BENDING TEST FOR SMALL-DIAMETER TIMBER

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ABSTRACT

In the last two decades, the utilisation of small diameter timbers in constructions has gained increasing attention from both researchers and sustainable building enthusiasts. Timbers, when used as structural elements in their natural circular form, showed not only a notably higher strength per unit weight than other timber materials but also lower environmental impacts than any other structural materials. In recent years, innovations in forest management policies and connection design have significantly reduced the barriers to adoption of structural small diameter timbers.

The purpose of this Bachelor´s Thesis was to examine the development of standardised strength testing methods for small-diameter timber to stimulate the structural use of natural round timber.

The existing data was collected from the bending test for round timbers from the Delft University of Technology laboratory. The extant information from the previous test was then analysed and recommendations for future development in bending test arrangement were provided.

Keywords small-diameter timber, bending test.

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GLOSSARY OF TERM

In natural language and in technical reference words, like learning outcomes, have a variety of meanings that can lead to confusion. To avoid this problem, a consistent set of definitions is provided below.

Terminology	**Definition**
BSI	British Standard Institution
CAD	Computer-Aided Design
CEN	European Committee of Standardisation
DUT	Delft University of Technology
LVDT	Linear Variable Displacement Transducer
3D Scanning	Three-Dimension Scanning

LIST OF SYMBOLS

$E_{m\ local}$	Local Modulus of Elasticity
$E_{m\ total}$	Total Modulus of Elasticity
f_m	Bending Strength
G	Shear Modulus
RD_{tl}	Relative Difference between Total and Local Values

1 INTRODUCTION

1.1 Background

In the past two decades, the diversity and sophistication of natural round timber construction practices have increased significantly. However, in the current European standards for the design of timber structures, the issues of strength-testing methods, strength classes, and grading are solved only for sawn timber. Previous research has been conducted to determine the characteristic strength of round timber and to establish a reliable grading system (de Vries, 1998). The research task is to identify the characteristic strength of round timber before developing suitable joints and connectors for the material.

1.2 Motivation

Natural round timber carries all of the beneficial characteristics of timber in general, with some additional advantages. Timber has been reported to have a lower effective embodied energy than the most commonly used structural systems, namely reinforced concrete and steel (Bukauskas, 2015, p. 11). Compared to conventional dimensioned timber products such as glue-laminated or sawn timber, natural round timber has lower embodied carbon, higher strength per unit weight and great environmental credentials.

The major obstacle preventing wider acceptance of small-diameter round timbers as a structural material is the complex and costly connections. The imperfections in the roundness and straightness of natural timber make it difficult to design structural connections that can transfer load between members in a structural system. Moreover, the reverse design process, in which the available lengths and sections of timber dictate the geometry of the structure, is not well-received by conventional designers.

In order to stimulate the wider adoption of structural small diameter round timber, non-destructive static transverse bending tests, typically "mechanical grading" or "machine stress grading" (de Vries, 1998), have been developed based on existing evaluation technique for sawn timber. The main objective of bending tests is to estimate the modulus of elasticity of the timber element, which is strongly correlated with the strength properties of the material. However, the highly irregular geometries of small-diameter timber make it challenging to obtain accurate measurements for the modulus of elasticity. Therefore, improvement in test arrangement and supports is necessary.

1.3 Research Aim and Objectives

Against the background earlier outlined, this research project will be undertaken with the aim of analysing the existing data generated from the previous Bending test conducted by the Delft University of Technology (de Vries, 1998).

To achieve this aim, the following objectives will be pursued:

Objective #1:	Conduct research of existing literature for a comparable study.
Objective #2:	Adapt and adopt the methodology for collecting data.
Objective #3:	Analyse the collected data from the bending test for round timbers.
Objective #4:	Discuss the findings.

The expected outcomes of the study include:

- The methodology will be adapted from the comparable study.
- The Bending Test for Round Timber will be used for the analysis of the existing data.
- The results will be similar to the findings of the other studies.
- The result of this research will determine the characteristic strength of round timbers in different cross-sections (Figure 1).

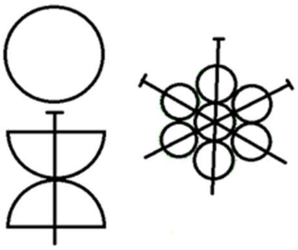

Figure 1. Different cross-sections of round timbers (Hochschule Mainz, 2018)

1.4 Scope of the Research

The scope of the study is limited to consider only one machine grading system for round timber, particularly bending test.

Chapter 1 introduces the background to the research problem with particular respect to bending test for small diameter round timber. The aims and objectives of the research along with the scope of the research are stated. The structure of the paper is also explained.

Chapter 2 presents and critiques the existing literature related to the utilization of round timber as a construction material and strength testing methods for small-diameter timber, in particular, bending test. The chapter introduces the historical background, recent policies, beneficial aspects, challenges, and existing types of connection for round timbers in the construction industry. After illustrating the test EN 408:1995 as a reference, the bending test for round timbers (de Vries, 1998) is described in detail in terms of test arrangement, design of test specimen, and test result.

Chapter 3 demonstrates the research methodology implemented for this research. The chapter gives an outline of the research strategy, the research method, the research approach, the methods of data collection, the research process, and the type of data analysis.

Chapter 4 contains an analysis of notable findings from the literature reviews. Key findings concerning the result of the bending test described by de Vries (1998), and the bundled column method (Bukauskas, 2015, p. 22) are discussed. The optimum bundled test piece is presented and analysed in this chapter.

Chapter 5 discusses the findings of the thesis and suggest directions for future research. The main focus of the findings interprets the arrangement of the bending test for round timbers, and the bundled column method. Future research topics including the determination of physical characteristics of round timbers, the design of bending test supports, and the application of hemp are given.

Chapter 6 concludes the research with a summary of findings, a summary of contributions, future work, and concluding remarks.

2 LITERATURE REVIEW

2.1 Overview

Timber, when used in their natural circular form, is the earliest construction material discovered by mankind. In the primeval time, round timber was utilised in simple pole structures for high axial, bending strength and flexibility to withstand lateral loads (Batchelar, 2012, p.558). Round timber elements appeared in classical churches, bridges, marine constructions, animal barns, fortifications, etc. for thousands of years.

With the introduction of advanced mechanical methods in fabrication, timbers of constant cross-section, including mechanically shaped cylindrical round timbers, became popular (Thépaut & Hislop, 2004, p. 3). Structural components processed by mechanical technique benefited from the simplicity in detailing, jointing construction, and more synchronised appearance. However, the mechanical debarking and manufacturing process significantly reduce the strength of the components and increase material wastage, raising both economic and environmental concerns (Bukauskas, 2015, p. 13).

The benefits of applying natural round wood in construction included low construction cost, higher strength per unit and strong environmental credentials (Thépaut & Hislop, 2004, p. 3). Round timber was reported to have a loading capacity of five times greater than the largest piece of dimensioned timber that be produced from the same cross-section (Wolfe, 2000, p. 21). The much lower effective embodied energy of timber compared to steel and reinforced concrete also drew high attention from the future low-carbon and renewable construction (Bukauskas, 2015, p.5).

Challenges faced by researchers in expanding the application of small-diameter timber were categorised into economics, forest management, engineered design, and construction (Wolfe, 2000, p. 21). The most well-known issue that limited the structural use of round timber was the artisanal and troublesome connections (Brito & Junior, 2012, p. 244).

While the demand for timber in the natural circular form rose significantly in recent times, the need for standardised grading methods for round timber remained unsolved. Many testing methods, including bending test, compression test, buckling test, tension test, dynamic modulus of elasticity test and X-ray density measurements, were developed based on the existing test for sawn plank in the European standards (Ranta-Maunus, 1999, p. 59).

In 1998, de Vries, and Gard described the development of a strength grading method for small diameter timber, reporting the outcome of the bending test to determine the Modulus of Elasticity (E_m) and bending strength (Modulus of Rupture, f_m) of round timber specimens. The result of the test demonstrated potential accurate measurements with specific modifications from the test built for sawn timbers.

In order to satisfy the design challenges for natural round timber, Bukauskas (2015, p. 14) described the *bundled column* method, which was expected to produce a practical, easily fabricated, and flexible structural system. The promising result in the buckling test for bundled column set a new task to develop other structural elements using an equivalent mechanism.

The goal of this literature review is to give an overview of small-diameter round timber as a construction material and to report existing testing methods related to round timber, in particular, bending test.

2.2 **Round Timber as a Construction Material**

2.2.1 Historical Background

Natural timber was the oldest construction material used by mankind. Evidence of the early application of timber members appeared in many societies around the world where an abundant natural resource of timber existed. Both classical Western and Oriental architecture were strongly influenced by the use of round wood for supports (Thépaut & Hislop, 2004, p. 2). This included the early historic bridges (see Figure 3) and agricultural buildings of China and Japan through to the Norwegian Stave Church constructed in the 12th century (see Figure 2). Another utilisation of round timber from the ancient time could be found in marine constructions such as jetties, piers, docks.

Figure 2. Norwegian Stave Church (Wikimedia Commons, 2018)

Figure 3. The Xianju Bridge in China (Wikimedia Commons, 2018)

In the old days, the total volume of construction was considerably smaller and the construction quality was considered secondary importance. This led to the preference of small-diameter timber as a construction material due to its convenient size, related to handling and transportation (Ranta-Maunus, 1991, p.15). Temporary construction and low-value buildings benefited from a tremendous volume of minimally processed small-diameter round timber. Notable examples illustrated the early application of small-diameter round timber include the Roman camp (see Figure 4) and fortification, barns, animal shelters, and artisan houses.

Figure 4. Roman camp with fortifications mad of small-diameter timbers (Wikimedia Commons, 2018)

At the beginning of the construction industry, round timber members were utilised as simple pole structures after minimal processing using hand tools. Prior to the introduction of mechanical jointing, lashings were the main type of connection. Timber members in its natural circular form optimised high axial, bending strength and flexibility to accommodate lateral loads (Batchelar, 2012, p. 558). In those countries where plenty source of natural timber is available above the ground, the log construction was born (Thépaut & Hislop, 2004, p. 4). Figure 5 illustrates a simple shelter made of the tree trunks from coniferous forests stacked on top of each other with the interlocking corner in the most elementary manner.

Figure 5. Simple timber shelter with an interlocking corner (ShutterStock Image, 2019)

2.2.2 Contemporary Application

With the involvement of mechanical methods (Figure 6) in the manufacture of round timbers, machine debarked elements with a circular cross-section (Figure 7) became more popular. The major goal in producing machine rounded timber is to obtain mechanically shaped cylindrical components of constant cross-section without affecting the natural taper of the original tree (Thépaut & Hislop, 2004, p. 5). Structural elements processed by mechanical methods can simplify detailing, jointing, and construction, as well as enhance the appearance of the structure.

Figure 6. Timber Rounding machine (Woodlandia, 2018)

However, mechanical debarking significantly reduced the strength of the components and increased material wastage. This was due to the fact that mechanically removal of bark damage the natural arrangements of the fibre that give the timber its strength (Gorman, 2012). An alternative to mechanical debarking was manual methods which can limit the harmful effects on the properties of natural timber (Thépaut & Hislop, 2004, p. 5).

Figure 7. Machine rounded timbers (Wooden Supplies, 2019)

Nowadays, the timber constructions built from the round timber members have become increasingly popular. In recent years, the enormous growth of the leisure industry and access to the countryside had directly associated with the need for round wood (Lokaj & Klajmonova, 2014). The utilisation of modern log construction (Figure 8) for residential buildings such as summerhouses or cabin and leisure facilities can be found all over Europe and North America (Thépaut & Hislop, 2004, p. 3). The machine-debarked round timbers were also widely used as conventional structural elements such as columns, beams, rafters, etc and as assemblies such as trusses and portal frames.

Figure 8. Modern summer log house (Pinterest, 2019)

In 2000, Wolfe revealed research from the US Forest Products Laboratory exposing an interesting fact that forest stands around the United States are overstocked with small-diameter trees due to their insignificant market value. Forest managers considered the overstocked small-diameter tree stands critical forest health issues. The forests which were crowded with suppressed and unhealthy trees were subject to attack from insects and disease and the risk of total destruction by fire (Gorman, 2012). In order to improve the health of wood and mitigate the risk from overstocked stands (Figure 9), excess woody biomass, including small-diameter trees, dead trees, excessive slash on the ground must be thinned out. Small-diameter timbers could be achieved in a large amount from the forest thinnings (Ranta-Maunus, 1999, p. 14).

Prior to more intensive investigations on the utilisation of small-diameter timbers, the most common approach towards this resource of wood was the manufacturing of low-value byproducts such as firewood or wood chips (Burton, Dickson, & Harris, 1998, p. 77). Another less environmentally friendly but economic method was burning.

Figure 9. Overstocked small-diameter timber stands (Northwest Natural Resource Group, 2018)

In the current forestry industry, forest thinnings has no longer been considered a secondary byproduct (Bukauskas, 2015, p.7). Changes have been undertaken with the aim of maximizing the value of thinnings as a profitable forestry resource. Upcoming developments concentrated on buildings that are both environmentally acceptable and incorporated with high technology and high quality (Wolfe, 2000, p.21). Small diameter timber was considered perfectly matched with this demand due to its environmentally friendly image and the application of high-tech connection systems.

2.2.3 Benefits of Round Timbers

The favourable context of round timbers in construction includes low construction costs, higher strength per unit and strong environmental credentials.

Research by Wolfe at the US Forest Product Laboratory (2000, p.21) demonstrated the low construction cost of small-diameter round timber as a structural material. In the manufacturing process of round timbers, felling, debarking, and any necessary cuts made were involved. All the steps included in the processing of natural timber into structural elements other than long-distance transport could be achieved by hand without the use of heavy machines. In terms of environmental impacts, this means potential energy savings and diminished reliance on fossil fuels. This interesting feature makes natural round timber notably appropriate for the construction market of low-cost materials in developing regions (Bukauskas, 2015, p.5).

When being compared to timber structural elements in the original circular form, the largest piece of dimensioned timber could only yield 20% of the load capacities that have been assigned to round timber (Gorman, 2012, p.155). This higher strength per unit weight of round timber was explained by three reasons, in particular, fibre continuity, sectional properties, and taper.

In natural conditions, the grain of the tree curves around knots and other imperfections as a way to cover these local weaknesses. The process of sawing timbers into prismatic elements (Figure 10) cuts through the valuable tree grain, which introduces the ends of the fibres that give a tree strength and uncovers local weaknesses. As a result, affecting fibre continuity reduced the strength of prismatic members by up to 2-3 times (Bukauskas, 2015, p.13).

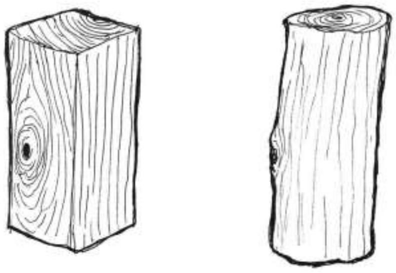

Figure 10. Effect of knots and other imperfections in dimensioned lumber vs. whole-timber as shown by grain patterns (Bukauskas, 2015, p. 13)

The sectional properties of round wood elements, in particular, cross-section and moment of inertia, witness great changes under the manufacturing process to sawn plank (Ranta-Maunus, 1999, p.30). A recent study (Bukaukas, 2015) reported that the largest prismatic component that can be derived from round wood (Figure 11) has its cross-section and moment of inertia reduced by 36% and 58% respectively. These directly related to a decrease in crushing and buckling capacity of sawn plank.

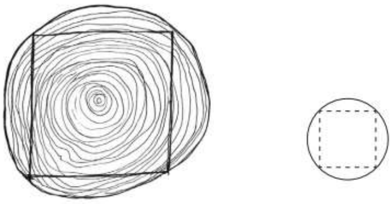

Figure 11. Cross-section of a whole timber with its largest inscribed square (Bukauskas, 2015, p.13)

Figure 12 demonstrates how the smaller end of a tapered timber determines the size of any prismatic or uniform-section circular member that can be manufactured from that timber. A calculation method for computing the buckling capacity of natural tapered wood showed a significant 43% greater in the buckling capacity of these elements in comparison with prismatic or uniform-section derived from them (Bukauskas, 2015, p. 14).

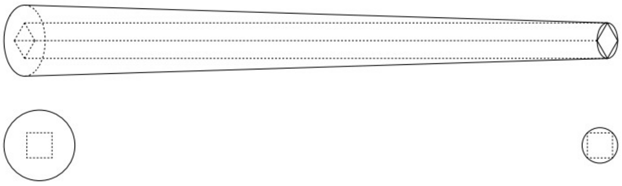

Figure 12. Naturally tapered whole-timber with the largest prismatic member it could yield (Bukauskas, 2015, p.14)

The most beneficial aspect of round timber as a structural material is its remarkable environmental credentials due to low embodied energy compared to other construction materials and renewability (Wolfe, 2000, p. 22). While analysis had proved that the structure of a building accounts for 71% of the energy needed in the construction process (Bukauskas, 2015, p. 11), it was crucial to diminish the embodied energy of the structural systems. In order to achieve this goal, the use of materials with low embodied energy in effective structural configurations that maximize structural capacity while minimizing material use should be promoted. The timber structural system was proved to have a lower effective embodied energy than its commonly used counterparts (see Table 1) such as steel and reinforced concrete (Hammond & Jones, 2011). In addition, atmospheric carbon was temporarily sequestered in a timber structure. At the end of life of a building, timber members can be recycled, left to biograde, or be burned in the form of biofuel. Hence, timber has all the potential to become the most applicable low-carbon and renewable material in the future.

Table 1. Embodied Carbon Coefficients of Various Structural materials. Unit: kg CO_2 e/ kg

	EC_{fos}	EC_{bio}	EC_{total}
Steel (General)	n/a	n/a	1.46
Glue-Laminated Timber	0.42	0.45	0.87
Sawn Softwood	0.2	0.39	0.59
Whole-timber	0.2	n/a	0.2

Note: For all embodied carbon coefficients, CO_2e, meaning CO_2 equivalent is used (Bukauskas, 2015, p. 12)

2.2.4 Challenges

The development of structural use of small-diameter round timber faces a number of challenges in economics, forest management, engineered design and construction (Wolfe, 2000, p. 23).

A major economic barrier to expanding the use of small-diameter round timber encompassed the perception that the market value of the material does not surpass the cost of harvesting, processing and transporting. Promoters have emphasized the better characteristics of round timber compared to sawn plank when introducing the material (Wolfe, 2000). However, the majority of design engineers, building contractors and architects hold a sceptical and conventional opinion against the use of small-diameter timber due to various technical issues (Brito & Junior, 2012). Hence, the feasibility of utilising round wood requires extensive changes in the marketing philosophy of the forest products industry as well as explorations of possible new markets.

In terms of forest management, the challenges include the cost of forest thinnings and the limited means to identify the quality of structural small-diameter timber. Forest managers did not consider thinning small-diameter timber cost-effective due to the absence of subcontracted harvest. Moreover, the lack of existing grading methods for natural round timber also complicates the categorising process after thinnings (Ranta-Maunus, 1999, p. 29).

The most well-known obstacle against the acceptance of small-diameter timber in the construction industry is the complexity of its connections. Although connections play the key role in the safety of round timber structures (Brito & Junior, 2012, p. 244), detailed guidance on the design of those connections in accordance with official building codes is not readily available. Hence, contractors held resistance against the use of small-diameter timber unless a standardized way of manufacturing the connections is provided.

2.2.5 Available Connections for Round Timbers

Connections of round timber members plays a key role in the safety of timber structures. However, the joints of the structural components made of round timbers require a more intensive approach than the sawn plank counterparts (Lokaj & Klajmonova, 2014, p. 103). In most cases, the connections must be sawn by hand under the supervision of experienced carpenters to achieve the expected quality (Brito & Junior, 2012, p. 244). This posed the major problem of utilising round wood in construction that people held strong resistance against the artisanal and troublesome methods of manufacturing the connections.

In order to stimulate a more efficient use of the connection between round wood structural components, various types of joints were introduced in the construction industry. Brito and Junior (2012, p. 244) classified the main varieties of connections with round timber for structural components in accordance with its function, including:

- notches in wood,
- wooden dowel,
- threaded rods with washers and nuts,
- dowel nut,
- steel plate external fixed with screws,
- steel plate internal fixed with screws,
- galvanised perforated steel plate and nailed,
- steel straps woven into,
- steel rings with threaded rods fixed with washers and nuts,
- steel connectors for structures mixed round wood and concrete,
- details on the interface of the timber structure with masonry,
- connection system for log home walls,
- connections in parts compressed, and
- connections to bases of columns.

In most of the listed joints, the connections include metal components such as threaded steel bar, metal pin, and metal ring.

According to Lokaj and Klajmonova (2014, p. 103), bolted joints with or without internal metal plates bolted are the most popular connections used in the recent construction of round timbers.

In the bolted joints (Figure 13), threaded steel rods are placed through transverse pre-drilled holes passing through the longitudinal axis of the elements and tightened by washers and nuts on the extremities. Any further tightening process can be carried out when the timber has reached the equilibrium moisture content (Brito & Junior, 2012, p.246).

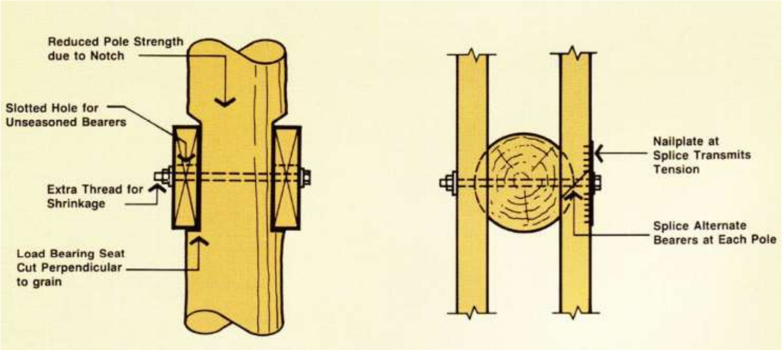

Figure 13. Bolted joints connection (Pinterest, 2019)

The bolted connections with slotted-in metal plates described in Figure 14 share the same operating principle with the bolted joints. These connections contain metal plates being imputed into the cleft in the longitudinal axis of the timber component. The joint is performed via the bolts traverse across the plates and pieces of round timber (Brito & Junior, 2012, p. 246). When the washers and nuts on the end of the steel rods are being tightened, the inner faces of the wood and the faces of the metal sheet are compressed by the locking system.

Figure 14. Bolted joints with slotted-in metal plates variations (Lokaj & Klajmonova, 2014, p. 104)

The design of steel connection for round timbers is based on the principle of avoiding the splitting failure mechanisms. The reinforcement is expected to possess two fundamental effects: transferring the tensile stresses perpendicular to the grain and increasing the embedding capacity of the reinforced timber area (Lokaj & Klajmonova, 2014, p. 104).

In 2014, the tension test carried out by researchers from the Technical University of Ostrava showed that round timber samples with bolted joints or bolted joints with slotted-in steel plates had the ability to absorb more pressure before collapse than the unreinforced ones. Both connections showed profitable due to the usage of affordable parts.

2.3 **Testing Methods**

2.3.1 Overview

As the use of timber in the natural circular form has increased recently, a complete method of sorting round timber according to strength classes is crucial. In the current European standards for the design of timber structures, the issues of strength-testing methods, strength classes, and grading are solved only for sawn timber (de Vries, 1998, p. 184). For round timber, there was no existing grading system that associates the characteristics of the material to its strength values.

Researchers had concentrated on the applicability of the European Committee of Standardisation (CEN) standards written for sawn timber to develop more completed procedures for natural round timber. Various issues have been discussed including the strength testing methods, strength classes, strength grading and the effect of size on strength. The main objective of researchers was to resolve the characteristic values needed in the design of load-bearing round timber structures, examine the practicability of non-destructive methods in strength-grading, and establish a technique for developing international standards for visual strength-grading of structural round timber (Ranta-Maunus, 1999, p. 59). According to the Technical Research Center of Finland (1999), about 1400 bending tests and a minor number of compression and tension tests had been carried out to fulfil the proposed objective.

The strength test for round timber was closely related to EN 408:1995 procedures (BSI, 1995, p. 2), which are designed for testing sawn timber (de Vries, 1998). Due to the variation of the diameter of round wood, the deviations from the standard were adopted if necessary. In 1999, Ranta - Maunus drafted a proposal for the testing standard of circular timber with modified testing methods. According to researchers from the Delft University of Technology (DUT), the real test showed minor tolerances with no significant influence on the result.

In the EN 408:1995 Standard issued by the CEN, specific laboratory methods for the determination of mechanical and physical properties of timber structural sizes are described. The following properties of structural timber can be determined by test methods: modulus of elasticity in bending; shear modulus; bending strength; modulus of elasticity in tension parallel to the grain; tension strength parallel to the grain; modulus of elasticity in compression parallel to the grain; compression strength parallel to the grain.

Additionally, the determination of dimensions, moisture content, and density are specified. The methods illustrated in the standard are applicable to rectangular or circular shapes of a considerably constant cross-section of solid unjointed, finger-jointed, and glue-laminated wood.

It is also worth noting that the standard is not intended for quality-control test purposes (BSI, 1995, p. 3).

Ranta-Maunus (1999, p. 59) introduced six different available strength testing methods for small-diameter round timber, namely bending test, compression test, buckling test, tension test, dynamic modulus of elasticity test and X-ray density measurements.

2.3.2 Bending Test EN 408

A four-point bending test was conducted to determine the modulus of elasticity of round timber elements. The modulus of elasticity would be obtained by measuring the local deflection between the load. A comparison between the global and local deflection was carried out to verify the value of the modulus of elasticity. The average diameter and the minimum diameter close to the collapsing position were used for calculating local Modulus of Elasticity ($E_{m\,local}$) and bending stress (f_m) respectively.

The procedure of conducting the test and test arrangement were demonstrated in the EN 408: 1995 Standard. In principle, the test piece shall be symmetrically loaded in bending at two points over a span of 18 times the diameter (Figure 15). Two symmetrical loads are placed at a distance of six times the diameter between them. In case these conditions were not precisely satisfied, the distance between the load points and the supports may be adjusted by an amount not greater than 1.5 times the piece depth, and the span and test piece length may be changed by an amount not greater than three times the element diameter,
while maintaining the symmetry of the test.

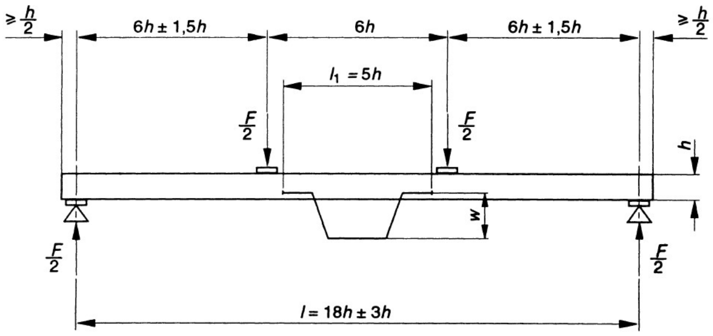

Figure 15. Test arrangement for measuring modulus of elasticity in bending (BSI, 1995, p. 6)

The supports for the test piece shall be simple. In order to minimize the indentation, small steel plates of length not greater than one-half of the depth of the test piece may be inserted between the piece and the loading heads or supports. Buckling would be avoided using any necessary lateral restraint that allows the test piece to deflect without significant frictional resistance.

The load applied to the piece shall be maintained at a constant rate movement not greater than 0,003 h mm/s. The maximum load applied shall not exceed the proportional limit load or cause damage to the piece.

An accuracy of 1% of the load applied to the test piece or, for loads less than 10 % of the applied maximum load, an accuracy of 0,1 % of the maximum applied load must be satisfied by the loading equipment.

Deformations shall be measured at the center of a central gauge length of five times the depth of the section. An accuracy of 1 % or, for deformations less than 2 mm, an accuracy of 0,02 mm is required in the measurement of the deformation (BSI, 1995, p. 7).

2.3.3 Bending Test for Round Timber

The test arrangement built for small-diameter timber based on the EN 408 description for testing sawn timber (de Vries, 1998, p. 188). With respect to the difference between sawn timbers and round timbers, the deflection measurements had been modified as shown in Figure 16 and Figure 17.

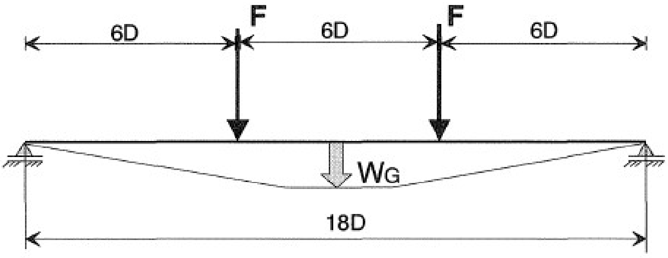

Figure 16. $E_{m\ total}$ deflection measurement (de Vries, 1998, p. 189)

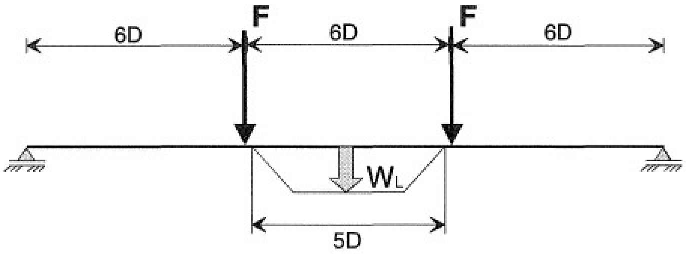

Figure 17. $E_{m\ local}$ deflection measurement (de Vries, 1998, p. 189)

In the test conducted by the DUT laboratories, the test arrangement included an Instron universal testing machine model 119S and a 3.5meter long I-beam. The test piece was reinforced by two end supports attached to the I-beam that allowed different specimen lengths to be tested (Figure 18).

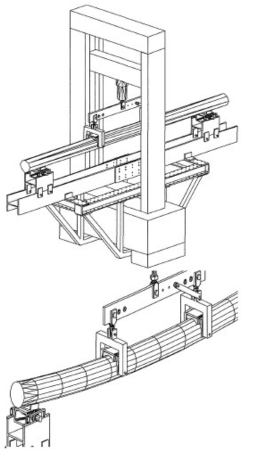

Figure 18. Test Arrangement (de Vries, 1998, p. 190)

The deflection was measured by a Linear Variable Displacement Transducers (LVDTs). The LVDTs (Figure 19) were attached to the test piece at three different reference points. A frame with the LVDT was mounted on two outer reference points. On a flat horizontal plane rotating around the center reference points axis, the LVDT core was installed. The deflection measurement accuracy was controlled using special LVDT configurations. Any potential rotation of the specimen during the measurement of local and global deflection was regulated by two LVDTs. The location of the LVDTs was described in Figure 20 and Figure 21.

Figure 19. Linear Variable Displacement Transducers (Direct Industry, 2019)

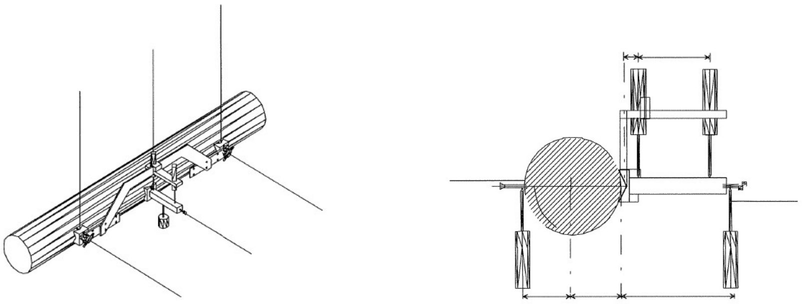

Figure 20. Measurement of EN 408 deflection (de Vries, 1998, p. 191)

The loading heads (Figure 21) were designed in the fundamental that enabled the loaded sections to rotate and alter the test specimen surface during the experiment. The axis of rotation of the loading heads located within the neutral plane of the test piece.

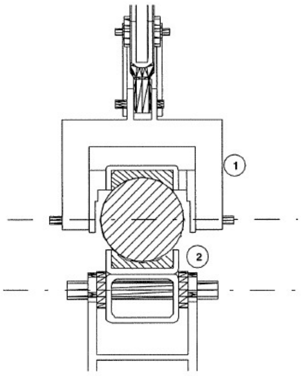

Figure 21. Loading head cross-section with total LVDT placements (de Vries, 1998, p. 191)

A small Modulus of Rupture test series for each diameter group was required to determine the expected failure load of the test piece. During the Modulus of Elasticity test, only 40% of the failure load was applied to the specimen. The test piece was loaded to failure again after relief to resolve the bending strength.

2.3.4 Test Pieces

Researchers harvested different materials from different countries for investigation, including Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*) from Finland, Sitka spruce (*Picea sitchensis*) from the UK, Larch *(Larix kaempferi*) from the Netherlands and Douglas fir (*Pseudotsuga menziesii F.*) from France (Ranta-Maunus, 1999, p. 71).

According to the EN 408 standard (BSI, 1995, p. 6), the determination of test pieces must satisfy requirements in dimension, moisture content, density and modulus of elasticity in bending.

The dimensions of the test pieces are measured to an accuracy of 1% and the measurements are taken not closer than 1500 mm to the ends. In the case of varying widths and length, the average of three separate measurements at different positions on the length of each piece will be the outcome dimensions. The test piece shall have a minimum length of 19 times the depth of the section.

All measurements were expected to be made at the standard environment of (20±2) °C and (65 ± 5) % relative humidity. The moisture content and density of the test piece shall be determined on a full cross-section cut as close as possible to the fracture.

A constant mass, which is attained from two successive weighings at an interval of six hours with no more than 0.1% difference, is also required. In addition to the test arrangement description in the EN 408:1995, various practical issues caused by the difference in the nature between sawn timber and natural round wood should be considered.

The most significant difference between round wood and sawn wood is the initial curvature possessed by natural round timber. This characteristic leads to the appearance of an elliptical-shaped cross-section that caused difficulty in measuring and calculating the moment of inertia. Diameter ranges could be used as an alternative to determining the span length, the moment of inertia, and the limit of deformation speed.

Exceptional attention should be paid to the rotation of the test piece when measuring the displacements by external devices during loading:

- The installing process of displacement measurement reference points at prescribed locations would be affected by the asymmetrical and cracked surface of round timber,
- A neutral plane of the pole should be identified in order for the load to be applied, and
- The determination of this neutral plane requires special load headings that can adapt to various diameter of the tapered poles.

Figure 22 described a potential method in fabricating the test pieces for bending tests using the "bundled column" method introduced by Bukauskas (2015, p. 14). In the bundled column system, round timber elements were packed together using shear bolt connections. The weight of all steel connectors in the column was estimated at 10% of the total timber weight. This method of connecting timber elements provided an applicable, easily fabricated and adaptable system that possessed high and equal crushing capacity at the end. The biggest challenge in the design and fabrication of bundled components is to establish a method to fasten the timbers together while enhancing adequate shear resistance against buckling.

Figure 22. Bundled column using 4 tapered timbers (Bukauskas, 2015, p. 14)

2.3.5 Test Results

The Modulus of Elasticity in bending was determined in two different ways of measurement.

In the EN 408 experiment, the force- deflection graph was influenced by only local specimen characteristics and modulus of elasticity. The EN 408 bending test resulted in the local modulus of elasticity in bending $E_{m\,local}$ and bending stress f_m, which could be expressed as:

$$E_{m\,local} = \frac{a{l_1}^2(\mathrm{F}_2 - \mathrm{F}_1)}{16I(w_2 - w_1)} \qquad (1)$$

$$f_m = \frac{a\mathrm{F}_{\max}}{2W} \qquad (2)$$

where:

- a is the distance between a loading position and the nearest support in a bending test, in millimetres;
- $\mathrm{F}_{\max}$ is the maximum load, in Newtons;
- $\mathrm{F}_2 - \mathrm{F}_1$ is an increment of load on the straight-line portion of the load
- deformation curve, in Newtons;
- I is the second moment of area, in millimetres to the fourth power;
- l_1 is the gauge length for the determination of modulus of elasticity, in millimetres;
- $w_2 - w_1$ is the increment of deformation corresponding to $F2 - F1$, in
- millimetres; and
- W is the section modulus, in millimetres to the third power.

(BSI, 1995, p. 7).

In the bending test using the measurement reference points in the middle section and on both ends of the specimens, the full specimen characteristics, modulus of elasticity and the shear modulus (*G*) had an influence on the force-deflection graph. The total value $E_{m\,total}$ was achieved by recording the displacement of the test piece middle section with respect to the end supports.

In theory, the relative difference between $E_{m\,total}$ and $E_{m\,local}$ would be used as the characteristics of the test arrangement. The results from different test arrangements were expected to yield comparable relative difference values. The relative difference between $E_{m\,total}$ and $E_{m\,local}$, RD_{tl}, would be calculated using the formula: $RD_{tl} = \frac{E_{m\,local} - E_{m\,total}}{E_{m\,local}}$.

The results presented by researchers from DUT laboratory in Table 2. showed correspondence to the theory. The mean value of $E_{m\,total}$ was greater than $E_{m\,local}$ in both test specimens. The standard deviation of the Douglas test piece was notably higher than that of the Larch.

Table 2. Results of the Modulus of Elasticity measurements

	Douglas					Larch					
	N	Min	Max	Mean	Std. Dev.	N	Min	Max	Mean	Std. Dev.	
$E_{m\,total}$	145	5.5	12.1	8.9	1.4	137	7.3	17.4	12.6	1.9	[GPa]
$E_{m\,local}$	138	4.2	21.6	9.6	3.1	137	7.3	20.5	13.3	2.4	[GPa]

Note: From " The development of a strength grading system for small diameter round wood " by P. de Vries, 1998, Center for Timber Research, p.193

The significant differences between the local and total values could be explained by identifying the error sources in the measurements, including:

- The effects of shear deformation resulted in lower values for $E_{m\,total}$,
- The variation caused by the difference in the characteristics such as density and knot along the test piece, and
- The variations of the central part properties used in the $E_{m\,local}$ measurement and the average properties used in $E_{m\,total}$ measurement resulted in the correlation coefficient (de Vries, 1998, p. 194).

The distribution of RD_{tl} values between the total and local moduli of elasticity was illustrated in Figure 23. Overall, the average values for RD_{tl} from both Douglas and Larch specimens showed a comparable rate of 5%. However, the standard deviations, which were 20% and 7% of Douglas and Larch respectively witnessed a significant difference between the test arrangements.

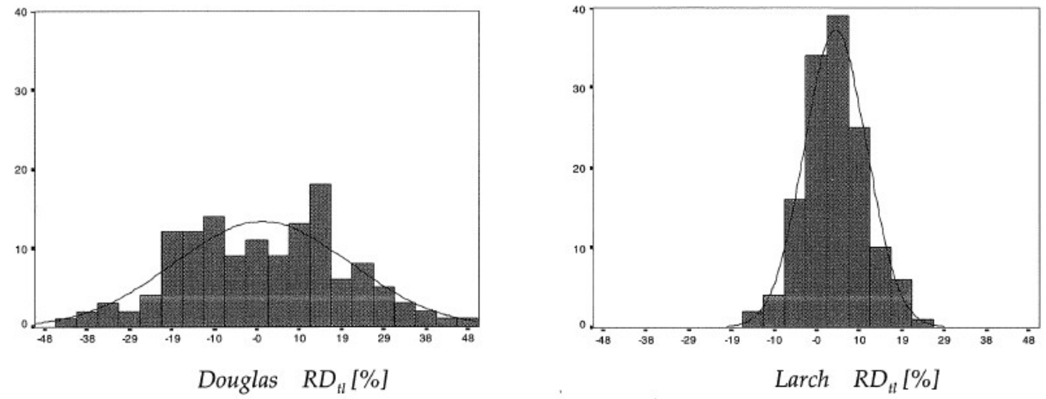

Figure 23. Relative Different between the local and total value of Douglas and Larch specimen (de Vries, 1998, p. 195)

The conclusion drew by the researchers from DUT laboratory (1998) showed the possibility of accurate measurements using both local and total bending test arrangements. However, it was recommended to use the modified EN 408 test to determine $E_{m\ total}$ as a reference due to error-prone measurements from the original standard.

2.4 **Summary Table**

The following is a summary table of literature used throughout the research, including the topic of the reference, method of data analysis used, and significant outcomes provided.

Table 3. Summary Table of Literature Reviews

Citation	Topic	Method	Significant outcomes
Batchelar (2012)	Innovative use of timber rounds in high-performance structures. "To introduce and highlight the potential applications of cored rounds for high-performance structures" (p. 1)	Quantitative descriptive	The use of round timber was not limited to simple structures.
Brito & Junior (2012)	Types of connections for structural elements roundwood used in Brazil. "To present the main usual types of connections used in structural systems and construction" (p. 1)	Quantitative descriptive	Most connections used for round timber structural elements used steel connectors.

Bukauskas (2015)	New structural systems in small diameter timber. "Focuses on the design of a structurally independent column in whole-timber" (p. 11)	Quantitative explanatory	• Natural round timber had additional advantages compared to other types of timber construction materials, especially in the environmental aspect. • The bundled column system provided a potential method to manufacture the test piece.
de Vries (1998)	The development of a strength grading system for small diameter round wood. " Concentrates on the test methods to determine the Modulus of Elasticity (E_m) and on the potentiality of E_m as a grading parameter with respect to strength class classification" (p. 184)	Quantitative explanatory	• The bending test built for round timber closely based on the EN 408 test for sawn timber. • The result of bending tests showed corresponding results to the theory.
Gorman (2012)	Assessing the capacity of three types of round-wood connections. "To improve the utilization of small-diameter round wood for use as structural members by evaluating structural connections" (p. 155)	Quantitative explanatory	– Connection using bolts and plates showed acceptable results in terms of loading capacity.
Lokaj & Klajmonova (2014)	Selected problems in using round timber in building structures. "To present specific problems of designing round timber structures, mainly joints" (p. 1)	Quantitative explanatory	The most popular types of connections used for structural round timbers were bolted joints and bolted joints with slotted-in plates.
Ranta-Maunus (1991)	Round small-diameter timber for construction. "To present research on material production and developments of small-diameter round timber structures " (p. 12)	Quantitative descriptive	• Various testing methods had been developed concerning the strength of round timber structural components. • Small diameter timbers could be harvested in large amounts from forest thinnings.

Thépaut & Hislop (2004)	Round timber in construction: An introduction. "To give an introduction of round timber in the construction industry" (p. 1)	Quantitative descriptive	• Round timbers had been used in construction from the prehistoric era • The machine rounded timber was described.
Wolfe (2000)	Research challenges for structural use of small-diameter round timbers. "To give an overview of the options for round timber structural applications and contains recommendations for research needed to promote acceptance of engineered applications" (p. 1)	Quantitative descriptive	The utilization of small-diameter timbers in construction faced both economic and technical challenges.

3 METHODOLOGY

This chapter includes the research methodology implemented in this study. In more detail, in this part, the author outlines the research strategy, the research method, the research approach, the methods of data collection, the research process, and the type of data analysis.

3.1 Research Strategy

The research held regarding this study was an applied one, but not new. Rather, various pieces of previous academic research exist with respect to the utilisation and testing method for small-diameter timbers, not only for Europe in specific, but also for other places of the world. Hence, the proposed research took the form of new research but on an existing research subject.

3.2 Research Method

In order to meet the objectives of the study, qualitative research was conducted. The typical attribute of qualitative research is that it is recommended during preliminary phases of research projects, while the design is expected to emerge as the study unfolds. The basic advantage of qualitative research, which also creates its basic difference with quantitative counterpart, is that it offers a complete description and analysis of a research subject, without limiting the scope of the research.

However, the effectiveness of qualitative research is heavily dependent on the skills and abilities of researchers, while the valuable findings from the research may be difficult to present. The qualitative research also requires a longer time to collect data and industry-related expertise from researchers.

3.3 Research Approach

The research approach implemented in this study was the inductive approach. According to this approach, researchers begin with specific observations and propose theories towards the end of the research process as a result of observations. The reason for occupying the inductive approach was that it aims to generate meanings from the data set collected in order to identify patterns and relationships to build a theory; however, the inductive approach does not prevent the researcher from using existing theory to formulate the research question to be explored. Inductive reasoning is based on learning from premises, in which patterns, resemblances, and regularities are observed in order to reach conclusions.

3.4 Data Collection Method

For the purposes of this research, secondary data collection method and experimental data collection method were used.

Secondary data is a type of data that has already been published in books, newspapers, magazines, journals, online portals, etc. The main advantage of secondary data is the availability of data used in previous work, which makes it time-saving and convenient for future research. In addition, secondary data also provides a baseline for primary research, to which the results of the primarily collected data could be compared. An appropriate set of criteria to select secondary data to be used in the study to minimise the risks in the research validity and reliability, including but not limited to date of publication, credential of the author, reliability of the source, quality of discussions, depth of analyses, the extent of contribution of the text to the development of the research area etc., must be applied.

Experimental data collection method was utilised to generate data from the optimum test piece fabrication. The key features of the experimental data collection method included accurate measurements which enabled the possibility to replicate the experiment.

3.5 Research Process

Data from secondary sources with respect to small-diameter round timber utilisation and testing methods, especially bending test, were collected during January and May 2019. More specially, the researcher held regular meetings with the supervisor to explain what have been found and discuss the findings, which could lead to new theories and areas relating to the research subject. The data is then analysed to identify resemblances between sources. In June 2019, an optimum test piece was fabricated using the bundled column method. Finally, new theories and research questions were formulated in the form of recommendations for future research.

3.6 Methods of Data Analysis

Secondary data analysis was used to analyse the data gathered from existing literature. Appropriate findings were extracted from validated sources and critique on existing data was given by the researcher. The main advantage of secondary data analysis is that it saves time by providing access to high-quality data sources while replicating findings using similar analyses. However, secondary data may not answer the specific research questions of the researcher or contain specific information that the researcher would like to have.

Qualitative data analysis was used to analyse the data generated from the optimum test piece fabrication. After the hypothesis arising during the secondary data analysed had been scientifically tested, the data from the experiment was analysed in order to compare the primary and secondary findings. The most important purpose of the qualitative data analysis in this study was to link the research findings to the research aim and objectives.

4 DATA ANALYSIS AND FINDINGS

This chapter contains an analysis of the findings. More specially, in this chapter, the author presents notable findings with respect to small-diameter round timber utilization, summarises the results of the bending test conducted by the DUT laboratory (1998), and demonstrates the bundled column method.

4.1 Notable Findings

4.1.1 Bending Test

The bending test carried out by the DUT laboratory (1998) showed a good result with respect to the theory. The mean value of $E_{m\ total}$ was greater than $E_{m\ local}$ in both laboratories. The standard deviation of the Douglas test piece was notably higher than that of the Larch. The correlation coefficients between local and total moduli of elasticity of Douglas and Larch were 0.74 and 0.91 respectively. It was reported that although the average values for RD_{tl} (5%) can be compared; the standard deviations (20%, 7%) show significant differences between test arrangements.

Possible errors resulting in the differences between local and total values of the test were identified. In order to mitigate the risk of errors in measurements, researchers from the DUT laboratory suggested using the modified EN 408 test to determine $E_{m\ total}$ as a reference.

4.1.2 Bundled Column Method

Bukauskas (2015, p. 14) introduced bundled column methods as an applicable, easily fabricated and adaptable system with high crushing capacity. The bundled system made use of shear bolts connections, which accounted for 10% of the total timber weight, to connect timber elements with a different cross-section. Although the bundling method was undeniable an attractive way to fabricate structural components made of small-diameter round timbers, the method of fastening timber elements within the systems remained a great challenge.

4.2 Bundled Test Piece

A prototype of the bundled column was built using four 1.4 meters long and 45-55 millimetre diameter small-diameter round timbers (Figure 24).

Each timber was first debarked using a crosscut saw. The debarked timbers were then measured to identify the original length, the diameters at both ends, and the length of the straightest part along the longitudinal axis of the member. A rip cut saw was used to cut the timbers into the desired length that can optimise the straightest parts of the elements. The system was joined temporarily using plastic cable ties (Figure 25). After being stabilised as shown in Figure 26, the members within the bundled system were connected by metal screws using a power drill. The 100 millimetres long and 5-millimeter diameter Torx compatible wood screw was used in the bundled system (Figure 27). Finally, an angle grinder was used to remove any exceed parts of the screws.

The connection method showed a good result with respect to the bundled column method with negligible damages in the timbers.

Figure 24. Debarked small-diameter timbers

Figure 25. Temporary connection using plastic cable tie

Figure 26. Stabilising the piece

Figure 27. Power drill and screw for connecting the members

5 DISCUSSION AND RECOMMENDATIONS

5.1 Discussion of Findings

As stated in Chapter 1, the aim of this research was to analyse the existing data generated from the previous Bending test undertaken by the Delft University of Technology laboratory (de Vries, 1998). At this stage of the research, a literature review on the utilization of small-diameter timber as a construction material and the bending test for round timber was conducted. Key findings from the research include the arrangement of the bending test for round timber and the bundled column method. In addition, a bundled test was fabricated using metal screws to join four small-diameter timbers.

5.1.1 Test Arrangement

The bending test for round timber (de Vries, 1998, p. 189) was developed based on the EN 408 test with modifications in supports and loading heads.

According to the CEN description for the bending test of timber, the test pieces shall be simply supported. The application of small steel plates inserted between the supports and the test pieces or any necessary lateral restraint would be considered in order to minimize the indentation and allow the test piece to deflect without significant frictional resistance. The same concept was applied in the supports of the bending test for round timbers. However, the variable cross-section of small-diameter round timber may require universal supports that could adapt to the various cross-sections. In this case, small steel plates would potentially play the main role in the supports.

In the bending test carried out by the DUT laboratory, the loading head was designed with the aim to enable the loaded sections to rotate and alter the test piece surface during the experiment. The most important aspect that may affect the design of loading heads made for the round timber bending test may be the determination of the neutral plane. In theory, the neutral plane of the test piece must be identified in order to locate the axis of rotation for the loading heads. However, the neutral plane of small-diameter timber test piece with curvature would require more investigation.

5.1.2 Bundled Column Method

The bundled column method introduced by Bukauskas (2015, p. 14) showed a potential way to fabricate the test piece for the bending test. The concept of bundled column system was to pack tapered timbers in even multiples using shear bolts as connectors between elements, which accounted for 10% of the total timber weight in the system. Theoretically, the bundled column system was expected to carry positive attributes of round timber in general and provide high and equal crushing capacity. The system showed good performance under the compression test.

However, certain modifications would be concerned in the design of the bundled specimen used in the bending test. Unlike the tapered timbers used in the bundled column system, small-diameter round timbers were characterised by the unruly initial curvature along the longitudinal axis of the pole. The significant curvature was developed as a reaction to the natural growing conditions of trees. The joining between small diameter timber members within a bundled system would be significantly affected by the straightness of the material. This unfavourable but typical characteristic also resulted in the appearance of an elliptical-shaped cross-section varying across the length of the pole. Consequently, the design of the test piece using the bundling principle would face the same challenges in determining the diameter and neutral plane of the specimen.

The connections between members within the bundled system would play an important role in the designing process. The design of a small-diameter round timber bundled test piece may consider adapting the connections in parts compressed (Brito & Junior, 2012, p. 242) to obtain a more stable cross-section. In these connections (Figure 28), cylindrical logs were connected using steel threaded bushings, washers and nuts, while certain parts of the member logs within the system may be sawn off. In addition to the bolted connections previously used by Bukauskas (2015), the application of slotted-in metal plates may be considered. Figure 26 described another possible type of connection for a bundled system using connections with metal rings, steel bars, washers, and nuts.

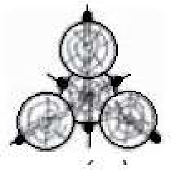

Figure 28. Connections in elements compresses (Brito & Junior, 2012, p.245)

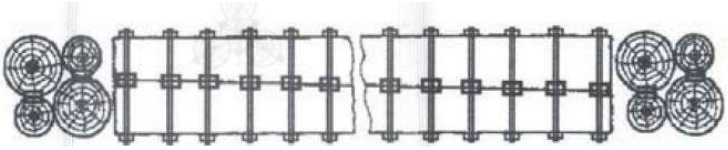

Figure 29. A system with metal rings, steel bars, washers and nuts (Brito & Junior, 2012, p. 245)

5.2 **Limitations of the Study**

This study used secondary data analysis method to evaluate the data gathered from the extant literature. The data collected from secondary sources were first validated in terms of date of publication, credential of the author, reliability of the source, quality of discussions, depth of analyses, the extent of contribution of the text to the development of the research area. However, the huge gap in the dates of publication of reviewed literature would put questions on the validity and relevancy of previous data.

The recently increasing diversity and sophistication of round timber practices resulted in a wide range of secondary data concerning various issues related to small diameter timbers. However, information about the specific research focus on bending test arrangement was neither readily available nor up to date.

Another consideration was the limitation of the qualitative research method implemented for this thesis. Although the chosen research method offered a complete description and analysis of the research subject, it had limited the measurement from the actual bending test.

5.3 **Recommendations for Future Research**

5.3.1 Application of High Technologies

In Section 5.1, the author discussed the challenge in determining the neutral plane of the small diameter round timber test piece. Due to the diversity in the curvature of small diameter timbers, the neutral plane would require an advanced measuring method. Traditionally, geometric information about round timber has been gathered using conventional manual measurement tools such as tape measure or tree calipers. In these cases, only basic measures could be recorded, while more sophisticated measurements such as taper or curve could be assumed. Nowadays, the measurements of highly irregular geometries in small-diameter round timber specimens would benefit from the development of three-dimension (3D) scanning technologies and computer-aided design (CAD) in the construction industry. With the involvement of 3D scanning technologies, a digital prototype of the specimen would be created with more precise physical properties regardless of irregular geometries. Future researchers would then import the digital prototype into the CAD program to analyse and determine necessary characteristic values required by the bending test description.

A key challenge with utilizing 3D scanning technologies for investigating physical characteristics of small-diameter round timbers was a representation of the scanning result into convenient forms for structural design, analysis, and fabrication. Future researchers are recommended to investigate the *skeleton* representations (Figure 30), in which the area centroid of circles fitted to a timber surface representation was used for the alignment of structural members during design.

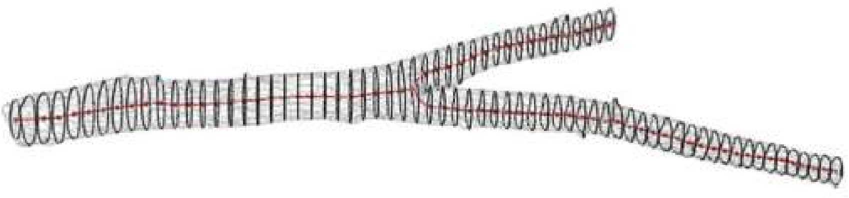

Figure 30. “Skeleton” representation of a whole timber generated from 3D scanning (GIM International, 2019)

At this point in the research, the author suggested using Autodesk Revit to create the digital prototype of the test piece. Future researchers would model curved beams using the Spline function when sketching the piece. The properties of the material could then be chosen from the Revit material library, while changes in properties of round timbers would be modified. The tapering characteristic of round timber could also be represented by altering the dimensions of the cross-sections in both ends of the beam.

However, in order to model a curved beam, only one reference plane is needed, which means that the beam can only be bent within one plane. Therefore, prototypes with highly irregular geometries that bend in more than one plane may not be effectively represented in Revit. Another challenge in utilising Revit was to select the suitable connections for the specimen. The author suggested investigating further on the connections for round timber prototype in Revit, possibly self-modified templates.

5.3.2 Design of Supports

As described in the EN 408 standard, the test piece should be simply supported. In the existing test for sawn timber specimen, the most popular types of support for the four-point bending test included cylindrical rollers and hardened knife-edge supports. While cylindrical rollers showed little potential for the circular cross-section of small diameter timbers, the knife-edge support (Figure 31) may be utilized with further investigation. The manufacturer of bending test equipment provided options of customized non-standard equipment unique to the specimen due to the awareness of the diversity and sophistication of testing methods and test pieces. The author recommended further research on the design of customized supports with unique attributes satisfying the test requirements.

Figure 31. Hardened support on a standard bend fixture (ADMET, 2019)

The design of universal supports had been mentioned in Section 5.1. Theoretically, the universal support would be designed in the way that various different cross-sections could be accommodated. In the bending test described by de Vries (1998), about 300 specimens with at least five different diameters had been tested. The supports used in de Vries experiment showed potential for the design of a universal support. However, there has been very little information about the development of universal supports for bending tests from other researchers. In addition, the supports used in the de Vries test only considered specimens with single circular cross-sections, while the adaptability of these supports to more complex cross-sections remained unknown. Therefore, future researchers should investigate the feasibility of universal support thoroughly before any further design would be discussed.

5.3.3 Hemp

In order to enhance the physical appearance of the structural members made of small-diameter timbers, the application of hemp should be considered. The use of hemp as a building material includes hempcrete, hemp fibre, and hemp oil sealant. In this case, hempcrete or hemp fibre could be wrapped around the small-diameter timber elements with highly irregular geometries to achieve elements with common cross-section and straightness. This process could potentially increase the overall strength of the structural members. In addition, the external hemp cover could act as a perfect insulating material for the timber core.

6 CONCLUSION

The aim of this thesis was to analyse the existing data generated from the previous Bending test conducted by the Delft University of Technology (de Vries, 1998). To achieve this aim, the following objectives were proposed to be pursued:

Objective #1: Conduct research of existing literature for a comparable study.

Objective #2: Adapt and adopt the methodology for collecting data.

Objective #3: Analyse the collected data from the bending test for round timbers.

Objective #4: Discuss the findings.

The expected outcomes of the study included adapting the methodology from the comparable study, using the bending test for round timber to analyse the existing data, achieving similar results to that of the other studies, and determining the characteristic strength of round timbers in different cross-sections by applying the result from this study.

To approach the aim of the study, a literature review was conducted. The literature review first focused on various aspects concerning the utilisation of round timber as a construction material including the historical background, the contemporary applications, benefits of the material, the challenges for wider acceptance in the construction industry, and available structural connections for round timbers. The information from the extant literature which related to the bending test for round timbers in terms of test reference, test arrangement, test piece, and test result were then presented.

The research method in this thesis was to conduct a qualitative research using the inductive approach. The notable findings obtained from the secondary sources in the literature review, which were the utilisation of round timbers, the bending test arrangement, and the bundled column method, were analysed and discussed. Recommendations for future research on the application of high technologies and the design of test supports were given after the discussion.

At this stage of the research, the expected objectives were completed as follows:

Objective #1: Conduct research of existing literature for a comparable study.

A literature review was conducted concerning the utilisation of round timbers in construction and bending test for round timbers

Objective #2: Adapt and adopt the methodology for collecting data.

The bundled column method was adapted and adopted to fabricate an optimum bundled test piece

Objective #3: Analyse the collected data from the bending test for round timbers.

The bundled test piece had been analysed.

Objective #4: Discuss the findings.

The notable findings from literature review had been discussed.

The ultimate goal of this research was to stimulate the adoption of small-diameter round timber as a structural material. The purpose of this research was to analyse the existing data generated from the previous Bending test conducted by the Delft University of Technology (de Vries, 1998) in order to develop suitable test arrangement and test specimen design, which ultimately increase the accuracy of the experiment.

To address the challenge of effectively determining physical characteristics of irregular small diameter timbers and designing suitable supports for the bending test, some important research questions to be explored has been recommended in this thesis. These include:

- Accurately measuring the physical characteristics of small-diameter timbers with the application of 3D scanning and CAD programme.
- Developing customised supports with unique attributes satisfying the bending test requirements
- Adapting the application of hemp in the fabrication of test pieces.

It can be concluded that the most significant finding from this study seems to be the bundled system as a method to fabricate test pieces for the bending test. By adapting the bundled column method, an optimum test piece was produced. The design challenges of a bundled system are expected to be largely addressed through innovations in connections and the involvement of advanced measuring techniques. On the other hand, this research has shown that the design of appropriate supports is the key objective in the development of bending test for natural round timbers.

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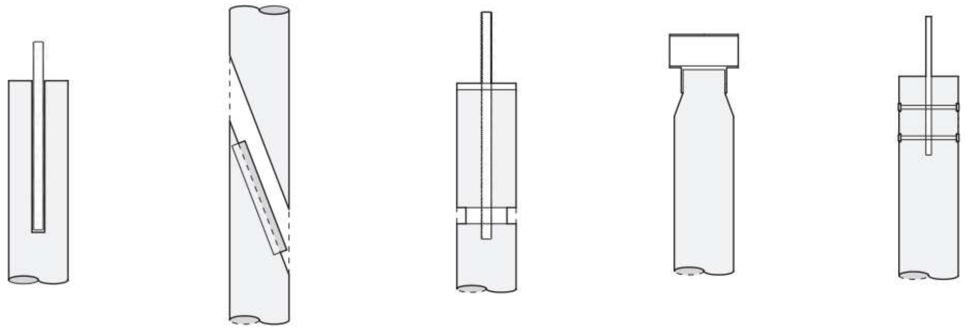
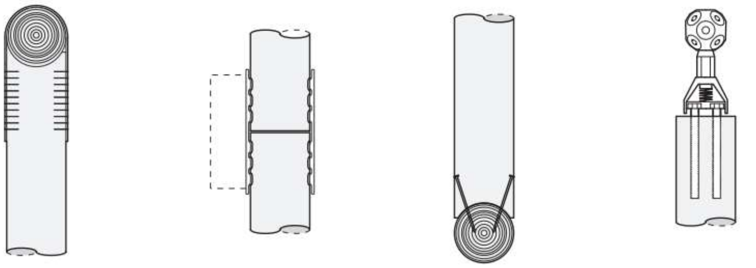
Appendix 1

SELECTED WHOLE TIMBER STRUCTURAL CONNECTIONS (Bukauskas, 2019, p. 759)



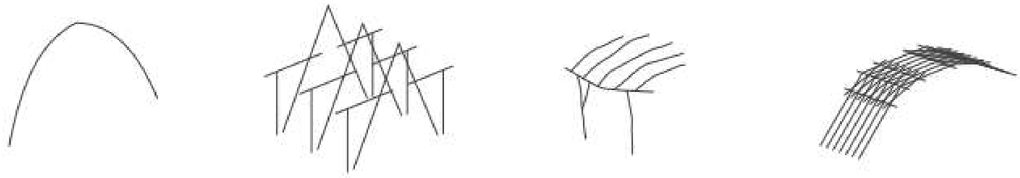
(a) Glued-In Rod (b) Splice (c) Dowel-Nut (d) Pipe Socket (e) Flitch Plate



(f) Nail Plate (g) Annular Groove (h) Toe-nailed Screw (i) Lag Screw in End-Grain

Appendix 2

SELECTED STRUCTURAL SYSTEM IN WHOLE TIMBER (Bukauskas, 2019, p. 761)

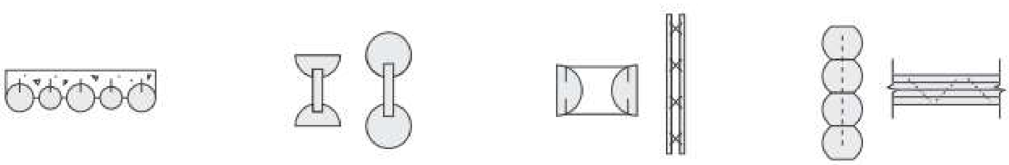


(a) Actively Bent Arch (b) A-Frame (c) Free-Form Post & Beam (d) Woven Timber Arch

(e) Free-Form Log Wall (f) Pin-ended Struts (g) Planar Truss (h) Spatial Truss

(i) Hybrid Steel & Round Timber Truss (j) Vierendeel Frame (k) Portal Frame (l) Tensile Net

(m) Single Layer Gridshell (n) Double Layer Gridshell (o) Shear Wall (p) Floor Panel



(q) Whole Timber-Concrete Floor / Bridge Deck (r) Hybrid Sawn and Whole Timber Beams (s) Half-Round Timber Stud Wall (t) Composite Log Wall

Appendix 3

THE ROOF TRUSS OF MUTORO INDOOR STADIUM IN JAPAN (Bukauskas, 2019, p. 777)

Appendix 4

CLASSIFICATION OF WHOLE TIMBER BY DEGREE AND TYPE OF PROCESSING (Bukauskas, 2019, p. 759)