



TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Civil Engineering and Architecture

VISUAL ASSESSMENT OF STIFFNESS-AFFECTING CHARACTERISTICS OF RECLAIMED STRUCTURAL TIMBER

**TAASKASUTATUD KONSTRUKTSIOONIPUIDU JÄIKUST
MÕJUTAVATE PARAMEETRITE VISUAALNE HINDAMINE**

MASTER THESIS

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THESIS TASK

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Main speciality: Structural Engineering
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Thesis topic:

(in English) Visual Assessment of Stiffness-Affecting Characteristics of Reclaimed Structural Timber

(in Estonian) Taaskasutatud Konstruksioonipuidu Jäikust Mõjutavate Parameetrite Visuaalne Hindamine

Thesis main objectives:

1. Develop a systematic approach for visual assessment
2. Determine stiffness using non-destructive bending tests
3. Investigate the relationship between visual characteristics and stiffness
4. Analyse the influence of visual characteristics on stiffness

Thesis task and time schedule:

Nr	Task description	Deadline
1.	Provide an overview of literature	
2.	Prepare the materials by marking and measuring	
3.	Set up and conduct testing	
4.	Perform test data analysis	
5.	Formulate the research	

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CONTENTS

PREFACE	7
List of symbols and terms.....	8
1. INTRODUCTION.....	9
2. REVIEW OF LITERATURE.....	11
2.1 Reclaimed timber as a structural material	11
2.2 Structural stiffness and its relevance in reuse assessment	12
2.3 Visually observable characteristics affecting stiffness.....	14
2.3.1 Knots and stiffness behaviour	14
2.3.2 Grain deviation and fibre orientation	15
2.3.3 Cracks, checks and surface defects	15
2.4 Visual assessment approaches beyond traditional grading.....	16
2.5 Non-destructive methods for stiffness assessment	17
2.6 Different techniques and data-driven approaches in timber assessment.....	18
3. MATERIAL AND METHODS.....	21
3.1 Material	21
3.2 Documenting the specimens' geometry	22
3.3 Visual assessment of stiffness-affecting characteristics	23
3.3.1 Considered visual parameters	24
3.3.2 Visual assessment approach	29
3.4 Non-destructive bending tests according to EN 408.....	29
3.5 Determination of modulus of elasticity	32
3.5.1 Global modulus of elasticity	32
3.5.2 Local modulus of elasticity	33
3.6 Relationship analysis between visual characteristics and stiffness	34
3.6.1 Spatial comparison of visual characteristics and stiffness.....	35
3.6.2 Comparative and statistical evaluation	36
4. CALCULATIONS	38
5. RESULTS AND DISCUSSION.....	40
5.1 Overview of the investigated dataset.....	40
5.2 Comparative evaluation of global and local modulus of elasticity	42
5.2.1 Statistical evaluation and characteristic stiffness values.....	44
5.3 Relationship between visually observable characteristics and stiffness	46
5.3.1 Defect occurrence and stiffness behaviour	46
5.3.2 Spatial relationship between knot severity and spatial stiffness behaviour	46

5.4	Limitations and future research	51
	SUMMARY	53
	KOKKUVÕTE	55
	REFERENCES	57
	Appendix 1 Coordinate-based knot dataset for specimen Q1	59
	Appendix 2 Bounding box-based defect dataset for specimen Q1	61
	Appendix 3 Coordinate-based hole dataset for specimen Q1.....	62

PREFACE

This thesis has been completed as a master's thesis within the integrated study program in structural engineering and construction management at the Faculty of Engineering, Tallinn University of Technology. The topic of the thesis has been developed in connection with the European research project RAW, in which Tallinn University of Technology participates. The work is linked to an ongoing research framework focusing on the non-destructive assessment and reuse of reclaimed timber, including the use of CT scanning and data-driven modelling approaches. Specifically, this thesis focuses on the visual assessment of stiffness-affecting characteristics and their relationship with the mechanical performance of reclaimed timber elements.

I would like to express my sincere gratitude to my supervisor Maarja Kauniste and co-supervisor Senior Lecturer Eero Tuhkanen for their guidance, support, valuable feedback throughout the preparation of this thesis and for assistance with the experimental work. In addition, I would like to thank Omtre AS for providing the timber material and supporting the research.

Keywords: reclaimed timber, visual assessment, MoE, stiffness, master's thesis

List of symbols and terms

Latin upper-case letters

A	cross-sectional area, in square millimetres;
$E_{m,g}$	global modulus of elasticity in bending, in newtons per square millimetres;
$E_{m,l}$	local modulus of elasticity in bending, in newtons per square millimetres;
$E_{0,05}$	5-percentile characteristic value of modulus of elasticity parallel to grain;
F	load, in newtons;
F_{max}	maximum load, in newtons;
$F_{max,est}$	estimated maximum load, in newtons;
G	shear modulus, in newtons per square millimetres;
I	second moment of area, in millimetres to the fourth power;

Latin lower-case letters

a	distance between a loading position and the nearest support in a bending test, in millimetres;
b	width of cross section in a bending test, or the smaller dimension of the cross section, in millimetres;
h	depth of cross section in a bending test, or the larger dimension of the cross section, or the test piece height perpendicular to the grain and shear tests, in millimetres;
w	deformation or displacement, in millimetres;

Abbreviations

MoE	modulus of elasticity
Global MoE	global modulus of elasticity
Local MoE	local modulus of elasticity

1. INTRODUCTION

The increasing emphasis on sustainability and resource efficiency has brought the construction sector into focus as one of the major contributors to environmental impact. As a significant consumer of raw materials and producer of waste, the sector plays a key role in the transition towards a circular economy. In this context, strategies such as material reuse and the extension of service life have gained growing attention as means to reduce environmental burden and improve resource efficiency.

Timber has emerged as a particularly attractive material within this transition due to its renewable nature, relatively low embodied energy and capacity to store carbon during its service life. In addition to newly produced timber, the reuse of structural elements from existing buildings offers further environmental benefits by reducing the demand for virgin materials and limiting waste generation. However, despite this potential, the practical reuse of structural timber remains limited, primarily due to uncertainties related to its mechanical performance and structural reliability.

One of the main challenges associated with reclaimed timber is the assessment of its mechanical properties. Unlike newly processed timber, reclaimed material has been subjected to varying environmental conditions, mechanical loads and ageing processes over time. As a result, its internal structure and performance characteristics are often heterogeneous and difficult to predict. Conventional grading systems, which are largely developed for new timber, rely heavily on visual inspection and predefined criteria. While these methods are effective for standardized materials, they may lead to overly conservative evaluations when applied to reclaimed timber, where visible defects do not always directly reflect the actual structural behaviour.

In particular, the relationship between visually observable characteristics and stiffness remains insufficiently understood. Stiffness, commonly expressed through the modulus of elasticity, is a key parameter governing deformation behaviour and structural performance. Although visual grading considers features such as knots, grain deviation and cracks, their influence on stiffness is often treated in a simplified manner. At the same time, more advanced techniques, such as non-destructive bending tests and imaging methods, have demonstrated that stiffness can vary significantly along a single timber element, often due to localized characteristics that may or may not be clearly visible on the surface.

This creates a need to better understand how surface-visible features relate to the actual mechanical behaviour of reclaimed timber. Visual assessment, when approached

systematically, can be interpreted not merely as a grading tool but as a method for describing and analysing material characteristics. By linking observed features with measured stiffness values, it becomes possible to establish relationships that improve the interpretation of visual information and reduce uncertainty in the assessment process.

The present study addresses this challenge by investigating reclaimed structural timber and examining how visually identifiable characteristics influence its stiffness. The work focuses on developing a structured approach to visual assessment and analysing its relationship with stiffness determined through non-destructive bending tests. In doing so, the study aims to contribute to a more reliable and informative use of visual inspection in the evaluation of reclaimed timber, particularly in contexts where advanced testing methods are not readily applicable.

The research is based on reclaimed timber originating from a dismantled structure, which has been subjected to detailed visual documentation and systematic mechanical testing. All experimental work, including visual assessment and bending tests, was conducted at TalTech's Structural Hall. Compared with conventional reclaimed timber assessment approaches, the study applied a more detailed spatial evaluation methodology, that went beyond conventional visual grading practices, where visually observable characteristics were documented separately for each beam face and linked with local and global modulus of elasticity measurements performed at 250 mm intervals along the timber members. The analysis combines visual observations with measured stiffness data to identify patterns, correlations and potential limitations of visual assessment.

This thesis is structured into two main parts. The first part presents the theoretical background, including the mechanical behaviour of timber, stiffness-related properties and the role of visual characteristics in structural performance. It also reviews current approaches to timber assessment and highlights their limitations in the context of reclaimed materials. The second part describes the experimental programme, including the material, testing methods and data analysis procedures. The results are then presented and discussed, followed by conclusions and recommendations for future research.

2. REVIEW OF LITERATURE

2.1 Reclaimed timber as a structural material

Reclaimed structural timber refers to load-bearing wooden members that are dismantled from existing structures and reintroduced into structural applications without being reprocessed into new products. In contrast to recycled timber, which is mechanically transformed into secondary materials, reclaimed timber preserves its original structural identity and geometry. Unlike simple reuse, structural reclamation requires mechanical reassessment prior to reinstallation. [1] The engineering challenge therefore lies not in material recovery itself, but in evaluating whether the element remains mechanically suitable for load-bearing use.

The mechanical performance of reclaimed timber has been investigated in several studies focusing on aged or existing wooden structures. Previous studies indicate that chronological age alone does not necessarily lead to a significant reduction in mechanical properties. Experimental results have shown that aged structural timber can retain stiffness and strength values comparable to newly produced material of the same species, provided that biological degradation or severe mechanical damage is absent. [2] Similar conclusions are reported in assessment-oriented studies of existing timber structures, where the primary concern is not ageing itself, but the presence of defects and deterioration mechanisms. These findings challenge the common assumption that older timber is inherently weaker and support the need for condition-based, rather than age-based, mechanical evaluation. [3]

Despite the potential retention of mechanical capacity, reclaimed timber is characterised by increased variability. Timber is inherently anisotropic and biologically heterogeneous: growth ring structure, density variation, knots, and fibre orientation already introduce mechanical non-uniformity in new material. In reclaimed members, this natural heterogeneity is compounded by service-induced effects such as moisture cycling, creep, local crushing, mechanical fastening, drilling, and crack formation. As a result, the mechanical response of reclaimed timber may exhibit greater spatial variability along the member length and across the cross-section. [4], [5]

Beyond inherent material heterogeneity, the assessment of reclaimed timber involves additional sources of uncertainty. The original strength class, grading method, previous grading history and timber source are often unknown. Modifications during service life, such as cross-section modifications and geometric irregularities, further complicate evaluation. Visual grading standards were primarily developed for new timber under

controlled production conditions and may not fully account for service-related alterations. Consequently, assessing reclaimed timber requires careful consideration of both observable defects and their mechanical implications. [6]

Under these conditions of increased heterogeneity and incomplete information, the selection of an appropriate mechanical parameter becomes critical for reliable reassessment. [6] Parameters used for reassessment must not only reflect structural behaviour but also be measurable using non-destructive or minimally destructive techniques. This consideration provides the basis for examining structural stiffness as a key parameter in the evaluation of reclaimed timber. [7]

2.2 Structural stiffness and its relevance in reuse assessment

In structural timber engineering, stiffness is commonly expressed through the modulus of elasticity (MoE), which describes the proportional relationship between stress and strain within the elastic range of material behaviour. This relationship corresponds to the initial linear portion of the stress-strain curve, where deformation is directly proportional to the applied load. As illustrated in Figure 2.2-1, the slope of this linear region varies between materials and represents their stiffness. In bending, the modulus of elasticity characterises the resistance of a member to deformation under applied load. [5]

While different materials exhibit distinct stress-strain behaviours, the initial slope of the curve remains the defining parameter for stiffness. For example, structural steel shows a steep initial slope and a well-defined yield region, whereas rubber exhibits a much lower stiffness and highly non-linear behaviour. In comparison, wood demonstrates an approximately linear elastic response up to the proportional limit, followed by non-linear behaviour leading to failure.

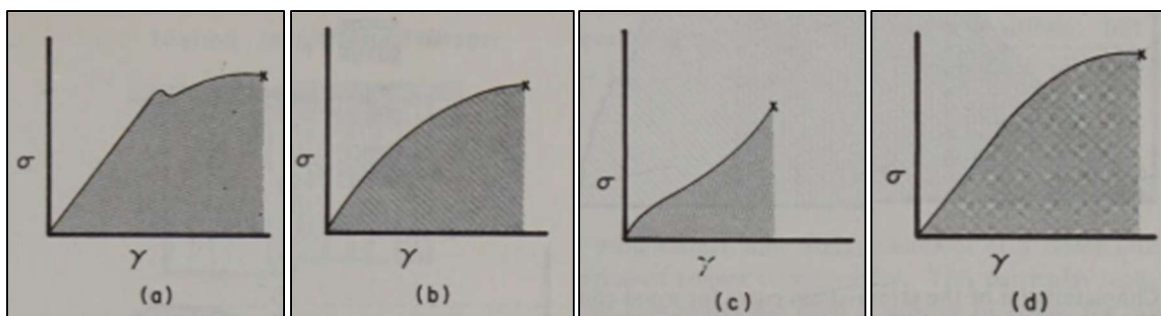


Figure 2.2-1 Typical stress- strain curves for various materials: (a) structural steel, (b) cast iron, (c) rubber, (d) wood [5]

According to EN 408 [8], stiffness in timber beams may be determined as a global modulus of elasticity ($E_{m,g}$), which includes the influence of shear deformation over the span, or as a local modulus of elasticity ($E_{m,l}$), measured within a constant bending moment zone and therefore less affected by shear effects. These values represent different measurement configurations rather than different intrinsic material properties.

Stiffness governs deformation behaviour under service-level loading conditions. In structural design, serviceability limit states, as defined in EN 1995-1-1 [9], are directly controlled by stiffness through deflection limits and vibration performance requirements. Timber members often reach serviceability criteria before ultimate strength capacity is exhausted, particularly in slender beam configurations. For this reason, the modulus of elasticity is a primary parameter in evaluating structural usability rather than simply a secondary material property. [10]

A fundamental mechanical distinction exists between stiffness and strength. Strength represents the maximum stress that a material can withstand before failure and is governed by the weakest cross-sectional region. In timber, bending failure typically initiates in the tension zone, often controlled by local defects such as large knots, fibre deviation or cracks. Stiffness, in contrast, reflects the elastic response of the member over a larger material volume. It is determined by the distribution of material properties along the span and across the cross-section rather than by a single critical flaw. [5], [10]

Because stiffness represents a distributed deformation response, it generally exhibits lower variability than strength. [5], [10] Non-destructive measurements used in timber grading often rely on stiffness-related properties, such as the modulus of elasticity, because these can be measured reliably and are useful indicators for estimating structural properties of timber. [7] This distinction becomes particularly relevant in heterogeneous materials, where density variation, growth characteristics and defect distribution may differ significantly within a single member. [4]

In reclaimed timber, intra-member variability may be further increased due to the presence of defects, geometric irregularities, and changes induced during service life, such as cracking and material degradation. While such features may substantially reduce ultimate strength if located in critical tension zones, their influence on global bending stiffness may be less pronounced unless fibre continuity is severely disrupted across a significant portion of the cross-section. [3], [6] Strength is therefore a local failure-controlled property, whereas stiffness represents a more integrated mechanical response. [5], [7]

For reclaimed structural timber elements, destructive strength testing is typically not feasible. Non-destructive stiffness-based measurements allow mechanical characterisation without compromising structural integrity. [11]

2.3 Visually observable characteristics affecting stiffness

Visual inspection allows identification of material characteristics that may influence the mechanical behaviour of timber members. In the context of reclaimed timber, such characteristics include both natural growth features and service-induced defects that remain observable on the surface of the element.

While many of these features are traditionally associated with strength reduction, their influence on stiffness is less direct. Stiffness reflects the integrated deformation response of the member and is therefore affected by how defects influence fibre continuity and material distribution within the cross-section. The mechanical relevance of a given characteristic depends not only on its presence, but also on its size, position and interaction with the stress distribution in bending.

2.3.1 Knots and stiffness behaviour

Knots are among the most significant naturally occurring features in timber and cause local disturbances in fibre orientation and continuity. While they are commonly associated with strength reduction, their influence on stiffness depends on how they affect the overall deformation behaviour of the member. [3], [5] In bending, stresses are not uniformly distributed across the cross-section: maximum tensile and compressive stresses occur at the outer fibres, while stresses near the neutral axis are minimal. [5] This non-uniform stress distribution makes the position of a knot within the cross-section a key factor in its mechanical relevance.

Knots located in the outer regions of the cross-section, particularly in the tension zone, have a greater influence on mechanical behaviour than those located closer to the neutral axis. In terms of strength, a single knot in a critical location may initiate failure. In contrast, the effect on stiffness depends on the extent to which fibre continuity is disrupted across the load-carrying section. [5], [11] A large individual knot may therefore have a limited influence on global stiffness if the surrounding material maintains sufficient continuity to transfer stresses.

The distribution of knots can also influence stiffness behaviour. Isolated knots tend to cause localised disturbances, whereas clusters of knots or regions with frequent knot

occurrence lead to more extensive deviations in fibre orientation and a reduction in the effective cross-sectional properties. [5] In such cases, the cumulative influence of multiple defects becomes more relevant to stiffness than the presence of a single knot.

2.3.2 Grain deviation and fibre orientation

Grain deviation refers to the misalignment of wood fibres relative to the longitudinal axis of the member and is commonly expressed as the slope of grain. [7] Timber exhibits highly anisotropic behaviour, meaning that its mechanical properties are strongly dependent on fibre direction. The modulus of elasticity is highest parallel to the grain and decreases as the loading direction deviates from the fibre direction due to the orthotropic nature of wood. [5] As a result, slope of grain reduces stiffness due to the misalignment between the fibre direction and the principal stress direction. [7], [12]

This effect is linked to how fibres contribute to load-carrying behaviour in bending. When fibres are aligned with the member axis, stresses are primarily carried along their length, resulting in a more efficient elastic response. Fibre deviation introduces components of stress perpendicular to the grain, where stiffness is significantly lower, leading to increased deformation under load. [5] Unlike localised defects, this mechanism affects stiffness in a more distributed manner, as it influences the overall material response rather than a single critical region. [13]

In practice, grain deviation is assessed visually based on surface fibre orientation, although it does not necessarily represent the actual internal fibre orientation. [7] Surface-visible slope of grain can indicate potential stiffness reduction, but internal deviations, particularly around knots or growth irregularities, may differ from what is observed externally. This creates uncertainty in visual assessment, as the relationship between visible grain direction and actual fibre continuity within the cross-section is not always direct. [13]

2.3.3 Cracks, checks and surface defects

Cracks and checks are common features in timber and may originate either from natural drying processes or from service-related effects. Shrinkage cracks typically develop due to moisture loss and are often oriented along the grain, while structural cracks may form as a result of loading or mechanical damage. Although both types are visually detectable, their mechanical implications differ depending on their depth, orientation and location within the cross-section. [14], [15]

The influence of cracks on mechanical behaviour differs for stiffness and strength. In terms of strength, cracks may act as initiation points for failure, particularly when

located in the tension zone or when they significantly reduce the effective cross-section. [7], [15] Their effect on stiffness is less direct and depends on the extent and location of the crack. Shallow or surface-level cracks aligned with the grain may have limited influence on global bending stiffness, as load transfer can still occur through the surrounding intact material. More pronounced reductions in stiffness occur when cracks extend deeper into the cross-section or disrupt fibre continuity across regions that contribute significantly to bending resistance. [7], [14]

From a visual assessment perspective, cracks are relatively easy to detect, yet their mechanical relevance is not always straightforward to interpret. Standard grading approaches often treat cracks conservatively, associating their presence with reduced performance. [13], [15] However, the actual impact on stiffness is difficult to quantify based solely on surface observation, as internal crack propagation and depth cannot be fully assessed visually. This introduces uncertainty in evaluating whether visible cracks meaningfully affect the deformation behaviour of reclaimed timber members. [13], [14]

2.4 Visual assessment approaches beyond traditional grading

Visual grading is a widely used method for assessing the mechanical quality of structural timber. It is based on the identification and evaluation of visible characteristics such as knots, grain deviation and cracks, which are used to assign strength classes according to established grading rules. This approach has been developed primarily for newly produced timber, where grading conditions are controlled and standardised. [16]

The underlying principle of visual grading is that certain observable features are indicative of reduced strength. As a result, grading rules are generally conservative and focus on limiting defects associated with strength reduction. [13], [16] However, this strength-oriented framework does not directly address stiffness, which reflects the overall deformation behaviour of the member rather than local failure mechanisms. [7], [15] The relationship between visually assessed characteristics and stiffness is therefore not always consistent, particularly when defects influence strength and stiffness in different ways. [13]

These limitations become more pronounced in the context of reclaimed timber. Visual grading systems developed for new material may not adequately account for service-induced defects, modifications, or unknown material history. [16] In addition, the absence of original grading information and the presence of atypical features complicate classification into predefined strength classes. As a result, strength-based grading may

not reliably represent the actual stiffness (e.g., MoE) behaviour of reclaimed timber elements. [13], [14], [15]

An alternative approach is to focus on the systematic identification and documentation of visually observable characteristics without directly assigning strength classes. In this context, visual information is treated as descriptive data that can be analysed in relation to measured mechanical properties. This allows the influence of individual features, such as knot position, fibre orientation or crack distribution, to be evaluated without relying on predefined grading limits. [7], [13], [19]

At the same time, visual assessment inherently involves a degree of subjectivity. The identification and interpretation of features depend on the observer, the level of detail recorded, and the assessment procedure used. Variability between assessors may affect repeatability, particularly for characteristics such as grain deviation or crack severity. For this reason, a clearly defined and systematic approach to visual assessment is necessary in order to ensure consistency and to enable meaningful comparison with measured stiffness values. [14]

2.5 Non-destructive methods for stiffness assessment

Non-destructive methods are widely used to evaluate the mechanical properties of timber without compromising structural integrity. Among these, bending-based stiffness measurements represent one of the most direct approaches for determining the modulus of elasticity. Standardised bending tests, as defined in EN 408 [8], allow the evaluation of both global and local stiffness by measuring deformation under controlled loading conditions. These methods provide a reliable assessment of the elastic behaviour of timber members and are commonly used as a reference for mechanical characterisation. [12]

In addition to bending-based approaches, acoustic methods have been developed for rapid estimation of stiffness. These techniques are based on the propagation of stress waves or vibrations through the material, where wave velocity is related to the dynamic modulus of elasticity. [12], [19] Acoustic methods offer practical advantages in terms of speed and ease of use, particularly in field applications. However, they provide indirect estimates of stiffness and may be influenced by factors such as moisture content, density variation and internal defects. [11], [19]

In the context of reclaimed timber, the application of non-destructive methods involves additional challenges. Increased material heterogeneity, service-induced defects and unknown internal conditions may affect measurement accuracy and interpretation. Local

irregularities, such as cracks, fibre deviation or areas of reduced cross-section, may affect the mechanical behaviour of timber and contribute to increased variability in material response. [18] As a result, non-destructive measurements should be interpreted in conjunction with visual observations in order to better understand the underlying mechanical behaviour. [19]

Stiffness measurements based on dynamic methods remain particularly relevant in reclaimed timber assessment, as they provide an evaluation of structural behaviour. When combined with systematic visual assessment, they enable the investigation of how observable characteristics relate to measured stiffness, forming the basis for a more comprehensive understanding of material behaviour. [19]

2.6 Different techniques and data-driven approaches in timber assessment

Advanced techniques, such as computed tomography (CT) scanning, have been developed to investigate the internal structure of timber and to provide a more detailed understanding of the relationship between material characteristics and mechanical behaviour. CT scanning enables non-destructive imaging of the internal geometry of timber elements, allowing the identification of features that are not visible on the surface, such as internal knots, fibre deviations, density variations and internal crack propagation. This detailed representation of internal structure provides valuable insight into how material heterogeneity influences the structural response of timber. [13]

Despite its capabilities, CT scanning is not suitable for large-scale structural assessment. The required equipment is expensive, scanning procedures are time-consuming, and the method is generally limited to controlled laboratory environments. As a result, its application in engineering practice remains limited. Nevertheless, CT data are highly valuable as a reference, as they reveal the internal features that directly influence mechanical behaviour and enable comparison between internal structure and externally observable characteristics. [13]

This distinction between internal and surface-visible features highlights a fundamental challenge in timber assessment. Mechanical behaviour is governed by the full internal structure of the material, while practical evaluation methods rely primarily on information that can be observed at the surface. [5], [13] The relationship between visible characteristics and internal features is therefore indirect and may involve uncertainty, particularly in heterogeneous materials such as reclaimed timber. [13], [19]

Within this context, visual assessment can be interpreted as a bridge between observable material characteristics and mechanical behaviour. By systematically identifying surface-visible features, such as knots, grain deviation and cracks, and relating them to measured stiffness, it becomes possible to approximate the influence of internal structure without directly accessing it. While this approach does not provide direct access to internal structure, it offers a practical and scalable framework for linking visual information with structural performance. [12], [19]

An example of this relationship is illustrated in Figure 2-6.1, where the bending stiffness of a timber beam is evaluated along its length. The stiffness profile shows local reductions in regions containing large knots, demonstrating how internal features directly influence mechanical behaviour. Although such variations are revealed here through detailed measurements, they are often associated with characteristics that can also be identified from the surface. [13] This highlights the potential of visual assessment to capture stiffness-affecting features, even when internal structure is not directly accessible.

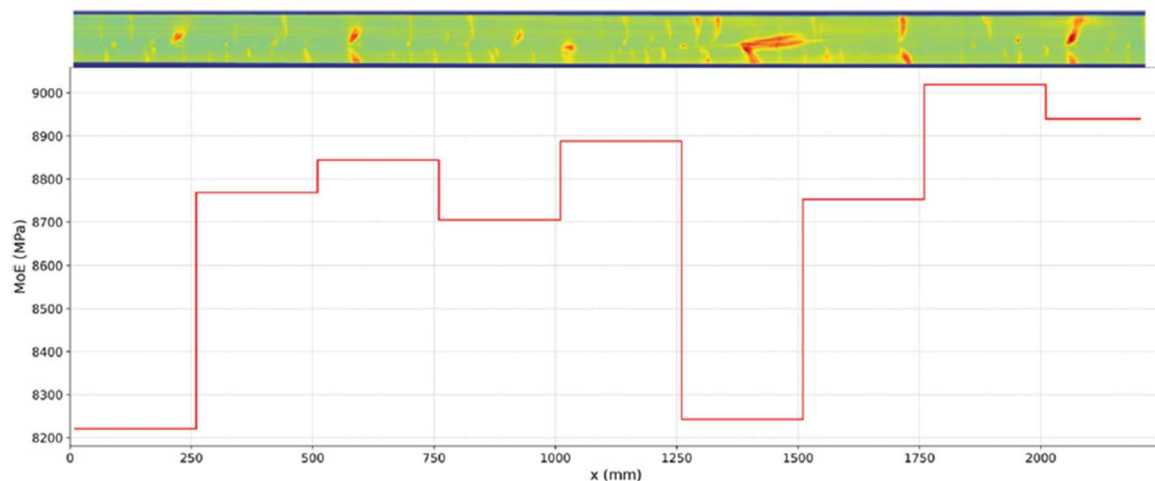


Figure 2.6-1 Bending stiffness variation along a timber beam in relation to internal features, showing reduced stiffness in regions with large knots [13]

In addition to these approaches, data-driven methods have emerged as a complementary tool in timber assessment. Image-based techniques and data-driven models enable the automated detection and quantification of surface-visible features, thereby reducing the subjectivity associated with manual visual grading. These methods provide detailed geometric and spatial information about defects, including their size, position and distribution, which are directly relevant for understanding mechanical behaviour. [16]

Furthermore, statistical modelling and machine learning approaches enable the integration of visual and measured data to predict stiffness-related properties. By analysing relationships between multiple features simultaneously, these models can capture complex interactions that are not addressed by traditional grading rules. In this way, data-driven approaches extend the role of visual assessment from qualitative evaluation towards quantitative prediction, providing a link between observable characteristics and underlying mechanical performance. [16], [19]

3. MATERIAL AND METHODS

3.1 Material

The material investigated in this study consists of reclaimed structural timber originating from a dismantled timber barn. The timber samples were supplied by the Norwegian company Omtre AS and were sourced from a traditional Norwegian barn structure located in Brøttum, Ringsaker (Photo 3.1-1). The investigated timber consisted of Norway spruce (*Picea abies*) [13]

The barn, constructed in the late nineteenth century, was a timber-framed structure, and the recovered elements are assumed to have served as load-bearing components within the building. Following dismantling, the timber was collected, cleaned from metal fasteners and prepared for further investigation. Due to the nature of the reclamation process, the exact original position and structural role of individual elements within the building are not fully known. [13]



Photo 3.1-1 Barn structure in Brøttum, Ringsaker and its dismantling process [13]

Due to its previous use, the material exhibited characteristics associated with prior service, including minor mechanical damage, surface alterations, holes, cut-outs and variability in geometric properties. In addition, the absence of detailed information regarding loading history and processing conditions introduces uncertainty in the assessment of mechanical behaviour. These aspects are characteristic of reclaimed construction timber and distinguish it from newly produced structural timber, where material origin and grading conditions are known and controlled.

The timber elements investigated in this study are part of a broader research framework and have previously been subjected to CT scanning. However, the CT data are not analyzed within the scope of this thesis. The availability of CT data for the same material provides opportunities for future studies to compare internal features with surface-

visible characteristics and measured stiffness behaviour. The findings of this study may support future machine learning approaches by identifying visually observable characteristics that are physically linked to stiffness behaviour.

3.2 Documenting the specimens' geometry

A total of 12 reclaimed timber specimens were included in this research. All specimens originated from the same source, as described in Section 3.1, ensuring consistency in material background while still representing the variability typical of reclaimed construction timber.

The cross-sectional dimensions of the specimens varied, and therefore the geometry of each individual timber element was measured separately prior to testing. For each specimen, the cross-sectional width and height, from three separate spots along the beam, were recorded and average was calculated to ensure accurate determination of stiffness-related properties. The basic geometric properties of the specimens are summarised in Table 3.2-1.

Table 3.2-1 Geometric properties of the timber specimens used in the study

Beam ID	Width (mm)	Height (mm)
Q1	128	47
U2	130	47
T3	131	44
X3	128	47
U1	127	47
U3	127	46
T1	135	49
S2	132	49
Q3	127	48
W1	129	49
Q2	128	47
O2	130	47

Each specimen was identified using a predefined labelling system established during prior CT scanning of the material. The same identification system was maintained throughout this study to ensure consistency between datasets. In addition to the specimen ID, all timber elements were marked on their four longitudinal faces using an A-B-C-D system.

The investigated specimens and their preparation prior to testing are shown in Photos 3.2-1 and 3.2-2. Visual defects were identified, documented and marked prior to testing,

and the geometric properties of each specimen were measured and recorded as part of the experimental procedure.



Photo 3.2-1 Reclaimed timber beams used in the study prior to testing



Photo 3.2-2 Measurement of specimen geometry and documentation of visual defects

The orientation of the specimens during testing was defined consistently with respect to the pith location. In all bending tests, the pith side (C-face) was positioned in the tension zone. This ensured a consistent reference framework for both mechanical testing and visual assessment.

The established marking and orientation system enabled a direct link between specimen geometry, visual observations and measured stiffness behaviour. By maintaining consistent identification of specimen faces throughout the study, it was possible to relate visually observed characteristics on specific surfaces to their corresponding mechanical response under bending.

3.3 Visual assessment of stiffness-affecting characteristics

The visual assessment was conducted using a defined coordinate system in order to ensure a consistent spatial description of all recorded features. The longitudinal axis of each specimen was defined as the x-axis, with the origin located at one end of the beam. The transverse position of features was described using a y-axis defined in the cross-

sectional plane and measured relative to a reference axis of the specimen, while the z-axis corresponded to the depth direction perpendicular to the assessed surface.

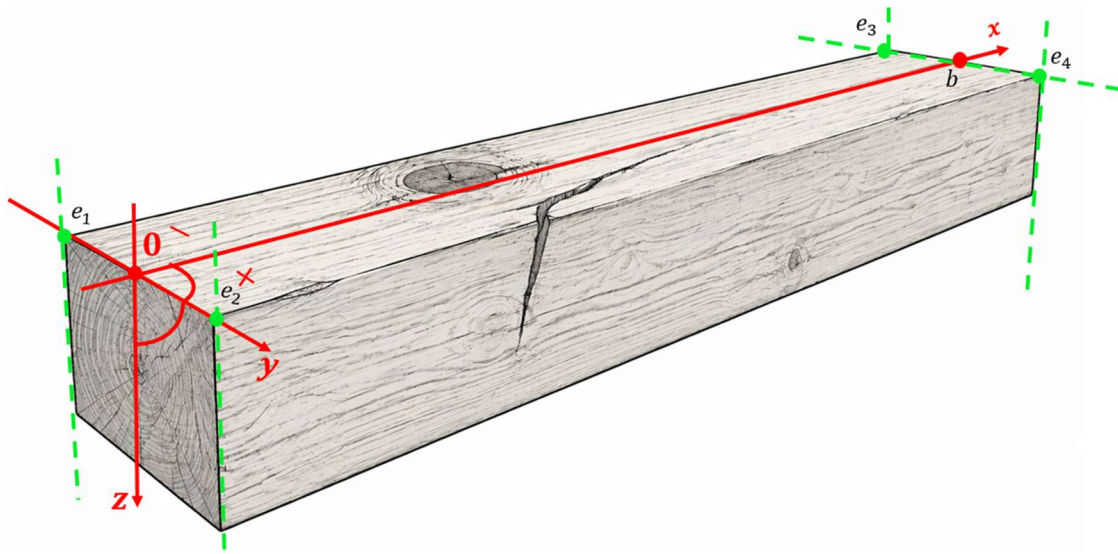


Figure 3.3-1 Nomenclature of axes

The reference axis of each cross-section was established by identifying the midpoint at both ends of the beam and connecting these points using a chalk line. The reference axis effectively divided each assessed surface into two regions. Features located on one side of the reference axis were assigned positive y-values, while features on the opposite side were assigned negative y-values. This allowed the position of features to be consistently described relative to the centreline of the cross-section.

The same coordinate system was applied independently to all four longitudinal faces (A–B–C–D) of each specimen. Although Figure 3.3-1 illustrates the coordinate system for a single face, the same principle was consistently used for all sides of the beam. This ensured that the spatial distribution of features could be directly compared between different faces and specimens.

3.3.1 Considered visual parameters

The visual assessment focused on the identification of surface-visible characteristics that may influence the stiffness behaviour of reclaimed timber. All observations were recorded separately for each of the four longitudinal faces (A–B–C–D), and their positions were defined using the coordinate system described in Section 3.3. This enabled a consistent spatial description of all features in relation to the geometry and orientation of each specimen.

Knots were documented as one of the primary visual features. For each knot, the size was determined by measuring the largest diameters in two perpendicular directions within the cross-sectional plane, defined as $D1x$ and $D1y$, corresponding to the x- and y-directions, respectively. These measurements describe the in-plane dimensions of the knot and were used as indicators of knot size. For knots located near the edges of the cross-section, the depth of the knot (Dz) was also recorded along the z-axis. This allowed the extent of the knot into the cross-section to be considered in addition to its surface dimensions.

The position of each knot was defined using its longitudinal coordinate (x) and transverse coordinate (y). The sign of the y-coordinate indicated the location of the knot relative to the reference axis, with positive and negative values corresponding to opposite sides of the centreline.

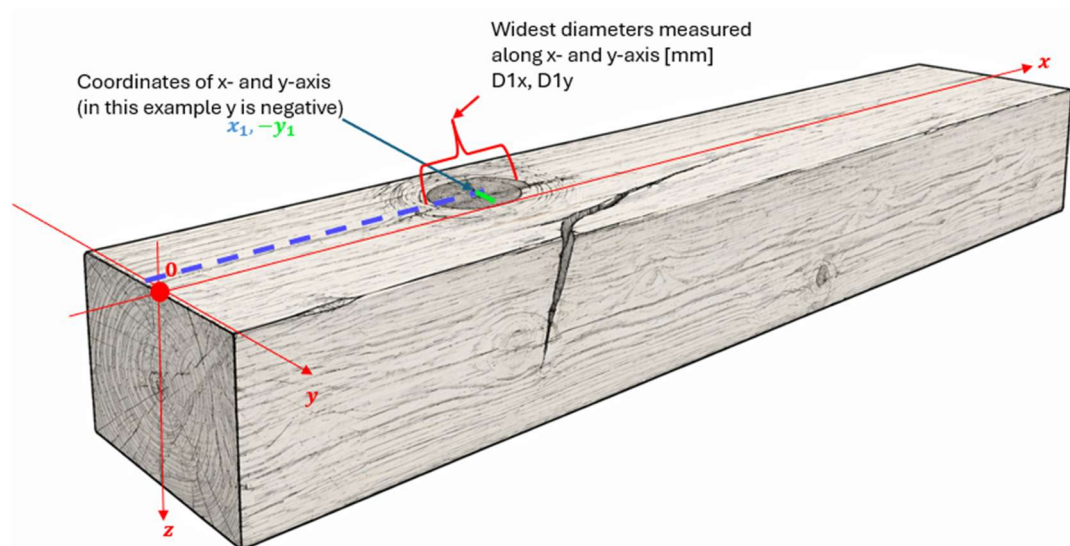


Figure 3.3.1-1 Measurement of knot size and position using the defined coordinate system, including in-plane diameters ($D1x$, $D1y$), depth (Dz) and coordinates (x, y)

Cracks were described using a bounding box approach to define their spatial extent and position. For each crack, the start point ($C1$) and end point ($C2$) were identified by their x- and y-coordinates. These points correspond to the diagonally opposite corners of the bounding box enclosing the crack. The longitudinal coordinates ($C1x$ and $C2x$) were used to determine the crack length along the beam, while the combination of x- and y-coordinates allowed the position of the crack to be defined relative to the geometry of the specimen and the reference axis.

In addition to geometric extent, the maximum opening of each crack was measured and recorded as an indicator of crack severity. This parameter provides additional

information on the potential influence of the crack on the mechanical behaviour of the timber.

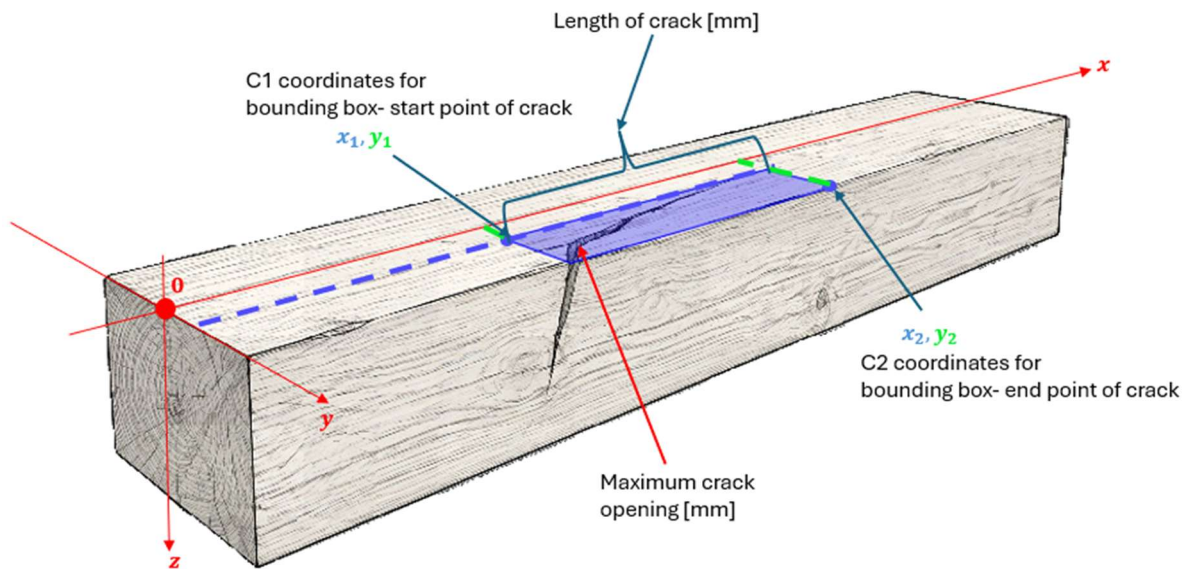


Figure 3.3.1-2 Characterisation of cracks using a bounding box approach, showing start and end coordinates (C1 and C2), crack length along the x-axis, and maximum crack opening

Cut-outs were documented using the same bounding box approach as applied for cracks. For each cut-out, the geometry of the removed section was defined by identifying two diagonally opposite points, C1 and C2, both described by their x- and y-coordinates.

The longitudinal coordinates (C1x and C2x) were used to describe the length of the cut-out along the beam, while the combination of x- and y-coordinates allowed its position to be defined relative to the geometry of the specimen and the reference axis.

In addition to the in-plane dimensions, the depth of each cut-out (z) was measured along the z-axis. This parameter describes the extent of material removal perpendicular to the surface and provides additional information on the potential influence of the cut-out on the structural behaviour.

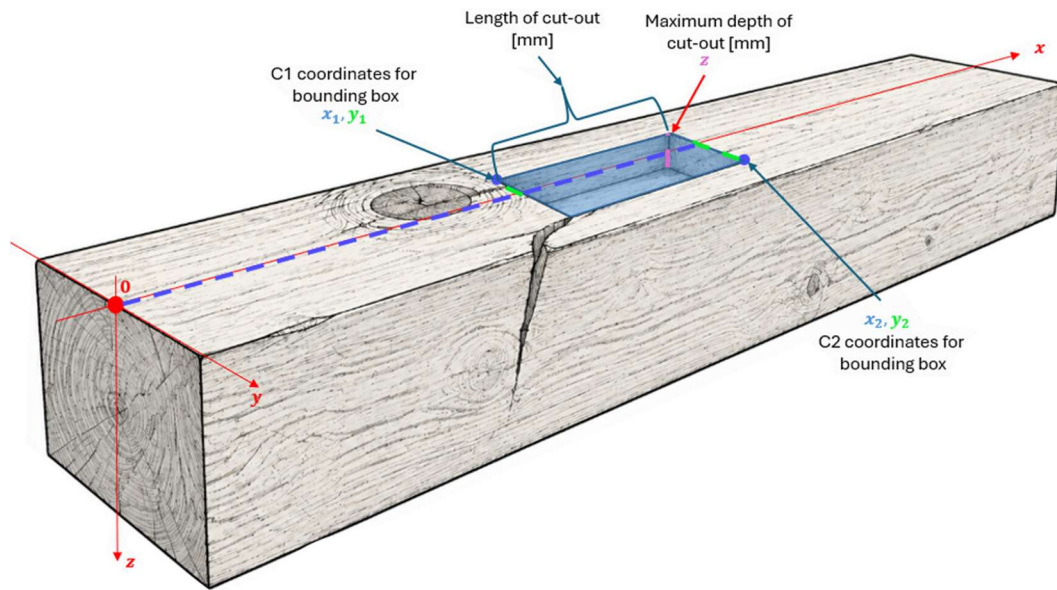


Figure 3.3.1-3 Characterisation of cut-outs using a bounding box approach, showing start and end coordinates (C1 and C2) and depth of the cut-out (z)

Wane represents a reduction in the original cross-sectional geometry and typically occurs along the edges of the timber element. Unlike the previously described features, wane is not localised to a single point but extends continuously along a portion of the beam. To describe this, the start and end points of the wane were identified along the x -axis, using coordinates x_1 and x_2 . This allowed the total length of the wane to be determined.

In addition to its longitudinal extent, the severity of the wane was characterised by measuring its maximum depth. This was done in both the transverse (y) and depth (z) directions, corresponding to the largest deviation from the original cross-sectional geometry. These measurements were taken at the locations where material loss was greatest.

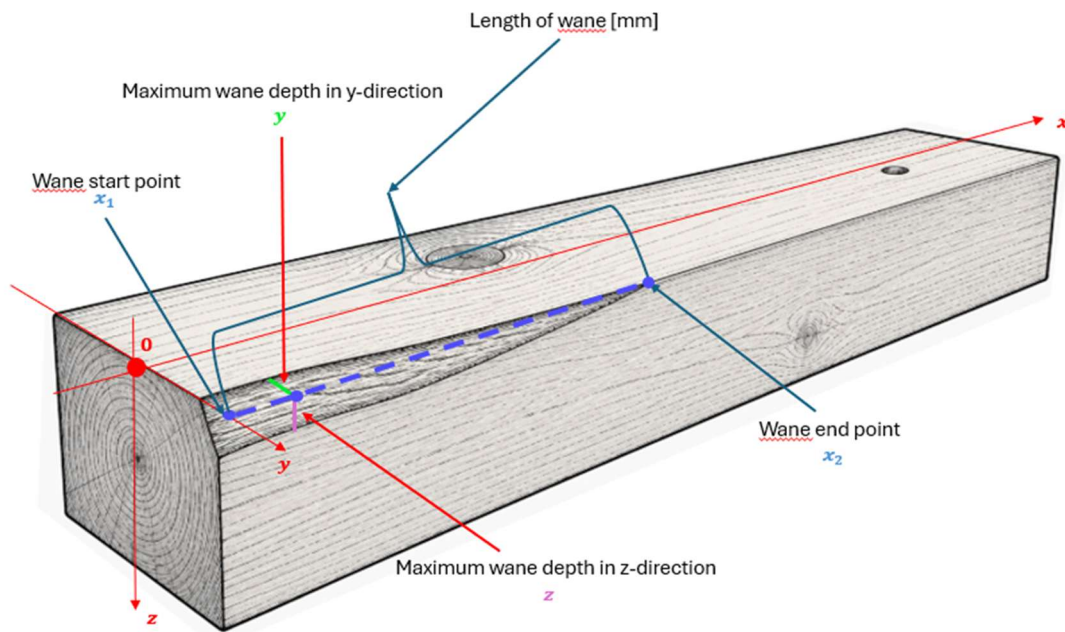


Figure 3.3.1-4 Characterisation of wane, showing start and end coordinates (x_1 and x_2), wane length along the x-axis, and maximum depth in the y- and z-directions

Holes resulting from previous mechanical fasteners were documented based on their spatial position. For each hole, the location was defined using its longitudinal coordinate (x) and transverse coordinate (y), corresponding to the coordinate system described in Section 3.3. The coordinates were determined based on the centre point of the hole. The sign of the y-coordinate indicated the position of the hole relative to the reference axis, allowing its location to be consistently described within the cross-section.

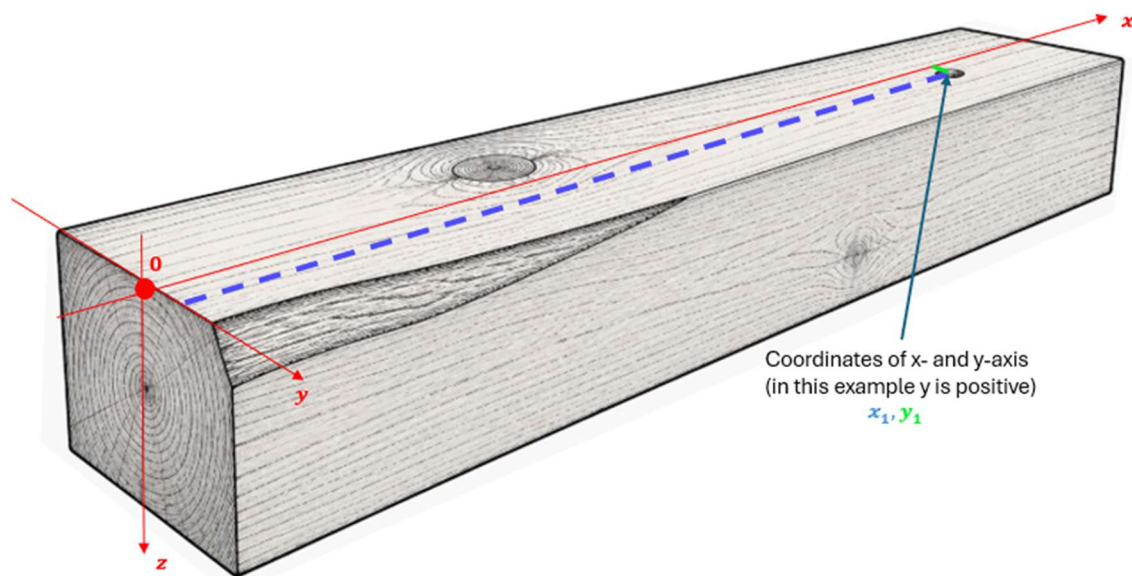


Figure 3.3.1-5 Definition of hole position using longitudinal and transverse coordinates (x , y) within the defined coordinate system

3.3.2 Visual assessment approach

The visual assessment was carried out prior to the mechanical testing and covered the full length of each specimen. In this study, the aim was not to assign strength classes or to predefine the structural performance of the timber elements. Instead, the focus was placed on systematically documenting surface-visible characteristics in a form that could later be compared directly with the measured stiffness. No qualitative judgement or ranking of the specimens was performed during this stage, allowing the visual data to remain independent from the subsequent analysis.

All observations were recorded separately for each of the four longitudinal faces, following the coordinate system defined in Section 3.3. This allowed each recorded feature to be consistently related to the orientation of the specimen during bending. Distinguishing between the faces was essential, as it enabled the distribution of characteristics to be examined with respect to their position within the cross-section.

The assessment approach was developed in accordance with the logic of the bending tests. Since the pith side was consistently positioned in the compression zone, the visual characteristics observed on each surface could be interpreted with respect to their role in the loading configuration. This created a direct link between the recorded surface features and the mechanical response of the specimen under bending.

All recorded data were stored in a structured tabular format, where each feature was described by its type, size and spatial coordinates. This approach ensured that the visual information remained objective and reproducible, while also enabling flexible post-processing and analysis. Rather than simplifying the observations into predefined categories, the full set of recorded parameters was retained to allow for a more detailed investigation of relationships between visible characteristics and stiffness.

3.4 Non-destructive bending tests according to EN 408

The bending stiffness of the timber elements was evaluated using four-point bending tests carried out in accordance with the European standard EN 408. The tests were performed using a universal electromechanical floor-standing testing machine LMF 600 manufactured by Walter+Bai AG. The specimens were tested as simply supported beams subjected to two symmetrically applied point loads.

The test setup was designed according to the requirements of EN 408 for the determination of global and local modulus of elasticity in bending. The distance between the supports was 1000 mm and the distance between the loading points was 290 mm, corresponding approximately to $6h$, where h represents the average cross-sectional

height of the tested boards. For the determination of the local modulus of elasticity, the distance between the local deformation measurement points was 240 mm, corresponding approximately to $5h$.

Each beam was tested repeatedly along its length. The specimens were loaded from side A at intervals of 250 mm, resulting in approximately 17–19 measurement positions per beam. Both global and local displacements were measured during the same loading sequence. This approach enabled the evaluation of both the overall bending behaviour of the beam and the local stiffness variations along the member length.

The general test arrangements for determining the local and global modulus of elasticity are illustrated in Figures 3.4-1 and 3.4-2. The figures present the measurement principles used in the bending tests.

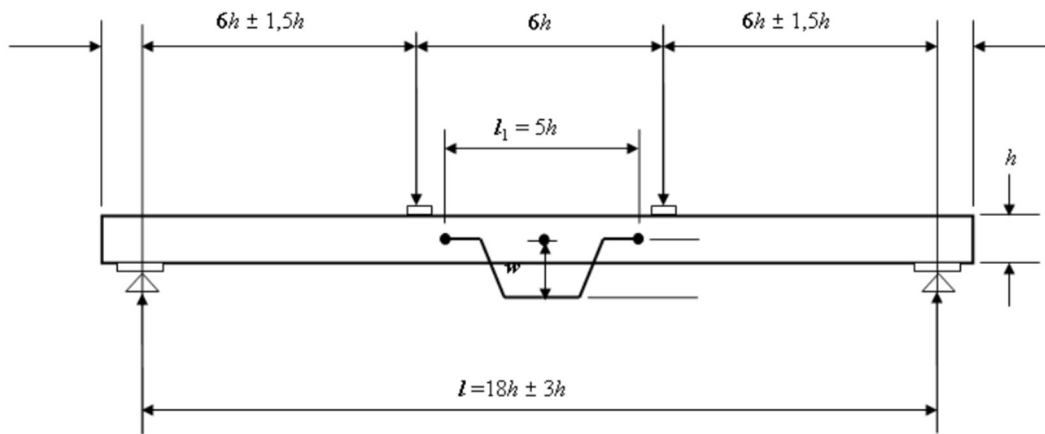


Figure 3.4-1 Principle of the test arrangement for measuring local modulus of elasticity in bending according to EN 408 [8]

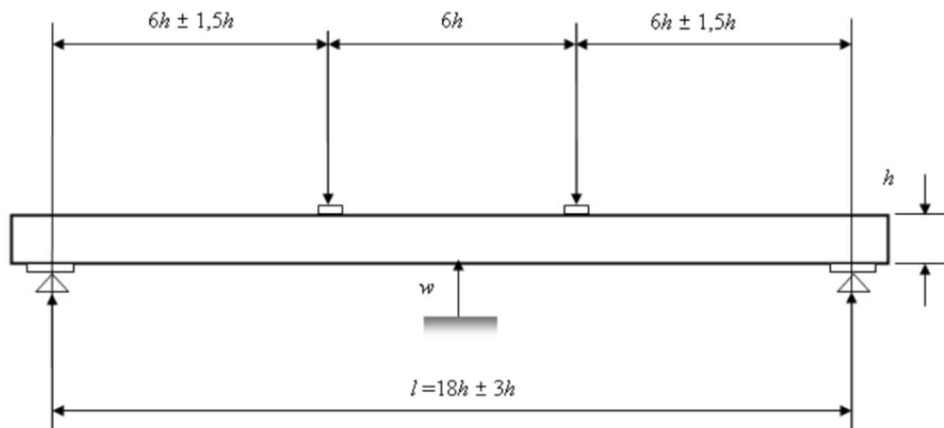


Figure 3.4-2 Principle of the test arrangement for measuring global modulus of elasticity in bending according to EN 408 [8]

The experimental setup used for the bending tests is shown in Photo 3.4-1. The figure illustrates the four-point bending configuration, support conditions and displacement measurement arrangement used during testing.

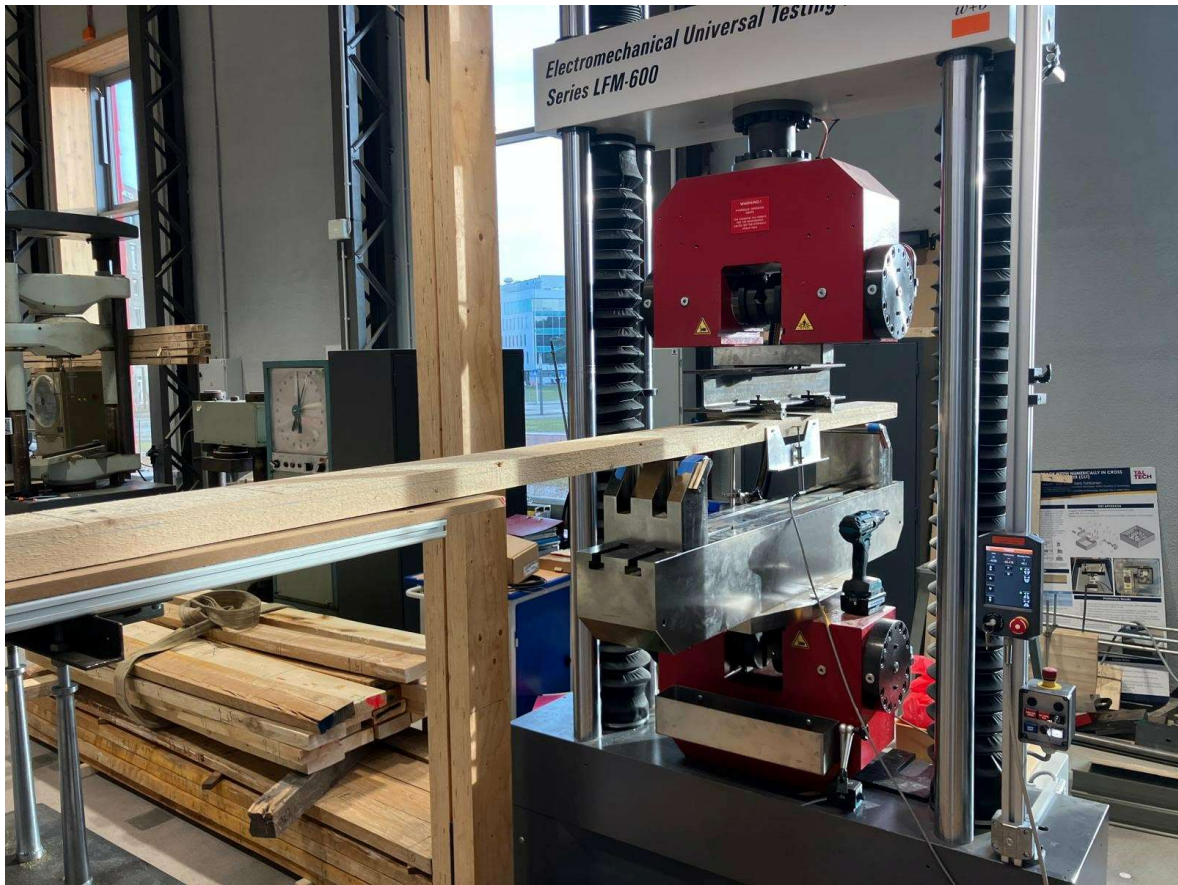


Photo 3.4-1 Experimental setup used for non-destructive four-point bending tests on reclaimed timber specimens

The applied load was limited to the elastic range of material behaviour in accordance with EN 408, where the maximum load during testing shall not exceed $0,4 F_{max, est}$. Based on preliminary theoretical calculations, $0,4 F_{max, est}$ was determined to correspond to a load level of 4 kN, representing approximately 40% of the estimated bending capacity of the specimens. The estimated bending capacity was derived from the average cross-sectional dimensions and the expected bending strength of the material.

The deformation behaviour of the specimens was recorded throughout the tests using linear displacement transducers. Local displacements were measured using WA 50 displacement sensors and global displacements using WA 100 displacement sensors, both manufactured by HBM. The displacement data together with the applied load were continuously recorded using the QuantumX MX840B universal data acquisition module and Catman Easy software.

The recorded load–displacement data were subsequently processed using a Python script developed for the analysis of the measurements. The script identified the linear region of the load–displacement curve with a correlation coefficient of at least 0.99, after which the global and local modulus of elasticity values were calculated using the corresponding expressions defined in EN 408.

3.5 Determination of modulus of elasticity

The modulus of elasticity (MoE) was used as the primary parameter to describe the bending stiffness of the timber elements. It was determined based on the relationship between the applied load and the resulting deformation within the elastic range of material behaviour. This approach allows the stiffness of the material to be quantified under controlled loading conditions. Both global and local modulus of elasticity values were determined from the load–displacement data obtained during the non-destructive bending tests described in Section 3.4.

The evaluation was based on the load–deflection relationship obtained during testing. A linear regression was performed within the load interval between $0,1 F_{max, est}$ and $0,4 F_{max, est}$, where the deformation behaviour can be assumed to be linear. The slope of the resulting relationship was used to determine the modulus of elasticity. This load range was selected to minimise the influence of initial seating effects and potential non-linear behaviour occurring at higher load levels.

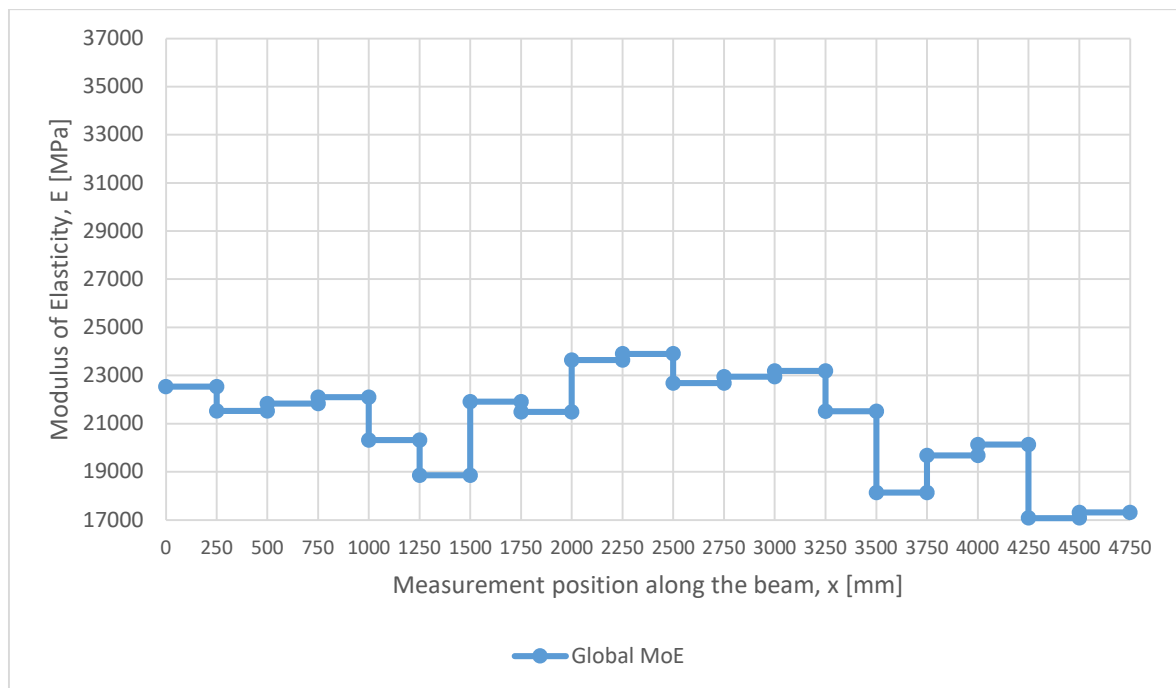
3.5.1 Global modulus of elasticity

The global modulus of elasticity describes the overall bending stiffness behaviour of the beam over the full span. Global displacement measurements were obtained during each loading sequence and used for the determination of global stiffness values at consecutive measurement positions along the beam.

The repeated measurements carried out at 250 mm intervals enabled the development of a global stiffness profile along the length of each timber element. This approach allowed the variation of global bending stiffness within individual reclaimed timber members to be evaluated.

The global modulus of elasticity is based on the total deformation measured during loading and therefore reflects the combined influence of bending and shear deformations within the member. As a result, the global modulus of elasticity provides an integral assessment of the structural behaviour of the timber element and is widely used in the evaluation of timber members for structural applications.

An example of the global modulus of elasticity profile obtained from Specimen Q1 is presented in Graphic 3.5.1-1. The graph illustrates the variation of global stiffness values measured at consecutive positions along the beam length.



Graphic 3.5.1-1 Global modulus of elasticity profile measured along a reclaimed timber beam at 250 mm intervals (Specimen Q1)

The obtained global modulus of elasticity values were used to assess the overall stiffness behaviour of the reclaimed timber elements and to compare stiffness variation between different specimens.

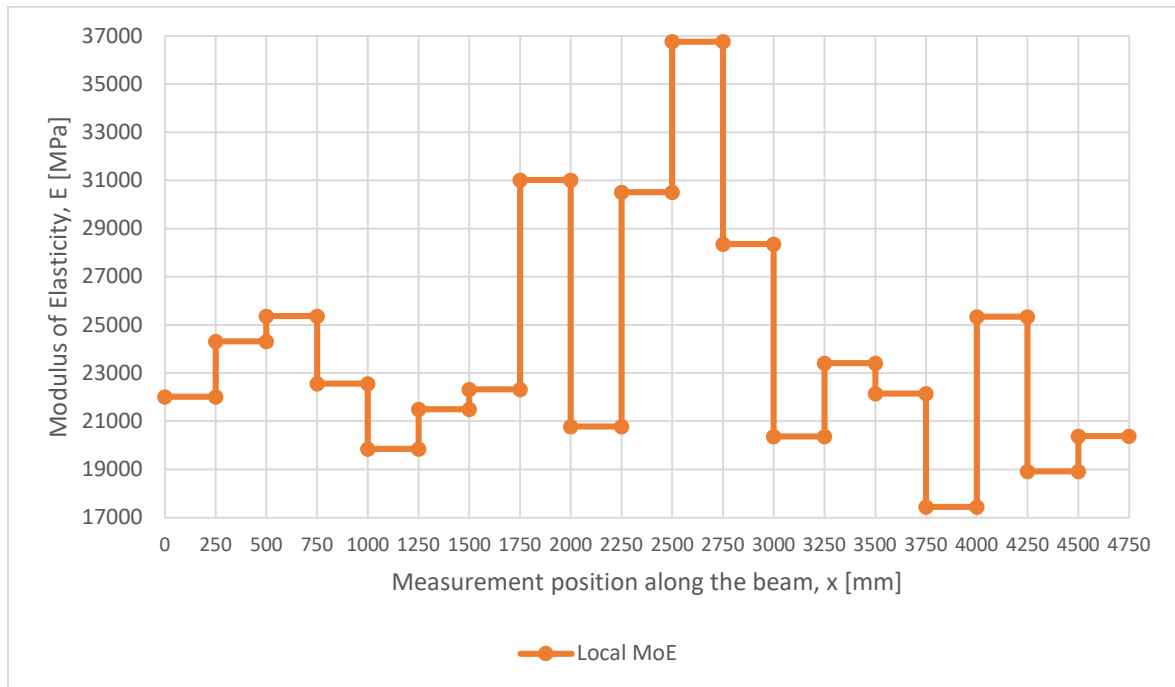
3.5.2 Local modulus of elasticity

In addition to the global evaluation, local modulus of elasticity values were determined from deformation measured within the constant bending moment region between the loading points. Local displacement measurements were recorded simultaneously with the global measurements during each loading sequence. The measurements performed at 250 mm intervals along the beam resulted in multiple local modulus of elasticity values for each timber element. This enabled the development of local stiffness profiles describing the variation of stiffness along the beam length.

Unlike the global modulus of elasticity, the local modulus of elasticity is less influenced by shear deformation and therefore reflects the local bending behaviour of the timber more directly. This makes the local evaluation more sensitive to material inhomogeneity and local defects such as knots, cracks and grain deviation. Since reclaimed timber often

exhibits considerable material variability, the local modulus of elasticity provides important information about the influence of local characteristics on mechanical behaviour.

An example of the local modulus of elasticity profile measured from Specimen Q1 is shown in Graphic 3.5.2-1. Compared to the global stiffness profile, the local measurements exhibit greater variation along the beam length, reflecting the influence of local material characteristics and defects.



Graphic 3.5.2-1 Local modulus of elasticity profile measured along a reclaimed timber beam at 250 mm intervals (Specimen Q1)

The obtained local stiffness values formed the basis for the subsequent comparison between visually assessed characteristics and the measured stiffness behaviour of the timber elements.

3.6 Relationship analysis between visual characteristics and stiffness

The analytical approach used in this study was based on combining the results of the visual assessment with the stiffness measurements obtained from the EN 408 bending tests. The purpose of the analysis was to evaluate whether visually observable characteristics identified on the surfaces of reclaimed timber members corresponded to variations in the measured modulus of elasticity. By examining the relationship between

visible characteristics and stiffness behaviour, the analysis also contributes to the broader understanding required for the future development of more reliable assessment and prediction approaches for reclaimed structural timber.

Since both the visual observations and the stiffness measurements were recorded along the longitudinal axis of the specimens, the datasets could be linked using a common coordinate system. This enabled the measured modulus of elasticity values to be compared directly with the location and distribution of visually observable characteristics along the beam length. The analytical procedure included comparison between local and global modulus of elasticity values, evaluation of different defect types and examination of knot severity in relation to measured stiffness values.

3.6.1 Spatial comparison of visual characteristics and stiffness

The comparison between visual characteristics and stiffness behaviour was carried out using measurement intervals defined at 250 mm spacing along the timber members. Both the visual assessment data and the stiffness measurements were organised according to their longitudinal position, allowing the occurrence of visible characteristics to be related to the corresponding stiffness values within the same region of the beam. This approach enabled the development of stiffness profiles together with the spatial distribution of visually observable defects along individual timber members.

In addition to recording the occurrence of defects, knot severity was evaluated using the *ratio_i* parameter, which describes the relationship between knot size and the corresponding cross-sectional dimension. Maximum *ratio_i* values were determined separately for each longitudinal face within the corresponding measurement interval. The use of *ratio_i* values allowed knot-related characteristics to be analysed not only according to their presence, but also according to their relative size within the cross-section. The obtained values were subsequently compared with both local and global modulus of elasticity values measured within the same beam regions.

Figure 3.6.1-1 illustrates an example of how visually identified knot features were compared with the measured stiffness profiles along one reclaimed timber specimen. The figure demonstrates the longitudinal relationship between knot distribution and the corresponding local and global modulus of elasticity values obtained from the bending tests.

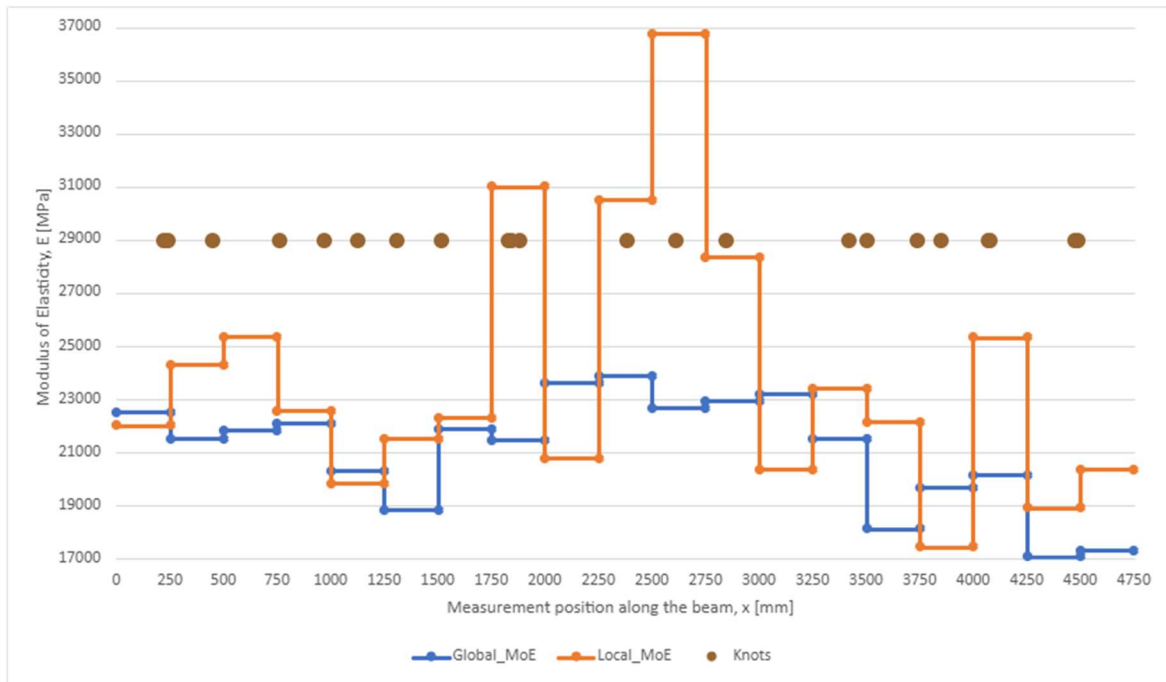


Figure 3.6.1-1 Comparison between global and local modulus of elasticity and the longitudinal distribution of visually identified knots on face C of specimen Q1.

The comparison was performed separately for local and global modulus of elasticity values to evaluate differences between the two stiffness measurement approaches. Local modulus of elasticity values describe the stiffness behaviour within a more limited section of the timber member and are therefore more sensitive to local variations within the material. Global modulus of elasticity values, on the other hand, represent the overall bending response over a larger beam length and provide a more integrated description of the structural behaviour of the specimen. Evaluating both measurement approaches within the same analytical framework made it possible to compare how localised visual characteristics relate to different representations of stiffness behaviour.

3.6.2 Comparative and statistical evaluation

The visually observable characteristics identified during the assessment were grouped according to defect type to evaluate their relationship with the measured modulus of elasticity values. The analysed characteristics included knots, cracks, holes and cut-outs observed on the timber surfaces. In the comparative defect analysis, the total occurrence of each defect type was determined for every timber member, allowing the overall amount of visually observable characteristics within individual specimens to be compared with the corresponding local and global modulus of elasticity values.

The analysis included both specimen-level evaluation and comparison across the complete dataset. Local and global modulus of elasticity values were examined using

descriptive statistical methods and graphical comparisons to evaluate differences in distribution, variability and overall stiffness behaviour between the two measurement approaches. Correlation analysis was additionally used to examine potential relationships between defect occurrence, maximum *ratio_i* values and measured stiffness values. The analytical approach focused on evaluating how the type, severity and spatial distribution of visually observable characteristics correspond to stiffness behaviour in reclaimed timber members and how such relationships may support the future development of assessment methods for structural reuse.

4. CALCULATIONS

Local modulus of elasticity $E_{m,l} \left[\frac{N}{mm^2} \right]$ was determined based on the load–deflection curves in accordance with EVS-EN 408:2010+A1:2012. [8] The longest continuous segment of the curve with a correlation coefficient of ≥ 0.99 was identified within the load interval between $0,1 F_{max, est}$ and $0,4 F_{max, est}$. This segment was required to include at least the range from $0,2 F_{max, est}$ and $0,3 F_{max, est}$. The local modulus of elasticity was then calculated using the following expression:

$$E_{m,l} = \frac{al_1^2(F_2 - F_1)}{16I(w_2 - w_1)} \quad (4.1)$$

where

- a is distance between a loading position and the nearest support in a bending test, in millimetres;
- l_1 is gauge length for the determination of modulus of elasticity or shear modulus, in millimetres;
- I second moment of area, in millimetres to the fourth power;
- $(F_2 - F_1)$ is an increment of load in newtons on the regression line with a correlation coefficient of 0,99 or better;
- $(w_2 - w_1)$ is the increment of deformation corresponding to $F_2 - F_1$, in millimetres.

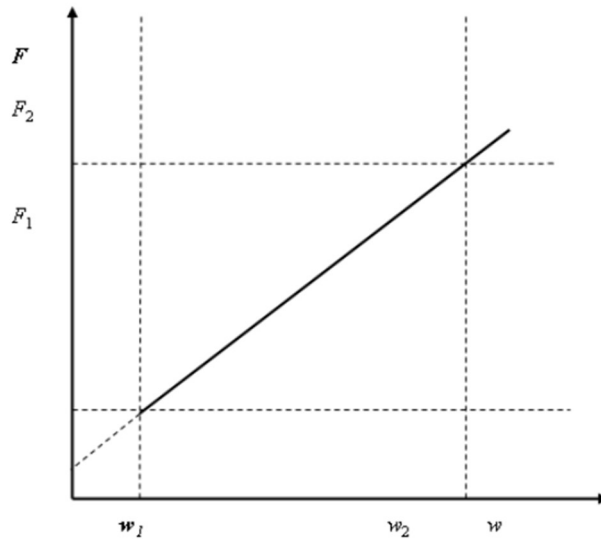


Figure 3.6.2-1 Load-deformation graph within the range of elastic deformation [8]

Global modulus of elasticity $E_{m,g} \left[\frac{N}{mm^2} \right]$ was determined from the load–deflection curves in accordance with EVS-EN 408:2010+A1:2012. The longest continuous segment with a correlation coefficient of ≥ 0.99 was identified within the load interval between $0,1 F_{max, est}$ and $0,4 F_{max, est}$. This segment was required to include at least the range from

0,2 $F_{max, est}$ and 0,3 $F_{max, est}$. The global modulus of elasticity was then calculated using the following expression:

$$E_{m,g} = \frac{3al^2 - 4a^3}{2bh^3 \left(2 \frac{w_2 - w_1}{F_2 - F_1} - \frac{6a}{5Gbh} \right)} \quad (4.2)$$

where

- b is width of cross section in a bending test, in millimetres;
- h is depth of cross section in a bending test, in millimetres;
- G is the shear modulus taken as 650 N/mm² (for coniferous wood species);
- $(F_2 - F_1)$ is an increment of load in newtons on the regression line with a correlation coefficient of 0,99 or better;
- $(w_2 - w_1)$ is the increment of deformation corresponding to $F_2 - F_1$, in millimetres.

5. RESULTS AND DISCUSSION

5.1 Overview of the investigated dataset

The investigated dataset consisted of twelve reclaimed timber specimens originating from previously used structural timber members. Following the visual assessment and EN 408 bending tests, each specimen was characterised according to the occurrence of visually observable defects, knot severity and measured stiffness properties. The collected dataset therefore combined both visual and mechanical information, allowing the relationship between visible characteristics and stiffness behaviour to be evaluated in later stages of the analysis.

Table 5.1-1 Summary of visually observable characteristics and stiffness values of the investigated reclaimed timber specimens

Beam	Count of defects					Average maximum ratio_i	Average global MoE [MPa]	Average local MoE [MPa]
	Knots	Cracks	Holes	Cut-outs	Wane			
Q1	83	4	15	2	-	0,219	21096	23862
U2	65	3	6	-	-	0,285	17695	18059
T3	49	22	-	-	5	0,122	17639	22250
X3	106	37	-	4	-	0,391	12949	14008
U1	51	30	5	-	-	0,252	21285	22527
U3	65	17	2	-	-	0,236	19681	17220
T1	80	50	2	2	2	0,111	16616	17654
S2	132	21	18	1	-	0,356	12376	13269
Q3	90	26	2	1	-	0,236	16140	20367
W1	71	36	4	2	-	0,643	16805	21101
Q2	123	17	10	1	-	0,258	18611	17967
O2	115	18	3	-	1	0,508	12643	11945

Table 5.1-1 summarises the visually observable characteristics identified within each investigated timber specimen together with the corresponding global and local modulus of elasticity values obtained from the bending tests. Considerable variability was observed between the specimens in terms of both defect occurrence and measured stiffness values. The number of identified knots ranged from 49 to 132 per specimen, while the number of cracks varied between 3 and 50. Holes and cut-outs occurred less frequently within the investigated material, although their occurrence also differed noticeably between individual specimens.

Variability was also observed in the measured stiffness values. The global modulus of elasticity values ranged from 12 376 MPa to 21 285 MPa, whereas the local modulus of elasticity values ranged from 11 945 MPa to 23 862 MPa. In addition to the measured stiffness values, the maximum *ratio_i* values differed considerably between the specimens, indicating substantial variation in the severity of knot-related characteristics within the reclaimed timber members. Some specimens exhibited relatively moderate defect severity together with comparatively high stiffness values, while others contained larger *ratio_i* values and lower measured stiffness properties, illustrating the heterogeneous nature of the investigated material.

The overall distribution of visually observable characteristics within the dataset is presented in Figure 5.1-1, where the occurrence of different defect types is shown separately for each longitudinal beam face.

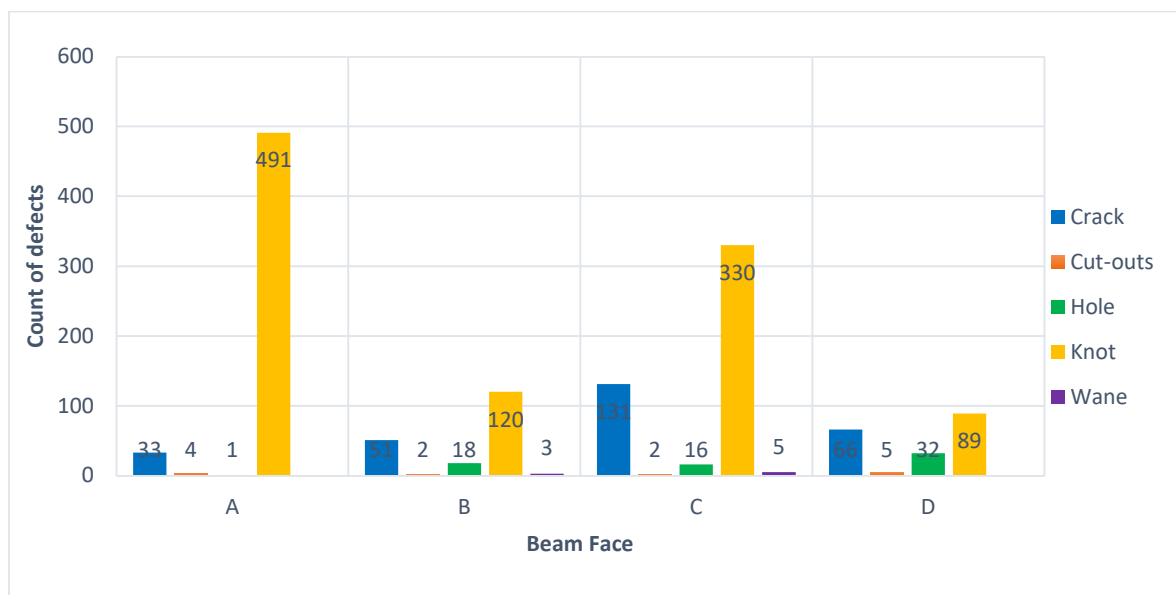


Figure 5.1-1 Distribution of visually observable defects by beam face and defect type within the investigated reclaimed timber dataset

Figure 5.1-1 illustrates that knots represented the most dominant visually observable characteristic within the investigated material and occurred considerably more frequently than other defect types on all beam faces. The largest number of knots was recorded on faces A and C, whereas faces B and D generally exhibited lower overall defect counts. Compared with knots, cracks, holes, cut-outs and wane occurred less frequently throughout the investigated material, although their distribution still varied noticeably between the beam faces.

The presented defect distribution provides a general overview of the visually observable characteristics identified within the investigated reclaimed timber dataset. Together with

the measured modulus of elasticity values summarised in Table 5.1-1, the dataset formed the basis for the subsequent comparison between stiffness behaviour and visually observable characteristics.

5.2 Comparative evaluation of global and local modulus of elasticity

The investigated reclaimed timber specimens exhibited variability not only in the occurrence of visually observable characteristics, but also in the measured stiffness values. In order to evaluate how the stiffness behaviour differed between the two measurement approaches, the global and local modulus of elasticity datasets were compared with respect to their variability, distribution and overall behaviour.

Table 5.2-1 Descriptive statistics of global and local modulus of elasticity values of the investigated reclaimed timber specimens

	Count	Average [MPa]	Standard deviation [MPa]	Coefficient of variation	E _{0,05} [MPa]
Global	12	16960	3067	18,1%	11649
Local	12	18350	3842	20,9%	11715

The descriptive statistics presented in Table 5.2-1 indicate that the local modulus of elasticity values were generally higher and more variable than the corresponding global values. The average local modulus of elasticity was 18 350 MPa, whereas the average global modulus of elasticity was 16 960 MPa. In addition to the higher mean value, the local measurements also exhibited larger standard deviation and coefficient of variation values compared with the global modulus of elasticity measurements.

The coefficient of variation values of 18.1% for the global modulus of elasticity and 20.9% for the local modulus of elasticity indicate moderate variability within both datasets. However, the higher variability observed in the local measurements suggests greater sensitivity to local stiffness fluctuations and material heterogeneity within the reclaimed timber specimens. These differences in variability and distribution are also reflected in Figure 5.2-1.

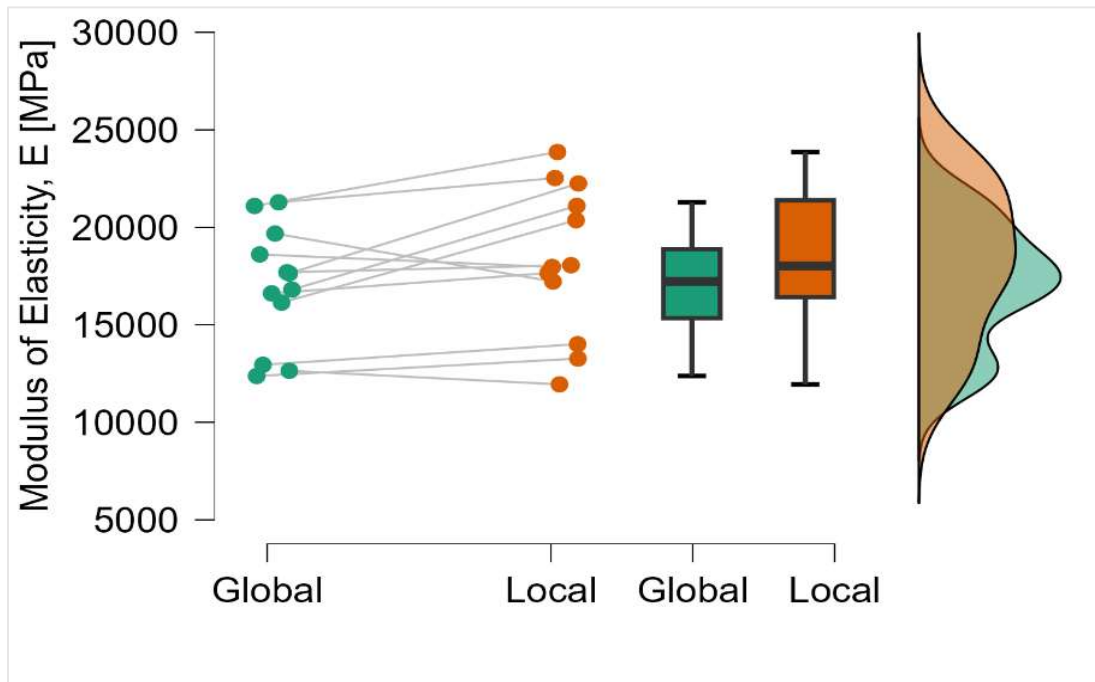


Figure 5.2-1 Comparison of global and local modulus of elasticity values of the investigated reclaimed timber specimens using paired observations, boxplots and density distributions

Figure 5.2-1 illustrates the distribution and variability of the measured global and local modulus of elasticity values. The paired observations shown on the left side of the figure enable direct comparison between the two measurement approaches for each individual specimen. In most cases, the paired values shifted from the global modulus of elasticity towards higher local modulus of elasticity values, indicating that the local measurements produced higher stiffness values.

In some specimens, the difference between the local and global modulus of elasticity values was noticeably larger than in the remaining dataset. One possible explanation may be related to the presence of longitudinal cracks within the measurement region during local stiffness evaluation. During testing, it was observed that if part of the local deformation measurement system was positioned across an existing crack, the measured deformation behaviour could be influenced by crack opening rather than by bending deformation alone. Under loading, the crack may have opened locally while the surrounding timber section exhibited limited bending deformation, potentially resulting in artificially increased local modulus of elasticity values.

The boxplots presented in the centre of the figure describe the median values, interquartile ranges and overall spread of the measured data. The local modulus of elasticity values exhibited both a higher median value and a wider interquartile range compared with the global measurements, indicating greater variability within the local

stiffness measurements. According to the Tukey fence criterion, all measured values remained within the calculated upper and lower boundaries of the boxplots, indicating the absence of statistical outliers within the investigated dataset.

The density distributions shown on the right side of the figure illustrate the overall shape and overlap of the measured datasets. Both measurement approaches exhibited relatively similar distribution patterns without pronounced skewness or isolated extreme values. However, the local modulus of elasticity values displayed a broader distribution, further indicating greater sensitivity to local stiffness fluctuations within the reclaimed timber material.

5.2.1 Statistical evaluation and characteristic stiffness values

In addition to the graphical comparison presented in Figure 5.2-1, statistical analysis was performed to evaluate the distribution characteristics of the measured stiffness datasets and to assess the similarity between the global and local modulus of elasticity values. The statistical evaluation included Shapiro–Wilk normality tests, Q–Q plot analysis and ANOVA comparison between the two measurement approaches.

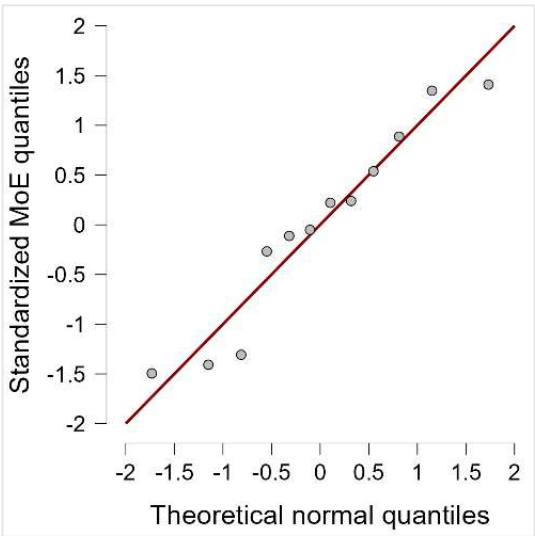


Figure 5.2.1-1 Q-Q plot of global modulus of elasticity dataset

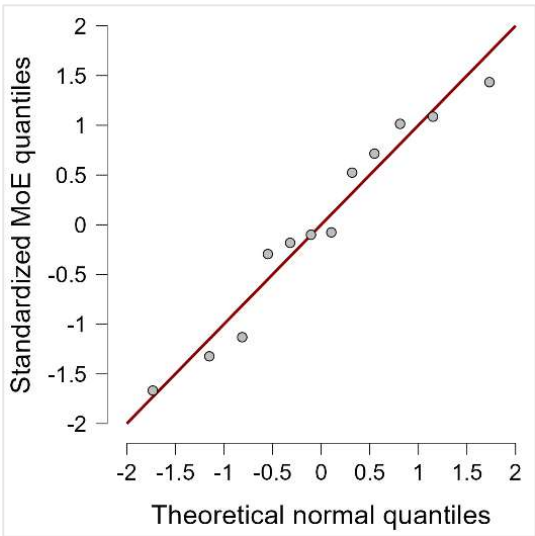


Figure 5.2.1-2 Q-Q plot of local modulus of elasticity dataset

Table 5.2.1-1 Statistical parameters and normality test results of the global and local modulus of elasticity datasets

	Global MoE	Local MoE
Count	12	12
Mean (arithmetic)	16960	18350
Std. Deviation	3067	3842
Shapiro-Wilk	0.925	0.948
P-value of Shapiro-Wilk	0.331	0.607
Minimum	12380	11950
Maximum	21290	23860

The Q-Q plots presented in Figure 5.2.1-1 illustrate the relationship between the theoretical normal distribution and the measured stiffness datasets. For both global and local modulus of elasticity values, the measured data points followed the theoretical diagonal trend relatively closely, indicating no substantial deviation from normal distribution behaviour. Slight deviations from the reference line were observed at the extreme ends of the datasets, which is expected considering the relatively limited sample size of the investigated reclaimed timber specimens.

The results of the Shapiro-Wilk normality tests further supported the observations obtained from the Q-Q plots. The calculated p-values remained above the significance threshold of 0.05 for both datasets, indicating that the null hypothesis of normal distribution could not be rejected for either the global or local modulus of elasticity values. The obtained p-values were 0.331 for the global modulus of elasticity dataset and 0.607 for the local modulus of elasticity dataset.

Since the investigated datasets did not exhibit substantial deviation from normal distribution behaviour, indicative characteristic stiffness values were estimated using the mean values and coefficients of variation presented previously in Table 5.2-1. The calculated characteristic modulus of elasticity values $E_{0.05}$ were 11 649 MPa for the global modulus of elasticity dataset and 11 715 MPa for the local modulus of elasticity dataset. Although the local modulus of elasticity values exhibited a higher average stiffness value, the greater variability observed within the local measurement dataset resulted in characteristic stiffness values that remained relatively close to those obtained from the global measurements.

In addition to the normality evaluation, ANOVA analysis was performed to compare the global and local modulus of elasticity datasets statistically. The analysis did not identify

a statistically significant difference between the two measurement approaches. Despite local modulus of elasticity measurements generally producing somewhat higher stiffness values, the overall stiffness behaviour described by both datasets remained broadly similar within the investigated reclaimed timber material.

The statistical similarity between the global and local modulus of elasticity datasets suggests that global modulus of elasticity measurements may provide a practical and less time-consuming approach for preliminary stiffness assessment of reclaimed timber members. At the same time, the local modulus of elasticity measurements remained more sensitive to local material variability and visually observable characteristics within the timber specimens.

5.3 Relationship between visually observable characteristics and stiffness

Following the evaluation of the global and local modulus of elasticity datasets, the relationship between visually observable characteristics and measured stiffness behaviour was analysed in greater detail. The objective of the analysis was to examine whether specific defect types or knot-related characteristics exhibited identifiable relationships with the measured stiffness values of the reclaimed timber specimens. Since reclaimed timber exhibits substantial natural variability and often contains multiple simultaneously occurring characteristics, the analysis focused primarily on identifying overall trends and spatial relationships rather than establishing direct causal relationships between individual defects and stiffness behaviour.

5.3.1 Defect occurrence and stiffness behaviour

To evaluate the relationship between visually observable characteristics and stiffness behaviour, the occurrence of different defect types within each reclaimed timber specimen was compared with the corresponding global and local modulus of elasticity values. The analysis included knots, cracks, holes and cut-outs identified during the visual assessment. For each specimen, the total number of observed defects was compared with the average global and local modulus of elasticity values obtained from the bending tests.

Table 5.3.1-1 Pearson correlation coefficients between visually observable defect occurrence and measured modulus of elasticity values.

	Global MoE				Local MoE			
	Knots	Cracks	Holes	Cut-outs	Knots	Cracks	Holes	Cut-outs
Pearson's r	-0,657	-0,283	0,059	-0,300	-0,704	-0,105	-0,006	-0,109
p	0,020	0,373	0,856	0,344	0,011	0,745	0,985	0,736

The correlation analysis presented in Table 5.3.1-1 indicates that knots exhibited the strongest relationship with the measured stiffness values among all investigated visually observable characteristics. A statistically significant negative correlation was observed between knot occurrence and both global modulus of elasticity ($r = -0.657$, $p = 0.020$) and local modulus of elasticity ($r = -0.704$, $p = 0.011$). The obtained results indicate that specimens containing a larger number of knots generally exhibited lower stiffness values.

Compared with knots, the remaining investigated defect types exhibited substantially weaker relationships with stiffness behaviour. Cracks showed weak negative correlations with both global and local modulus of elasticity values, although the obtained relationships were not statistically significant. Similarly, holes and cut-outs did not demonstrate meaningful relationships with the measured stiffness datasets within the investigated material.

The stronger relationship observed between knot occurrence and stiffness behaviour is consistent with the structural influence of knots on wood material behaviour. Knots interrupt fibre continuity and introduce local grain deviations within the timber structure, which may reduce the ability of the material to resist bending deformation efficiently. In reclaimed timber members, where natural variability and multiple simultaneously occurring characteristics are common, the influence of knots may therefore become more pronounced compared with other visually observable defect types.

Although several defect types exhibited only weak or statistically non-significant relationships with stiffness behaviour, the obtained results do not necessarily indicate that these characteristics are mechanically irrelevant. The relatively limited sample size together with the heterogeneous nature of reclaimed timber may have reduced the statistical sensitivity of the analysis. In addition, the interaction between multiple simultaneously occurring characteristics within the same timber member may further complicate the direct interpretation of individual defect effects.

Overall, the correlation analysis suggests that knots represented the visually observable characteristic most consistently associated with reduced stiffness behaviour within the investigated reclaimed timber dataset. Based on these observations, further analysis was focused on the relationship between knot severity and spatial stiffness behaviour using the *ratio_i* parameter.

5.3.2 Spatial relationship between knot severity and spatial stiffness behaviour

In addition to evaluating the overall occurrence of visually observable defects, knot-related characteristics were analysed in greater detail using the *ratio_i* parameter, which describes the relationship between knot size and the corresponding cross-sectional dimension. Maximum *ratio_i* values were determined separately for each longitudinal beam face within consecutive 250 mm measurement intervals and compared with the corresponding modulus of elasticity profiles measured along the same reclaimed timber specimen.

Table 5.3.2-1 Longitudinal modulus of elasticity profiles and maximum *ratio_i* values for specimen Q1

X [mm]	Global MoE [MPa]	Local MoE [MPa]	Max_ratio_A	Max_ratio_B	Max_ratio_C	Max_ratio_D
0	22535	22020	0,063	0,000	0,000	0,047
250	22535	22020	0,063	0,000	0,063	0,000
500	21533	24322	0,125	0,078	0,063	0,000
750	21835	25363	0,078	0,000	0,047	0,063
1000	22102	22567	0,078	0,047	0,070	0,000
1250	20319	19855	0,078	0,000	0,070	0,000
1500	18853	21503	0,063	0,000	0,039	0,000
1750	21909	22315	0,109	0,000	0,133	0,000
2000	21490	31011	0,219	0,063	0,133	0,125
2250	23638	20777	0,094	0,000	0,047	0,047
2500	23905	30511	0,094	0,000	0,078	0,047
2750	22685	36767	0,109	0,000	0,094	0,000
3000	22948	28360	0,141	0,000	0,000	0,125
3250	23189	20372	0,141	0,047	0,000	0,125
3500	21520	23411	0,102	0,000	0,141	0,000
3750	18135	22147	0,125	0,070	0,094	0,000
4000	19681	17449	0,117	0,000	0,148	0,000
4250	20136	25334	0,047	0,000	0,000	0,000
4500	17086	18918	0,086	0,000	0,148	0,000
4750	17320	20375	0,117	0,000	0,133	0,000

Table 5.3.2-1 presents the longitudinal stiffness profiles together with the corresponding maximum *ratio_i* values determined separately for each beam face. The table illustrates how both the measured stiffness values and knot severity varied along the timber member within the investigated measurement intervals. Considerable variation was observed in both the global and local modulus of elasticity values throughout the specimen length, while the maximum *ratio_i* values also fluctuated between different beam regions and faces.

To visualise the spatial relationship between knot severity and stiffness behaviour more clearly, the measured modulus of elasticity profiles and maximum *ratio_i* values were also compared graphically separately for each beam face. Figures 5.3.2-1 and 5.3.2-2 present example comparisons from specimen Q1 for faces A and C.

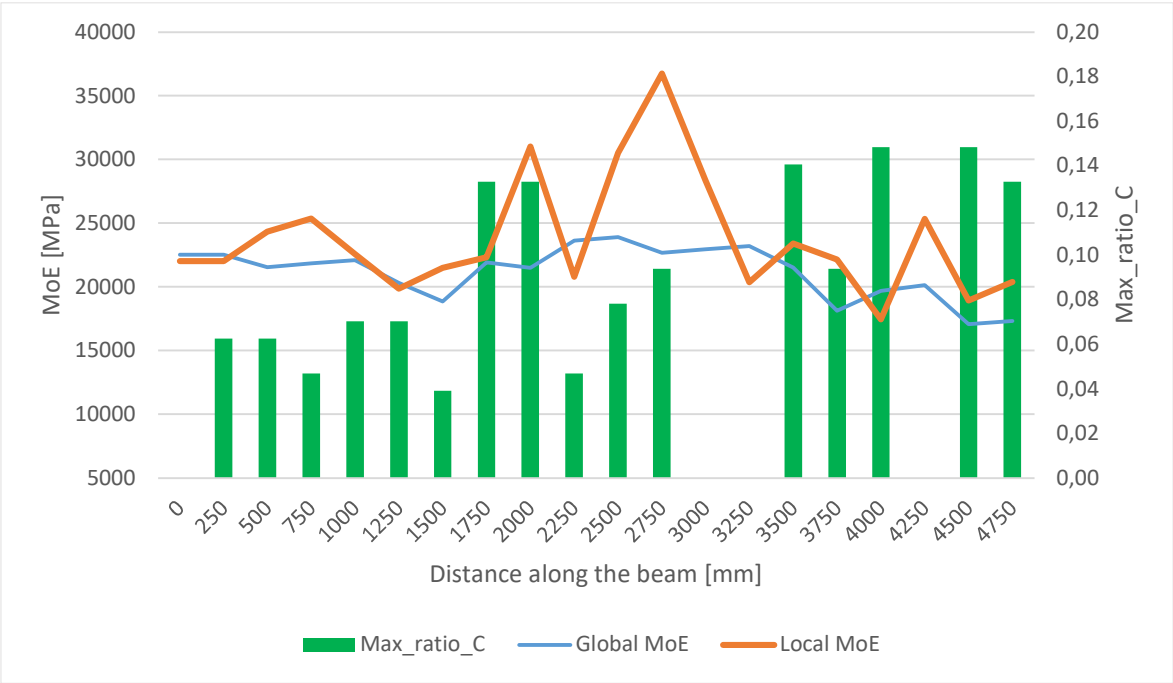


Figure 5.3.2-1 Example comparison between longitudinal modulus of elasticity profiles and knot severity values on tension face of specimen Q1

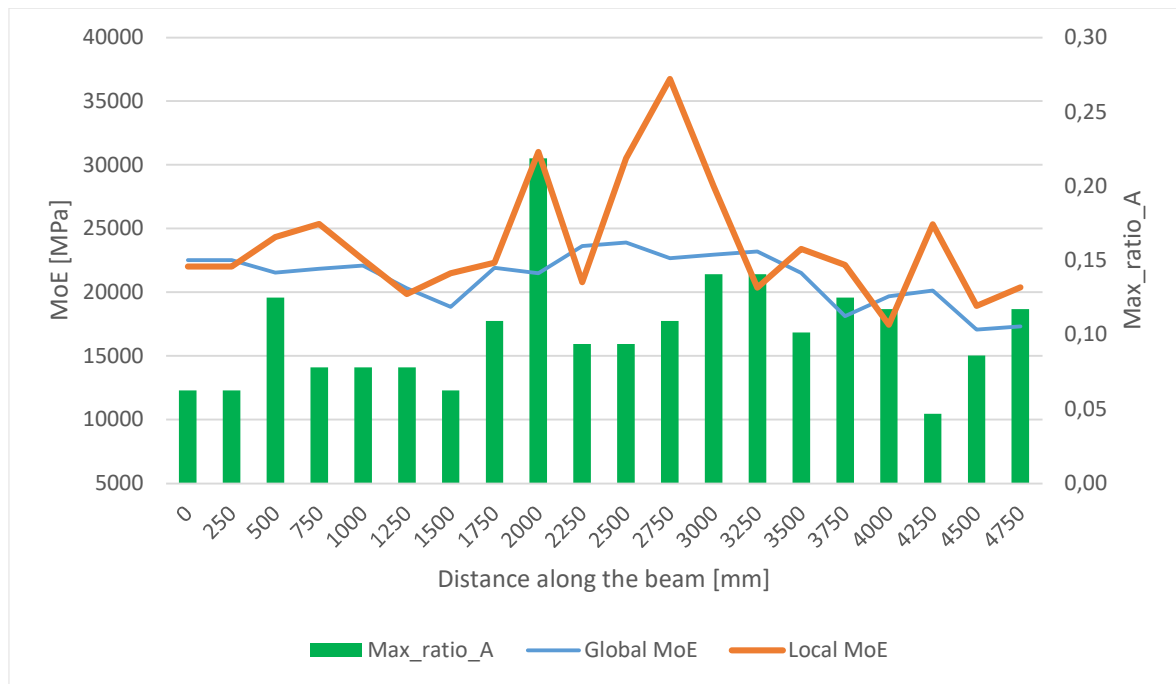


Figure 5.3.2-2 Example comparison between longitudinal modulus of elasticity profiles and knot severity values on compression face of specimen Q1

Figures 5.3.2-1 and 5.3.2-2 demonstrate that stiffness behaviour was not uniform throughout the reclaimed timber specimen, as both global and local modulus of elasticity values exhibited local fluctuations between neighbouring measurement regions. Compared with the global modulus of elasticity profiles, the local modulus of elasticity values generally showed larger changes between consecutive measurement intervals, indicating greater sensitivity to local material irregularities occurring within the evaluated beam regions.

Several local stiffness variations appeared to spatially coincide with regions containing elevated *ratio_i* values on the analysed beam faces. In particular, local reductions in modulus of elasticity values were observed near regions where larger knot severity values occurred within the investigated measurement intervals. At the same time, the relationship between knot severity and stiffness behaviour did not remain entirely consistent throughout the specimen, as some regions containing increased *ratio_i* values were associated with more pronounced stiffness changes than others.

The observed behaviour further highlights the complexity of relating visually observable characteristics directly to stiffness behaviour in reclaimed timber members. In addition to knot size, the mechanical influence of knot-related characteristics is likely affected by factors such as fibre orientation, knot geometry and the interaction between multiple simultaneously occurring defects within the timber member. Since the local modulus of elasticity values describe stiffness behaviour within a more limited beam region, the

local measurements also appeared more sensitive to localised material irregularities occurring along the specimen.

Although the presented comparisons do not establish a direct causal relationship between knot severity and stiffness behaviour, they provide a visual representation of how local stiffness variations may spatially coincide with regions containing more severe knot-related characteristics within reclaimed structural timber.

5.4 Limitations and future research

The results of the present study demonstrated that visually observable characteristics, particularly knot-related features, exhibited identifiable relationships with the stiffness behaviour of reclaimed structural timber. At the same time, the obtained results also highlighted the complex and heterogeneous nature of reclaimed timber material, where stiffness behaviour is influenced by multiple simultaneously occurring factors rather than by individual characteristics alone. The relationship between visually observable characteristics and measured stiffness behaviour therefore cannot always be interpreted as uniform or directly proportional throughout the investigated timber members.

One important aspect affecting the interpretation of the results was the relatively limited number of investigated reclaimed timber specimens. Due to the naturally heterogeneous nature of reclaimed timber, substantial variability may occur between individual members depending on factors such as growth conditions, previous service history, ageing effects and the distribution of defects within the timber structure. Although several consistent trends were identified within the investigated dataset, a larger sample size would improve the statistical reliability of the observed relationships and provide a broader representation of reclaimed structural timber behaviour. Expanding the investigated dataset would also provide better opportunities for evaluating how different visually observable characteristics influence stiffness behaviour under varying material conditions.

The study further demonstrated that visual assessment alone may not fully capture all characteristics affecting the mechanical behaviour of reclaimed timber members. While visually observable knot-related characteristics showed the strongest relationship with the measured modulus of elasticity values, the stiffness behaviour of reclaimed timber is also likely influenced by factors such as fibre orientation, local grain deviation, internal cracking and the interaction between multiple simultaneously occurring defects. Some local stiffness variations may therefore originate from characteristics that cannot be fully identified through surface-based visual inspection alone.

Despite these limitations, the applied methodology provided useful insight into how local stiffness variations may spatially coincide with visually observable knot severity within reclaimed timber members. The combination of visual assessment data, stiffness measurements and longitudinal profile comparisons enabled the behaviour of reclaimed timber to be evaluated from both spatial and statistical perspectives. The obtained results therefore support the potential of combining systematic visual assessment with stiffness evaluation methods when assessing reclaimed timber for structural reuse applications.

Future research could further develop the presented methodology by including larger reclaimed timber datasets, additional timber species and different cross-sectional dimensions. Increasing the number of investigated specimens would improve the statistical robustness of the observed relationships and provide a more representative overview of reclaimed timber variability. Additional research could also investigate how the location and orientation of visually observable characteristics within the cross-section influence stiffness behaviour during bending.

Further development of reclaimed timber assessment methods may also benefit from combining visual assessment with advanced non-destructive evaluation techniques capable of providing information about the internal structure of timber members. Methods such as CT scanning, ultrasonic testing and automated image-based defect recognition may improve the understanding of how internal and surface-visible characteristics together influence stiffness behaviour. In the future, combining systematic visual assessment data with mechanical testing and non-destructive evaluation methods may contribute towards the development of more efficient stiffness estimation and grading procedures supporting the structural reuse of reclaimed timber materials.

SUMMARY

The increasing importance of sustainability and circular economy principles has increased interest in the structural reuse of reclaimed timber. However, the structural reuse of reclaimed timber remains limited due to the lack of simple, reliable and cost-effective assessment methods for evaluating the influence of ageing, previous loading history and visually observable defects on mechanical behaviour. In particular, the relationship between visually observable characteristics and stiffness behaviour has not yet been fully understood.

The present thesis investigated the relationship between visually observable characteristics and the stiffness behaviour of reclaimed structural timber. The main objective of the study was to evaluate whether systematic visual assessment can provide useful information about stiffness-affecting characteristics in reclaimed timber members. The study also aimed to compare visually observed characteristics with stiffness values obtained from non-destructive bending tests and to evaluate the differences between global and local modulus of elasticity measurements.

The theoretical part of the thesis provided an overview of reclaimed timber as a structural material, the mechanical relevance of stiffness and the influence of visually observable characteristics on timber behaviour. The experimental part of the study was carried out using twelve reclaimed timber specimens originating from a dismantled Norwegian timber barn. Prior to bending tests, all specimens were subjected to systematic visual assessment using a coordinate-based methodology developed within the scope of the thesis. Knots, cracks, holes, cut-outs and wane were identified and recorded separately for each longitudinal face of the timber members together with their spatial location and geometric parameters.

Following the visual assessment, non-destructive four-point bending tests according to EN 408 were performed to determine both global and local modulus of elasticity values. The measurements were carried out repeatedly along the beam length at 250 mm intervals, enabling the development of longitudinal stiffness profiles for each specimen. The combined evaluation of reclaimed timber members using both local and global modulus of elasticity measurements represents a comparatively less explored approach within existing research. The obtained stiffness measurements were subsequently analysed together with the visual assessment data to evaluate possible relationships between visually observable characteristics and stiffness behaviour.

The results demonstrated that reclaimed timber exhibited substantial variability in both visually observable characteristics and measured stiffness values. Knots represented the most dominant visually observable defect type within the investigated dataset and exhibited the strongest relationship with stiffness behaviour among the investigated characteristics. Statistically significant negative correlations were observed between knot occurrence and both global and local modulus of elasticity values, indicating that specimens containing larger amounts of knot-related characteristics exhibited lower stiffness values.

Comparison between global and local modulus of elasticity values showed that local measurements produced somewhat higher and more variable stiffness values compared with the global measurements. However, statistical analysis indicated no significant difference between the two stiffness measurement approaches. The results therefore suggest that global modulus of elasticity measurements may provide a practical and time-efficient approach for preliminary stiffness assessment of reclaimed timber members, while local measurements remain more sensitive to local material irregularities.

The study further demonstrated that local stiffness variations often spatially coincided with regions containing elevated knot severity values. At the same time, the results highlighted the complex and heterogeneous nature of reclaimed timber material, where stiffness behaviour is influenced by multiple simultaneously occurring factors rather than by individual visually observable characteristics alone.

One of the main limitations of the study was the limited number of investigated specimens. Due to the naturally heterogeneous nature of reclaimed timber, larger datasets would improve the statistical reliability of the observed relationships and provide a broader representation of reclaimed timber behaviour. Future research could additionally combine visual assessment with advanced non-destructive evaluation techniques such as CT scanning and ultrasonic testing to improve reclaimed timber assessment methodologies.

Overall, the thesis fulfilled its objectives and demonstrated that systematic visual assessment combined with non-destructive stiffness evaluation can provide useful insight into the stiffness behaviour of reclaimed structural timber. The presented methodology may therefore provide a valuable basis for the future development of stiffness-oriented grading and structural reuse assessment approaches for reclaimed timber materials.

KOKKUVÕTE

Jätkusuutlikkuse ja ringmajanduse põhimõtete kasvav tähtsus on suurendanud huvi taaskasutatud puidu konstruktsioonilise korduskasutuse vastu. Paraku ei ole taaskasutatud puidu konstruktsiooniline korduskasutus veel laialdaselt levinud, sest vananemise, varasema rakenduse ja looduslikult esinevate defektide mõju hindamiseks puuduvad lihtsasti kättesaadavad ja usaldusväärsed meetodid. Lisaks ei ole taaskasutatud konstruktsioonipuidu puhul visuaalselt tuvastatavate omaduste mõju jäikuskäitumisele veel piisavalt selgelt mõistetud.

Käesolevas magistritöös uuriti visuaalselt tuvastatavate omaduste ja taaskasutatud konstruktsioonipuidu jäikuskäitumise vahelist seost. Uuringu peamine eesmärk oli hinnata, kas süstemaatiline visuaalne hindamine võimaldab saada kasulikku teavet taaskasutatud puitelementide jäikust mõjutavate omaduste kohta. Samuti oli eesmärgiks võrrelda visuaalselt tuvastatud omadusi mittepurustavate paindekatsete abil saadud jäikuse väärtustega ning hinnata erinevusi globaalse ja lokaalse elastsusmooduli mõõtmiste vahel.

Töö teoreetiline osa andis ülevaate taaskasutatud puidust kui konstruktsioonimaterjalist ning jäikuse mehaanilisest tähtsusest. Uuringu eksperimentaalne osa viidi läbi kaheteistkümne taaskasutatud puidust katsekehaga, mis pärinesid demonteeritud Norra puuküünist. Enne paindekatseid hinnati kõiki katsekehi süstemaatilise visuaalse hindamise metoodika abil, mis töötati välja käesoleva magistritöö raames. Tuvastati oksakohad, praod, augud, väljalõiked ja poomkandid ning registreeriti need eraldi iga puitelemendi külje kohta koos nende ruumilise asukoha ja geomeetriliste parameetritega.

Pärast visuaalset hindamist viidi vastavalt standardile EN 408 läbi mittepurustavad neljapunktilised paindekatseted, et määrata nii globaalse kui ka lokaalse elastsusmooduli väärtused. Mõõtmised teostati piki tala pikkust 250 mm intervallidega, võimaldades koostada iga katsekeha kohta pikisuunalised jäikusprofiilid. Käesolev töö laiendab senist uurimissuunda, rakendades taaskasutatud puitelementide hindamisel samaaegselt nii lokaalsete kui ka globaalsete elastsusmoodulite mõõtmist. Saadud jäikuste mõõtmistulemusi analüüsiti seejärel koos visuaalse hindamise andmetega, et hinnata võimalikke seoseid visuaalselt tuvastatavate omaduste ja jäikuskäitumise vahel.

Tulemused näitasid, et oksakohad olid uuritud andmestikus kõige domineerivam visuaalselt tuvastatud defektitüüp ning ühtlasi avaldasid need ka kõige tugevamat mõju jäikuskäitumisele. Statistiliselt olulised negatiivsed korrelatsioonid ilmnnesid

oksakohtade esinemise puhul nii globaalse kui ka lokaalse elastsusmooduli väärtuste vahel, mis viitab sellele, et suurema oksakohtade arvuga katsekehadel esines üldiselt madalam jäikus.

Globaalse ja lokaalse elastsusmooduli väärtuste võrdlus näitas, et lokaalsed mõõtmised andsid üldiselt mõnevõrra kõrgemaid ja suurema varieeruvusega jäikuse väärtusi võrreldes globaalsete mõõtmistega. Samas ei näidanud statistiline analüüs kahe jäikuse mõõtmismeetodi vahel statistiliselt olulist erinevust. Tulemused viitavad seega sellele, et globaalse elastsusmooduli mõõtmised võivad pakkuda praktilist ja ajasäästlikku lähenemist taaskasutatud puitelementide esmaseks jäikuse hindamiseks, samas kui lokaalsed mõõtmised jäävad tundlikumaks lokaalsete materjali ebakorrapärasuste suhtes.

Uuring näitas täiendavalt, et lokaalsed jäikuse varieerumised kattusid sageli ruumiliselt piirkondadega, kus esinesid suuremad oksa suuruse ja vastava ristlõike mõõtme vahelised seosed. Samal ajal tõid tulemused esile ka taaskasutatud puidu keeruka ja heterogeense olemuse, kus jäikuskäitumist mõjutavad mitmed samaaegselt esinevad tegurid, mitte üksnes üksikud visuaalselt tuvastatavad omadused.

Üheks uuringu peamiseks piiranguks oli katsekehade piiratud arv. Taaskasutatud puidu loomupäraselt heterogeense olemuse tõttu parandaks suurem andmestik täheldatud seoste statistilist usaldusväärsust ning annaks laiapõhjalisema ülevaate taaskasutatud puidu käitumisest. Tulevased uuringud võiksid lisaks kombineerida visuaalset hindamist arenenud mittepurustavate hindamismeetoditega, nagu CT-skaneerimine ja ultrahelitestimine, et parandada taaskasutatud puidu hindamismetoodikaid.

Magistritöö täitis oma eesmärgid ning näitas, et süstemaatiline visuaalne hindamine koos mittepurustava jäikuse hindamisega võib anda kasulikku teavet taaskasutatud konstruktsioonipuidu jäikuskäitumise kohta. Esitatud metoodika võib seega pakkuda kasulikku alust tulevikus jäikusele suunatud sorteerimis- ja konstruktsioonilise korduskasutuse hindamislähenemiste arendamiseks taaskasutatud puitmaterjalide puhul.

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APPENDIX 1 Coordinate-based knot dataset for specimen Q1

Beam	Beam face	ID	X1	Y1	DZ	D1y	D1x
Q1	A	1	72	30	0	6	5
Q1	A	2	74	-21	0	8	6
Q1	A	3	223	28	0	8	6
Q1	A	4	235	-16	0	7	6
Q1	A	5	445	60	0	16	8
Q1	A	6	455	-14	0	10	9
Q1	A	7	771	-43	0	10	7
Q1	A	8	779	12	0	7	9
Q1	A	9	980	50	0	9	5
Q1	A	10	980	-18	0	10	10
Q1	A	11	1134	-10	0	10	10
Q1	A	12	1320	6	0	9	12
Q1	A	13	1523	15	0	6	7
Q1	A	14	1527	-62	0	8	10
Q1	A	15	1845	-12	0	10	11
Q1	A	16	1850	19	0	14	13
Q1	A	17	1994	-30	0	14	12
Q1	A	18	1994	62	0	7	4
Q1	A	19	2101	-48	0	28	19
Q1	A	20	2101	35	0	8	8
Q1	A	21	2391	4	0	6	9
Q1	A	22	2392	-62	7	12	15
Q1	A	23	2622	21	0	12	14
Q1	A	24	2856	30	0	14	15
Q1	A	25	3144	-26	0	18	19
Q1	A	26	3159	66	8	15	14
Q1	A	27	3506	12	0	13	16
Q1	A	28	3744	60	0	16	9
Q1	A	29	3754	-12	0	14	11
Q1	A	30	3857	9	0	7	9
Q1	A	31	4076	-9	0	15	13
Q1	A	32	4084	25	0	12	14
Q1	A	33	4331	44	0	6	4
Q1	A	34	4476	17	0	11	13
Q1	A	35	4889	-12	0	15	13
Q1	A	36	4791	20	0	9	9
Q1	A	37	4888	67	3	6	10
Q1	A	38	4894	-1	0	14	12
Q1	A	39	5199	31	0	12	12

Beam	Beam face	ID	X1	Y1	DZ	D1y	D1x
Q1	A	40	5532	-63	14	28	24
Q1	A	41	5534	34	0	11	13
Q1	A	42	5563	5	0	12	13
Q1	B	1	436	-23	0	10	9
Q1	B	2	970	-18	0	6	5
Q1	B	3	1990	-30	0	5	5
Q1	B	4	2086	11	0	8	6
Q1	B	5	3147	-36	14	6	12
Q1	B	6	3733	-30	0	9	9
Q1	B	7	5527	17	4	12	11
Q1	C	1	216	-62	0	8	6
Q1	C	2	238	47	0	6	5
Q1	C	3	449	41	0	8	7
Q1	C	4	763	-16	0	6	7
Q1	C	5	966	53	0	9	7
Q1	C	6	1123	32	0	8	9
Q1	C	7	1310	1	0	9	11
Q1	C	8	1517	-26	0	5	5
Q1	C	9	1825	50	0	10	9
Q1	C	10	1839	-56	0	12	11
Q1	C	11	1883	-51	0	17	15
Q1	C	12	2381	5	0	6	8
Q1	C	13	2613	-35	0	10	10
Q1	C	14	2843	-50	0	12	13
Q1	C	15	3417	-56	0	18	16
Q1	C	16	3501	-15	0	14	18
Q1	C	17	3739	45	0	12	11
Q1	C	18	3850	-8	0	7	11
Q1	C	19	4072	47	0	19	15
Q1	C	20	4078	-48	0	13	11
Q1	C	21	4470	-37	0	13	16
Q1	C	22	4486	45	0	19	16
Q1	C	23	4784	-25	0	8	7
Q1	C	24	4893	33	0	17	15
Q1	C	25	5195	-60	0	18	22
Q1	C	26	5525	-67	13	3	10
Q1	C	27	5560	13	0	19	20
Q1	D	1	83	-24	0	6	7
Q1	D	2	760	12	0	8	6
Q1	D	3	1983	1	0	11	12
Q1	D	4	2095	20	0	16	16
Q1	D	5	2381	30	19	6	12
Q1	D	6	3133	-9	0	16	9
Q1	D	7	5545	22	28	14	23

APPENDIX 2 Bounding box-based defect dataset for specimen Q1

Cracks							
Beam	Beam face	ID	X1	Y1	X2	Y2	Widest opening
Q1	C	1	1863	23	2406	59	3
Q1	C	2	3349	39	3667	60	1
Q1	D	1	243	-25	1048	25	2
Q1	D	2	2409	-25	3053	25	3
Cut-outs							
Beam	Beam face	ID	X1	Y1	X2	Y2	Z
Q1	C	1	1827	-36	1901	7	4
Q1	C	2	3314	40	3350	60	12

APPENDIX 3 Coordinate-based hole dataset for specimen Q1

Beam	Beam face	ID	X1	Y1
Q1	A	1	2637	-10
Q1	B	1	45	-2
Q1	B	2	117	12
Q1	B	3	5403	-25
Q1	C	1	1964	-10
Q1	C	2	2024	29
Q1	C	3	2031	13
Q1	C	4	2188	14
Q1	C	5	2401	23
Q1	C	6	2553	-6
Q1	C	7	2591	28
Q1	C	8	2627	32
Q1	C	9	2665	9
Q1	C	10	2679	-17
Q1	C	11	2679	12