assume 45x170: A=7650mm^2, W=216.8*10^3 mm^3

Loads on connections

$$P_B = P_A = 2.58 \cdot (1 + \frac{2.439}{2}) + \frac{4}{2} \cdot 0.58 = 6.89kN$$

$$P_F = P_E = 2.58 \cdot \frac{6.25}{2} = 8.09kN$$

$$P_C = 2.58 \cdot 3.811 = 9.83kN$$

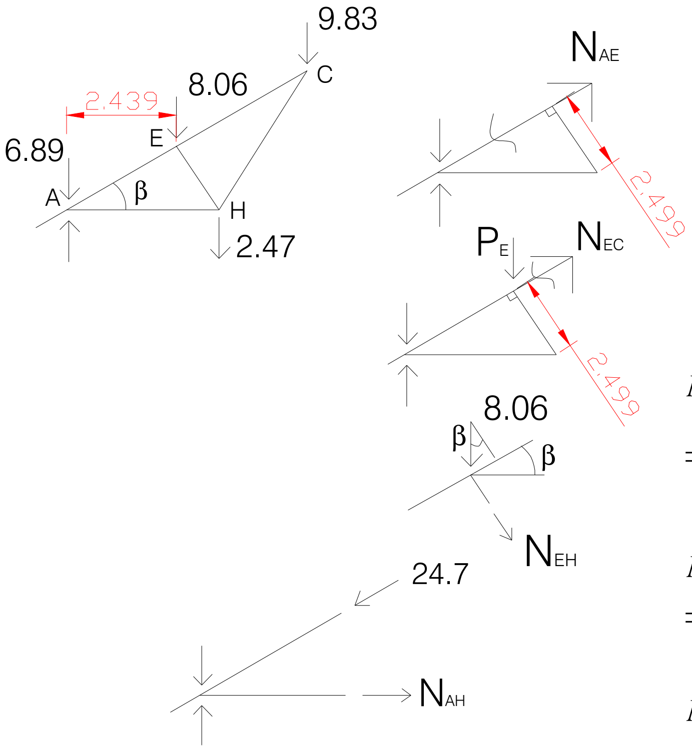
$$P_I = P_H = 0.58 \cdot \frac{4 + 4.5}{2} = 2.47kN$$

$$\sum P_i = 2 \cdot (6.89 + 8.06 + 2.47) + 9.83 = 44.67kN$$

Compare to: 14.5*2.58+12.5*0.58=44.66kN ok

Load at support: 44.67/2=22.34kN

Bar forces (kN)



$$N_{AE} \cdot 2.499 + 4 \cdot (18.82 - 5.8) = 0$$

$$\Rightarrow N_{AE} = -\frac{4 \cdot (18.82 - 5.8)}{2.499} = -20.8kN$$

$$N_{EC} \cdot 2.499 + 4 \cdot (18.82 - 5.8) - 6.84 \cdot (4 - 2.439) = 0$$

$$\Rightarrow N_{EC} = -16.6kN$$

$$N_{EH} + 6.84 \cdot \cos \beta = 0$$

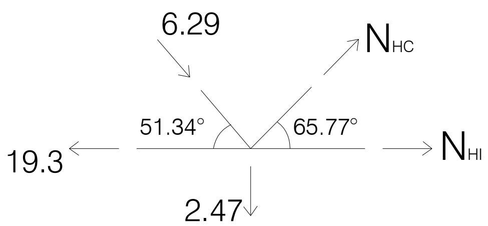
$$\Rightarrow N_{EH} = -6.84 \cdot \cos 38.66 = -5.34kN$$

$$N_{AH} - 20.8 \cdot \cos \beta = 0$$

$$\Rightarrow N_{AH} = 16.2kN$$

$$N_{HC} \cdot \sin 65.77 - 5.34 \cdot \sin 51.34 - 2 = 0$$

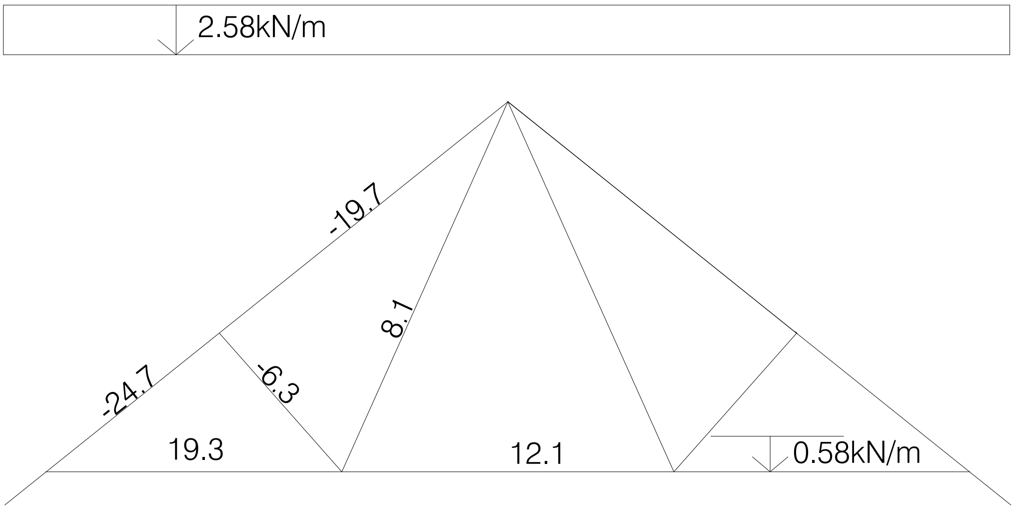
$$\Rightarrow N_{HC} = 6.77kN$$



$$N_{HI} + 6.77 \cdot \cos 65.77 + 5.34 \cdot \cos 51.34 - 16.2 = 0$$

$$\Rightarrow N_{HI} = 10.1kN$$

Results: Loads on connections (kN)



Bar E-C

$$\sigma_{my} = \frac{4.68 \cdot 10^6}{726 \cdot 10^3} = 6.44 MPa$$

$$\sigma_c = \frac{19.7 \cdot 10^3}{19800} = 0.99 MPa$$

$$Interaction: \left(\frac{\sigma_c}{f_{cd}}\right)^2 + \frac{\sigma_{my}}{f_{myd}} = \left(\frac{0.99}{11.77}\right)^2 + \frac{6.44}{12.46} = 0.52$$ ok

Bar A-E (45x220, c18)

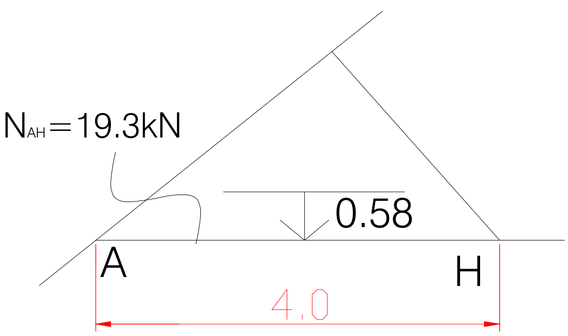
$$M_{\max} = \frac{2.58 \cdot 2.439^2}{8} = 1.92 kNm > 2.58 \cdot 1 \cdot 0.5 = 1.29 kNm$$

$$\sigma_{my} = \frac{1.92 \cdot 10^6}{726 \cdot 10^3} = 2.64 MPa$$

$$\sigma_c = \frac{24700}{19800} = 1.25 MPa$$

$$Interaction: \left(\frac{\sigma_c}{f_{cd}}\right)^2 + \frac{\sigma_{my}}{f_{myd}} = \left(\frac{1.25}{11.77}\right)^2 + \frac{2.64}{12.46} = 0.22$$ ok

Tie beam



$$M_{\max} = \frac{0.58 \cdot 4^2}{8} = 1.16 kNm$$

$$\sigma_m = \frac{1.16 \cdot 10^6}{216.8 \cdot 10^3} = 5.35 MPa$$

$$\sigma_t = \frac{19300}{7650} = 2.52 MPa$$

$$Interaction: \frac{5.35}{9.69} + \frac{2.52}{5.54} = 1.0$$ ok

Span H-I

$$\sigma_m = \frac{1.468 \cdot 10^6}{216.8 \cdot 10^3} = 6.77MPa$$

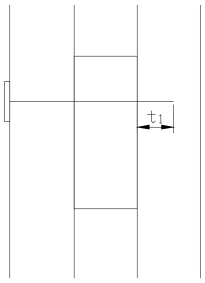
$$\sigma_t = \frac{12100}{7650} = 1.58MPa$$

$$Interaction: \frac{\sigma_m}{f_{md}} + \frac{\sigma_t}{f_{td}} \leq 1$$

$$\frac{6.77}{9.69} + \frac{1.58}{5.54} = 0.98$$ ok

Joint design

Wood against wood   c18 ρ=320kg/m^3



Anchor length: $t_1 \geq 8d$

Assume wire nail 125x43mm

t_1=125-2*45=35>8*4.3=34.4   ok

f_u=40*(20-4.3)=628MPa

M_{yRk}=0.45*628*4.3$^{2.6}$=12537Nmm

Contact pressure: (f_{h1k}= f_{h2k})

Without pre-drilling   0.068*320*4.3$^{-0.3}$=14.0MPa

With pre-drilling   0.068*(1-0.01*4.3)*320=20.8MPa

β=1   Anchor length ~ 8d => F_{axRk} ~ 0

Without pre-drilling

$$(g): f_{h1k} \cdot t_1 \cdot d = 14 \cdot 35 \cdot 4.3 = 2107N$$

$$(h): f_{h2k} \cdot t_2 \cdot \frac{d}{2} = 14 \cdot 45 \cdot \frac{4.3}{2} = 1355N$$

$F_{vRk} \leq$

$$(j): 1.05 \cdot \frac{f_{h1k} \cdot t_1 \cdot d}{2+\beta} \cdot \left(\sqrt{2 \cdot \beta \cdot (1+\beta) + \frac{4 \cdot \beta \cdot (2+\beta) \cdot M_{yRk}}{f_{h1k} \cdot d \cdot t_1^2}} - \beta \right) =$$

$$= 1.05 \cdot \frac{2107}{3} \cdot \left(\sqrt{4 + \frac{12 \cdot 12537}{2107 \cdot 35}} - 1 \right) = 1075N$$

$$(k): 1.15 \sqrt{\frac{2 \cdot \beta}{1+\beta}} \cdot \sqrt{2 \cdot M_{yRk} \cdot f_{h1k} \cdot d} = 1.15 \cdot \sqrt{1} \cdot \sqrt{2 \cdot 12537 \cdot 14 \cdot 4.3} = 1413N$$

With pre-drilling

$$(g): 20.8 \cdot 35 \cdot 4.3 = 3130N$$

$$(h): 20.8 \cdot 45 \cdot \frac{4.3}{2} = 2012N$$

$F_{vRk} \leq$

$$(j): 1.05 \cdot \frac{3130}{3} \cdot \left(\sqrt{4 + \frac{12 \cdot 12537}{3130 \cdot 35}} - 1 \right) = 1444N$$

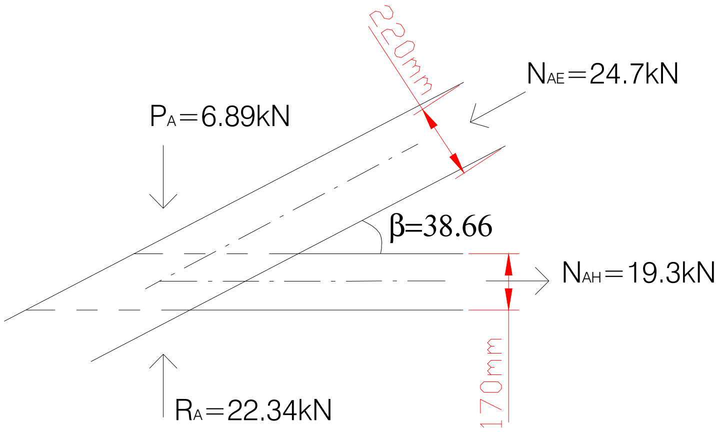
$$(k): 1.15 \cdot \sqrt{2 \cdot 12537 \cdot 20.8 \cdot 4.3} = 1722N$$

Without pre-drilling: $F_{vRk} \leq 1075N$ With pre-drilling: $F_{vRk} \leq 1444N$

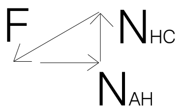
$F_{vRd}=0.9*1075/1.3=744N$

=>on each nail: 2*744=1488N (without pre-drilling)

Joint at support A



Transferred force according to Fig.:



$$F = \sqrt{22.34^2 + 19.3^2} = 29.5kN$$

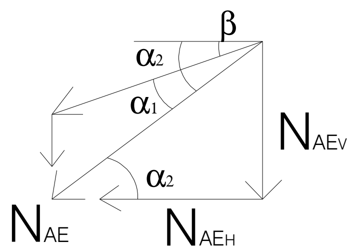
Angel between force and tie beam:

Vertical component:

6.89+24.7*sin38.66=22.32 kN=Ra ok

Horisontal component:

24.7*cos38.66=19.3kN=Nah ok



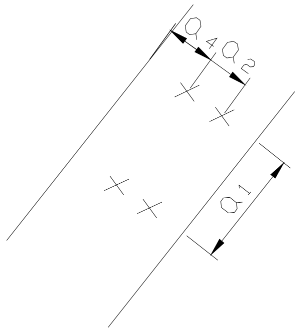
Angel between force and rafter:

$$\alpha_1 = \alpha_2 - \beta = 49.2 - 38.7 = 10.5°$$

Wire nail 125x43, d=4,3mm, F_{vRd}=1.49kN (without pre-drilling)

Least distance between nails without pre-drilled holes:

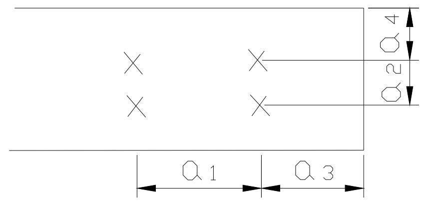
$$a_1 \geq parallell\_to\_grain = (5 + 5 \cdot |\cos 10.5|) \cdot 4.3 = 42.6mm$$
$$a_2 \geq 5 \cdot 4.3 = 21.5mm$$
$$a_3 \geq 10 \cdot 4.3 = 43mm$$
$$a_4 \geq 5 \cdot 4.3 = 21.5mm$$



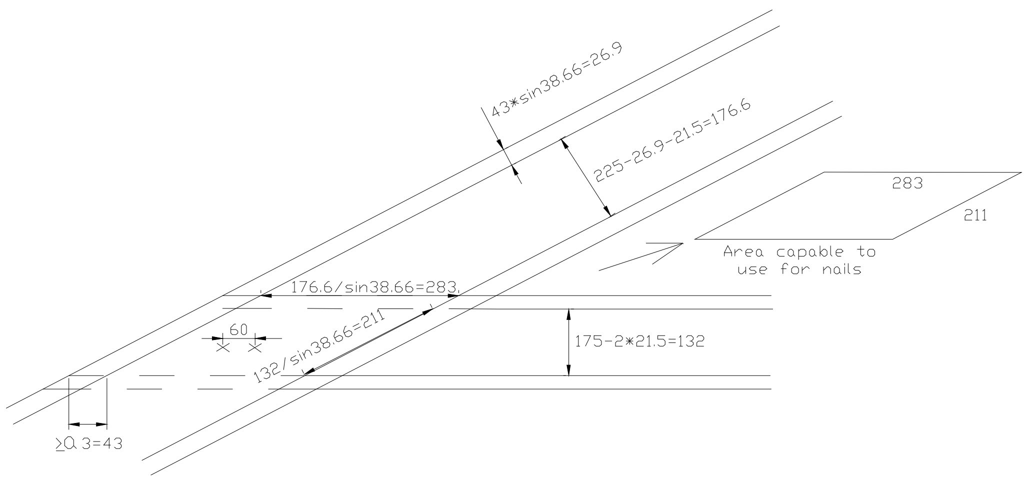
Distance between nails in tie beam, without pre-drilled holes

$\alpha = 49.2$

$a_1 \geq (5+5|\cos 49.2|)*4.3 = 35.5$mm, a_2, a_3, a_4 same as before



In the case of several nails parallel to grain, only an effective number is allowed to be used in the calculation => n_{ef}



[mm]

Assume 6 nails parallel to grain in tie beam:

283/5 = 56.6mm => Choose c/c = 56mm

$k_{eff} = 0.85+((13-10)/(14-10))*(1-0.85) = 0.963 \Rightarrow n_{ef} = 6^{0.963} = 5.61$

Assume 5 rows:

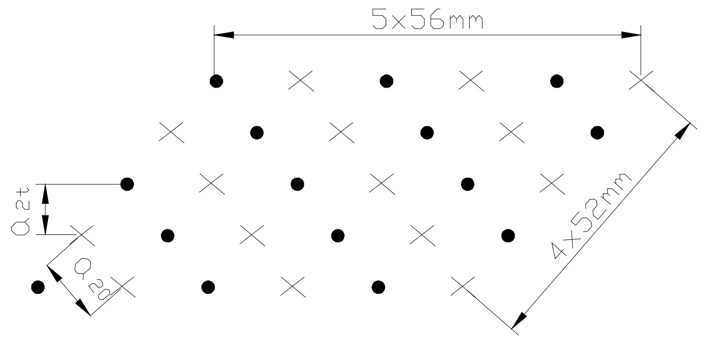
=> Nail distance parallel to grain: 211/4 = 52.8mm

Try c/c = 52mm in inclined direction: $a_1/d = 52/4.3 = 12.1$

$k_{eff} = 0.85+((12.1-10)/14-10))*(1-0.85) = 0.929$ => $n_{ef} = 5^{0.929} = 4.46$

The capacity of the joint:

4.46*5.61*1.488 = 37.2kN > 29.5kN ok

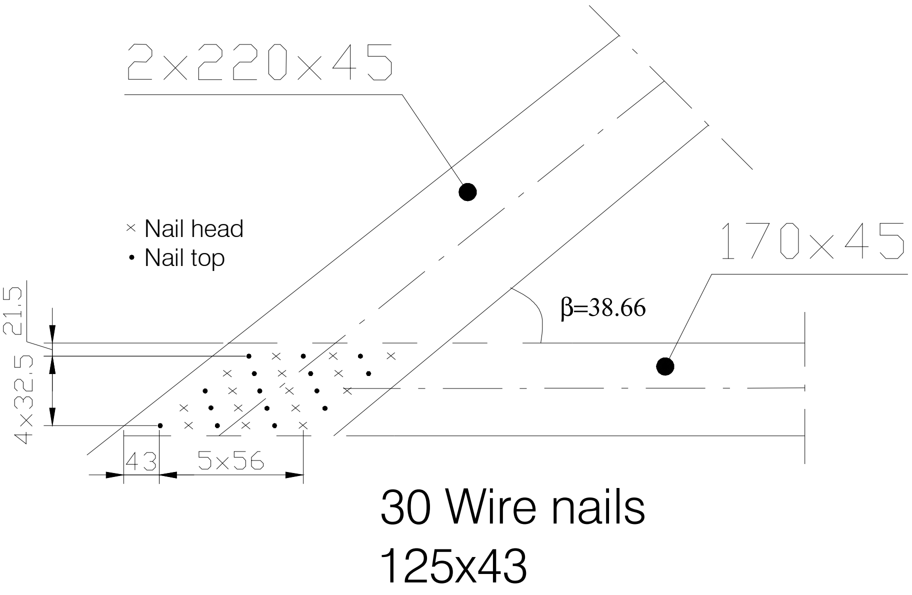


Control distance perpendicular to grain, a_2:

Rafter: $a_{20} = 56*\sin 38.66 = 35.0 > 21.5$mm ok

Tie beam: $a_{2t} = 52*\sin 38.66 = 32.5 > 21.5$mm ok

Drawing of the foot of the roof truss in mm:



Appendix C

Permissible moment capacity of the nail group

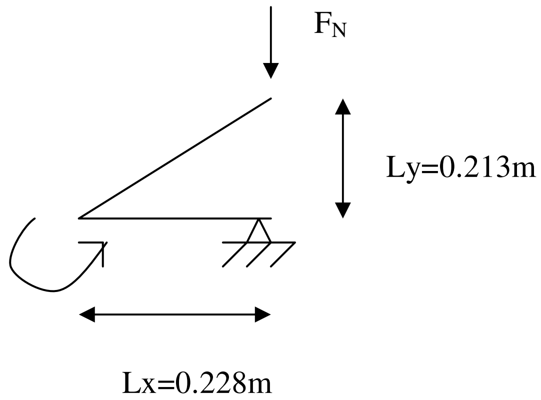
$$M_N = Q \cdot r_{max} \cdot \sum_{i=1} \left| \left(\frac{r_i}{r_{max}} \right)^{3/2} \right|$$

- *Connections for timber-framed structures,* Engström (1997)

Q = permissible load capacity of a single fastener

r_i = distance of the i:th nail to the centre of the nail group

r_{max} = the maximum value of r



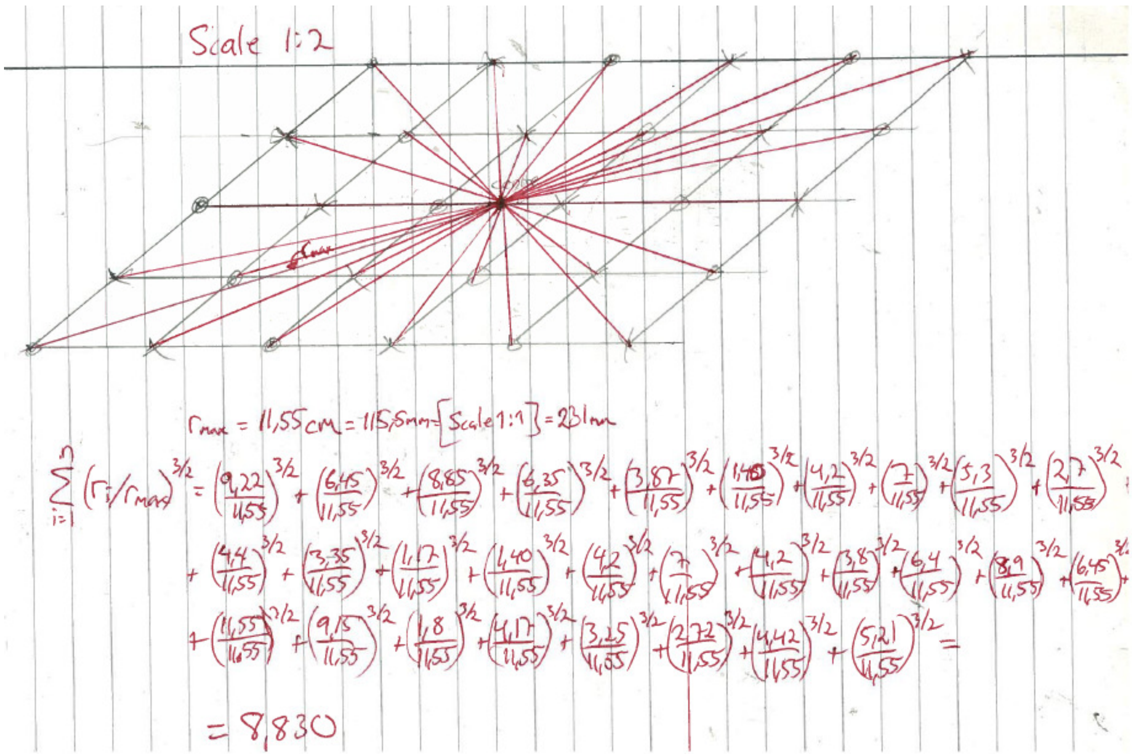
$Q = F_{vRk} = 1075N$

$r_{max} = 0.231m$

$$\sum_{i=1} \left| \left(r_i / r_{max} \right)^{3/2} \right| = 8.830$$

⇨ M_n=1075*0.231*8.830 = 2193Nm

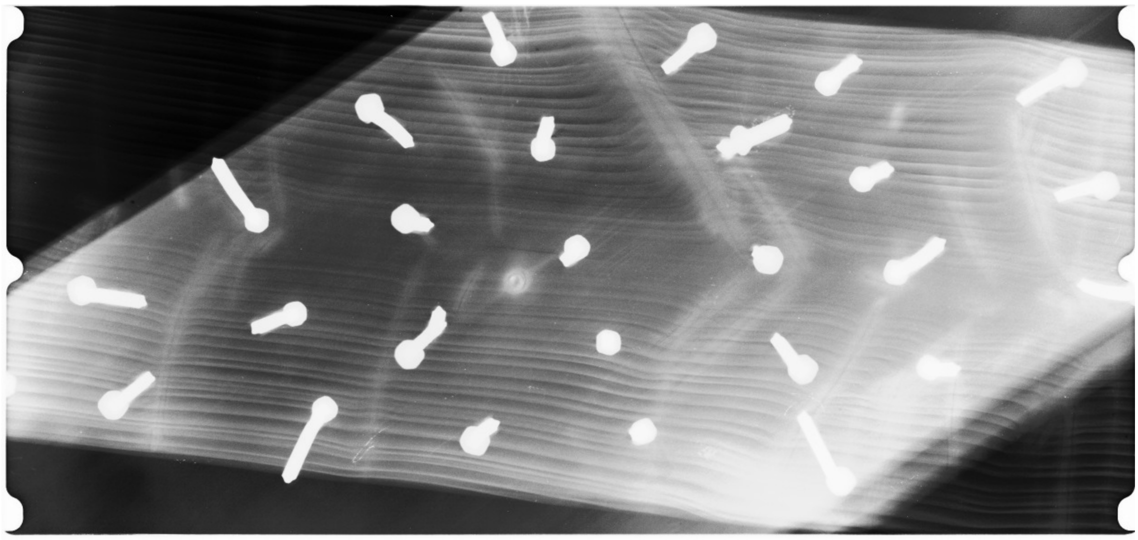
⇨ M_n = F*Lx $F_n = M_n/Lx$ = 2193/0.228 = 9618N ≃ 9.6kN



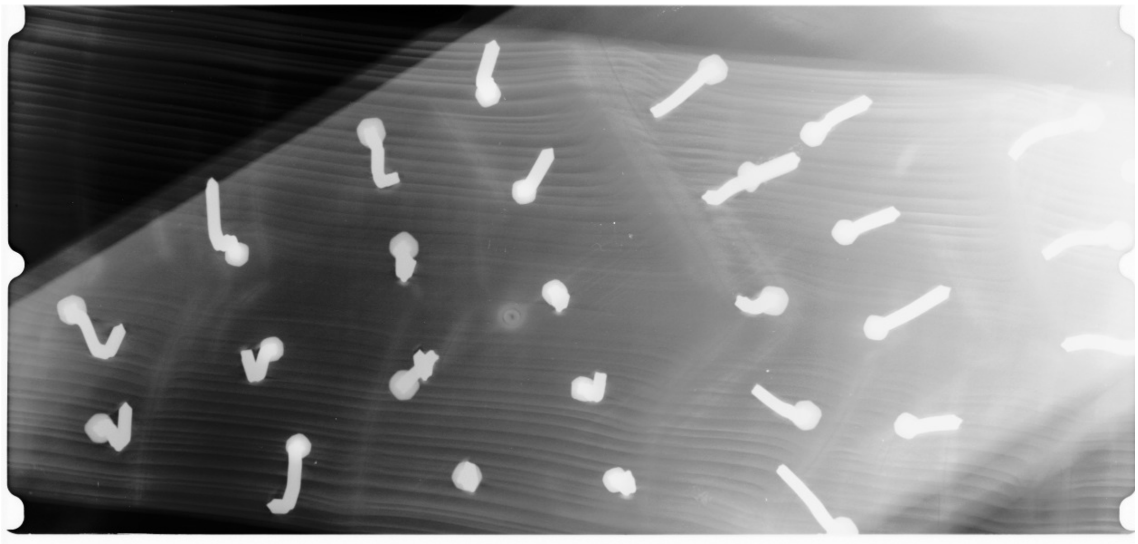
Appendix D

Further radiographs from the test

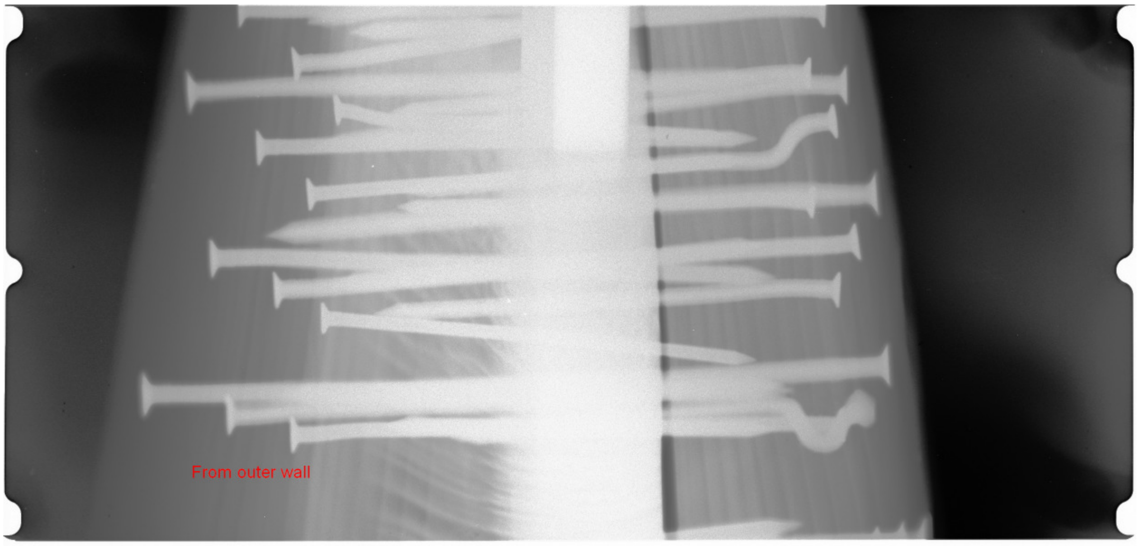
Before the test:



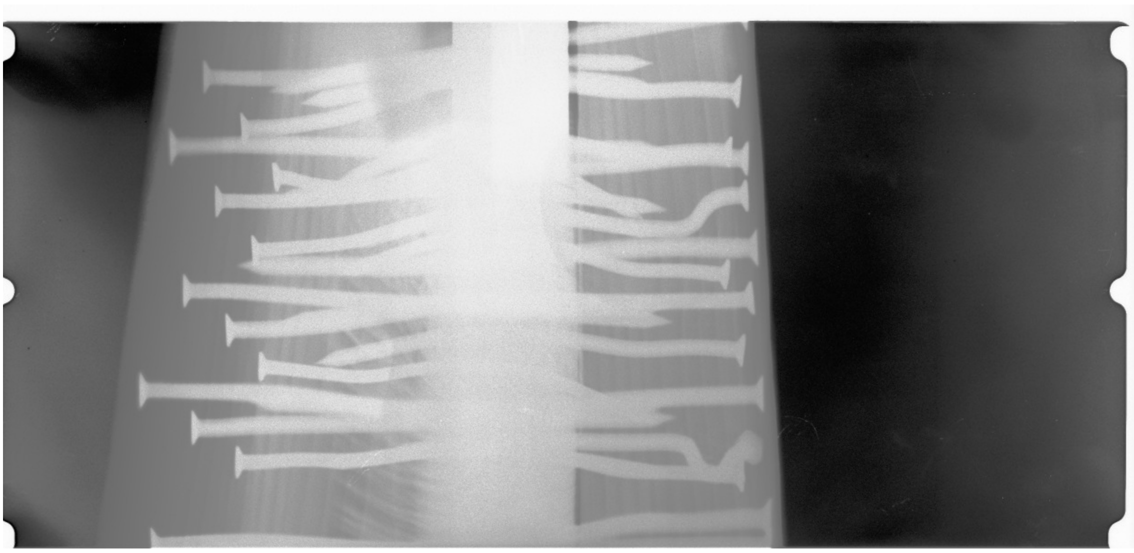
After the test:



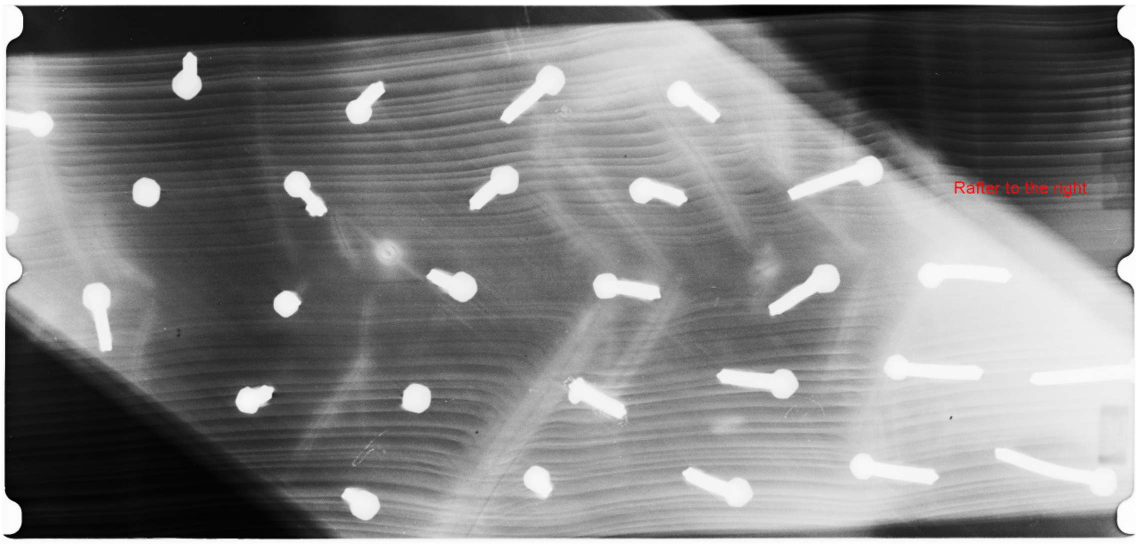
Before the test:



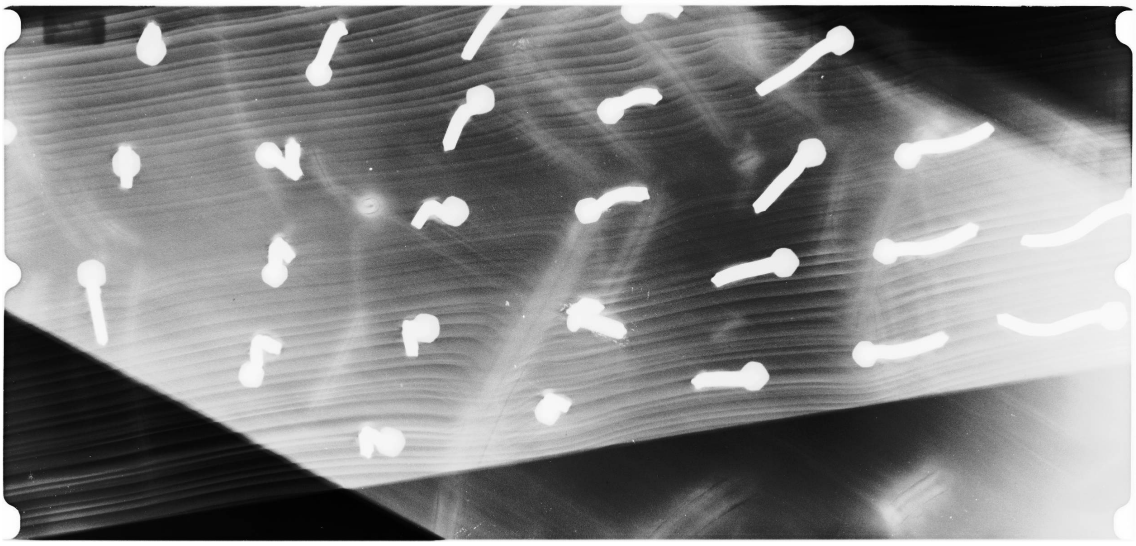
After the test:



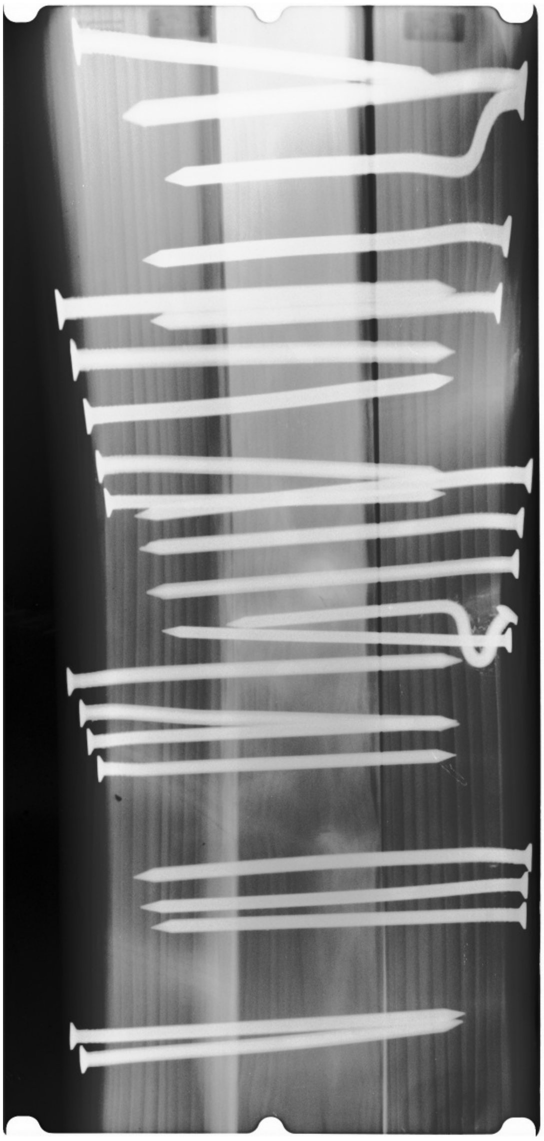
Before the test:



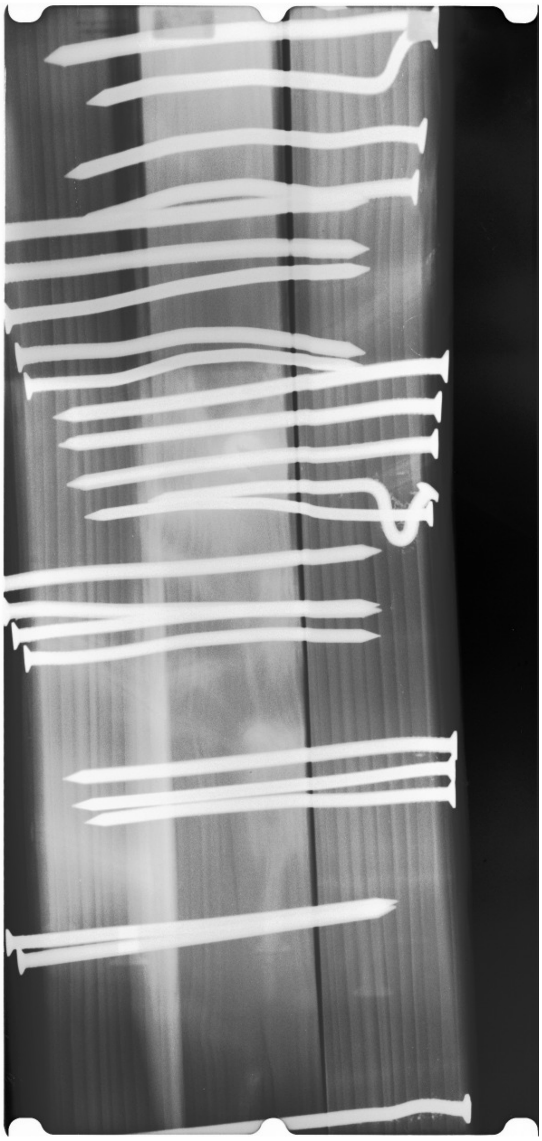
After the test:



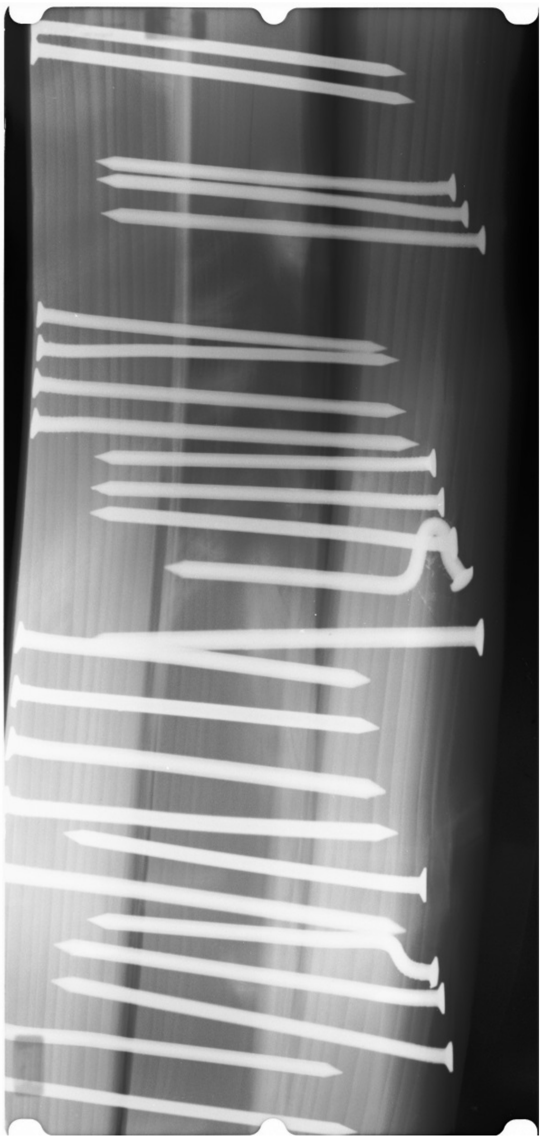
Before the test:



After the test:



Before the test:



After the test: