Withdrawal strength of self-tapping screws in tropical hardwood

Master Thesis

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Withdrawal strength of self-tapping screws in tropical hardwood

by

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Cover Image: Cut open Tali piece from pre-testing, photo: own work.

TU Delft

Preface

In 2017 I started with the pre-master Structural Engineering at the Technical University of Delft and continued my master in Structural Engineering specializing in steel and timber structures at the faculty of Civil Engineering and Geosciences. This thesis concludes my studies at the TU Delft. While searching for a master thesis topic I was not sure if I wanted to graduate with a steel or timber topic. In the end this became a timber related topic in the form of this report. The topic of this thesis was available at the Biobased Structures and Materials group at the TU Delft. Studying the withdrawal strength of self-tapping screws in tropical hardwood seemed to me like an interesting subject. The possibility of doing real life tests in the laboratory made it even more interesting to me.

First of all I want to thank my graduation committee members, Dr. ir. G.J.P. Ravenshorst, Ir. P.A. de Vries and Dr. ing. C. Sandhaas for their feedback during our mainly online meetings. I want to thank again Ir. P.A. de Vries and also R. Kunz and F. Schilperoort for their support in the laboratory. I also want to thank Prof. dr. ir. J.W.G. van de Kuilen and ir. C. Noteboom who joined the graduation committee in a later stage for their feedback. Finally I would like to thank my friends and family for their encouragement and support during my studies.

R.J. Nijkamp
Rijssen, April 2022

Summary

Self-tapping screws are popular tools used in timber engineering. The axial withdrawal strength of self-tapping screws could be used in timber structures as an active or passive application. An example of an active application is the use as a fastener in wall to wall connections. An example of a passive application is the use as reinforcement perpendicular to the grain, to prevent cracking along the grain. Existing methods to calculate the withdrawal strength of self-tapping screws are mainly based on tests done on softwood. Some screw manufacturers offer calculation methods for the use of their screws in hardwood from temperate regions in so called European Technical Assessments (ETAs). But the Eurocode and the ETAs offer no calculation methods for high density tropical hardwood species. Tropical hardwood species are generally used in The Netherlands for hydraulic and outside structures such as lock-doors, bridges, weirs and jetties. Tropical hardwood species are used because of their strength and durability in outside conditions. There are no well-established methods to calculate the withdrawal strength of self-tapping screws in tropical hardwood perpendicular to the grain and the purpose of this thesis is to gain more knowledge on this topic. The central question of this thesis is: What is the withdrawal strength of self-tapping screws in tropical hardwood species perpendicular to the grain and is it possible to develop a verification model for engineering purposes?

To find answers to the main question first a literature review has been conducted. Literature on timber anatomy, self-tapping screw properties and available calculation methods have been reviewed. This is followed by a literature review on possibilities to drive self-tapping screws into high density woods. This is problematic because screws could fail already during insertion or cause splitting of the timber. Screw modifications such as cutter tips could be used to reduce the insertion moment, but also pre-drilling of the timber could be done to avoid torque failure of screws or the splitting of timber. The literature study is finalized with an investigation to the influence of material properties on the withdrawal strength. Tropical hardwood species are often used in outside or wet structures so literature on the influence of moisture content has been investigated. In research done by Ringhofer et al. [22] it was found that if the moisture content increases above 12 % the withdrawal capacity significantly decreases. Pre-drilling of the timber helps to insert self-tapping screws more easily into timber, but this also removes material and could therefore reduce the withdrawal strength. Research done by Brandner, Ringhofer, and Reichinger [5] found that if the pre-drilling diameter is smaller or equal to 80 % of the nominal screw diameter pre-drilling had no influence on the withdrawal strength. The mentioned research however has been done on temperate hardwood and the question is whether this is the case for tropical hardwood as well. According to EN 1995-1-1:2011 pre-drilling is necessary if the characteristic density of the timber is larger than 500 kg/m^3. With increasing timber density the withdrawal strength also increases (Hubner, Rasser, and Schickhofer [13]). Regarding the screw diameter, with increasing diameter the withdrawal strength (f_{ax}, MPa) decreases as was found by for example Hubner, Rasser, and Schickhofer [13]. With increasing diameter the withdrawal capacity (F_{ax}, kN) also increases. With increasing effective length of self-tapping screws inserted in wood the withdrawal strength (f_{ax}, MPa) does not increase or decrease (Xu et al. [30]). The withdrawal capacity (F_{ax}, kN) however increases, a linear relationship between the effective length withdrawal capacity can be observed in research done by Xu et al. [30].

Findings in the literature study were the basis of how the test series were designed. EN1382:2016 describes how to test and determine the withdrawal strength of screws in timber. This standard also gives rules on the dimensions of the test piece. The width of the available tropical hardwood pieces was to small according to EN1382:2016 which states that a minimal edge distance of 5d has to be used. Methods from the EN 1995-1-1:2011 and ETA-11/0030:2020 from Rotho Blaas have been used to make a selection of screws that will be used in testing. The goal is to have withdrawal as main failure mode. The following screw diameters have been selected: 6, 8 and 11 mm. The diameter 11 mm screw has been tested in a pre-testing series with pre-drilling diameters: 0,7d and 0,8d; with insertion depth 90 mm; Also three tropical hardwood species with the highest density were selected to test the limits

of the materials. It was found that the smaller edge distances did not cause any problems. Further because of pre-drilling no damages occurred on the timber or screw, and there were no problems during screw insertion. No significant difference in withdrawal capacity was found between pre-drilling 0,7d and 0,8d so this was changed to pre-drilling 0,8d and 0,9d in the main test series. Also screw failure was observed for insertion depth 90 mm, this was changed to a maximum of 70 mm in the main test series to make sure screw withdrawal is the main failure mode.

For the main test series 6 tropical hardwood species were used (Kanda, Lati, Longhi, Tali, Limbali and Mukulungu), and also the softwood Spruce as a reference material. The diameter 6 mm, 8 mm and 11 mm screws were used with pre-drilling diameter 0,8d and 0,9d. Conditioning of the wet test pieces has been done by putting the timber blocks underwater. On every test piece or timber block four tests were done: two withdrawal strength tests (according to EN 1382:2016) and two stiffness tests (according to EN 26891:1991). Also the insertion moment was measured. After testing the density of every test piece was determined together with the moiture content.

The main test series provided a broad range of data. The following was measured: the density, the moisture content, the withdrawal capacity, the insertion moment and slip modulus. All results can be found in annex A. The test piece geometry was not according to EN 1382:2016, in general larger edge distances were required. Nevertheless did this not lead to any problems, no cracks or screw failure occurred during the insertion of the self-tapping screws nor was it any problem to insert the screws at all. This had all to do with the pre-drilling diameters of 0,8d and 0,9d what was used. Because of this very low insertion moments were measured. Also during and after withdrawal tests no significant damage was observed. Even in extreme situations that were tested during pre-testing there was no evidence that a larger edge distance was needed. In the analysis it was found that with increasing density the withdrawal strength also increases, this is in line with literature. It was also found that the species does influence the withdrawal strength, as was found by calculating the withdrawal strength to density ratio per species. With increasing screw diameter the withdrawal strength decreases as was found in this analysis, and also in line with literature. Only in the case of pre-drilling 0,9d for the diameter 8 mm screw this was not the case when comparing it to the diameter 6 mm screw, this probably was a result of pre-drilling accuracy. Regarding the influence of pre-drilling it was found that on average the withdrawal strength is reduced by a factor of 0,68 when the pre-drilled hole is 0,9d instead of 0,8d. In literature it was found that the effective screw length does not influence the withdrawal strength. No clear influence of effective length has been found, except for screw diameter 6 mm and 8 mm when pre-drilled 0,9d. The diameter 6 mm and 8 mm screws are HSBH screws with a larger inner diameter and it might be that the withdrawal strength is not optimal for these types of screw when inserted in 0,9d pre-drilled holes. During testing wet and dry pieces were tested. It was found that the moisture uptake rate is very different for the various tropical hardwood species that were tested. It was also found that as expected the withdrawal strength is negatively influenced by an increased moisture content. First of all it has to be mentioned that the scatter in data is larger when compared to the test data from withdrawal tests, this has to be taken into account. In the analysis it was found that with increasing density the slip modulus also increases. Also the timber species influences the slip modulus just like in the case of the withdrawal strength. No clear influence of screw diameter was found on the withdrawal strength. Just like for the withdrawal strength is the slip modulus influenced negatively when pre-drilling 0,9d has been used instead of 0,8d. This negative influence increases with increasing diameter. With increasing effective screw length also the slip modulus increases, this would be expected and was also found in the test results. Also a higher moisture content has a negative influence on the slip modulus, this was also as expected. A larger influence was observed in the case of timber species with the highest densities measured (Tali and Mukulungu), while for these species the lowest moisture content was measured in wet conditions compared to other species.

Finally two models have been proposed to better predict the withdrawal strength of self-tapping screws perpendicular to the grain in tropical hardwood. For the first model withdrawal strength f_{ax} parameters are determined per species, per timber condition and per pre-drilling diameter. The second model is one formula based on the density, screw diameter and effective screw length for all tested tropical hardwood species. Both proposed models show a good fit to the test data.

Contents

Nomenclature

Abbreviations

Abbreviation	Definition
CLT	Cross Laminated Timber
COV	Coefficient of variation
ETA	European Technical Assessment
GLT	Glue Laminated Timber
HSS	High strength steel
LVL	Laminated Veneer Lumber
m.c.	moisture content

1 Introduction

In this thesis the withdrawal strength of self-tapping screws inserted in tropical hardwood perpendicular to the grain will be investigated. Tropical hardwood species are known for their strength and durability. Many properties have already been researched, but not all properties. The withdrawal strength of self-tapping screws in tropical hardwoods is still unknown. This property could serve several purposes in engineering design and not just for fastening a screw to take tensile forces. The withdrawal strength could serve another useful goal: as reinforcement of timber elements. Screws could be applied perpendicular to the grain in timber elements prone to splitting parallel to the grain, by this splitting could be prevented. Self-tapping screws are a cheap and fast reinforcement solution. There is much more to it which will be explained in the next chapter. A research will be conducted regarding the withdrawal strength of screws in tropical hardwood perpendicular to the grain.

1.1. Problem analysis

1.1.1. Application of self-tapping screws inserted in timber

In timber engineering the use of screws in timber is very popular because this is a very cheap and easy to use fastener type. This fastener type could be loaded axially but also laterally. There are many screw types and variations available, but the focus in this thesis will be on axially loaded self-tapping screws. Self-tapping screws are a very common screw type. These screw types are capable to 'tap' them self into the wood. The idea behind self-tapping screws is that the thread of the screw cuts into the material when the screw is inserted into the wood by rotation. By cutting of the thread into the material the screw is 'anchored' in the material. The use of self-tapping screws inserted in timber is regulated by EN 1995-1-1 and by technical approvals for specific screws made by different manufacturers. In Europe these are European Technical Assessments (ETAs). Some examples of self-tapping screws are shown in figure 1.1. In figure 1.2 some examples of screws used as fasteners are shown, in this case in CLT wall and floor elements.

Figure 1.1: Some examples of self-tapping screws.

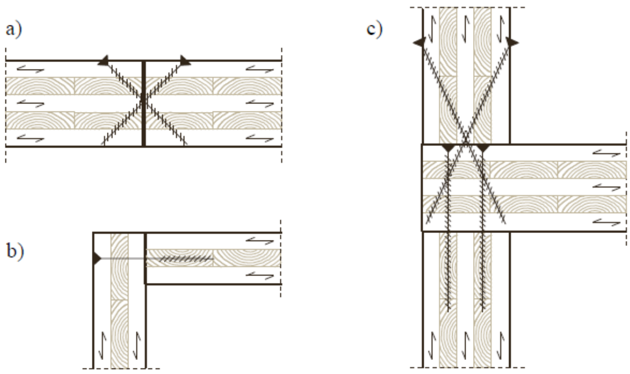

Figure 1.2: Examples of screws in CLT elements used as fasteners; a) Floor to floor connection; b) Wall to wall connection; c) Wall to floor to wall connection (Ringhofer [21]).

Self-tapping screws could not only be used as axially and/or laterally loaded fasteners in timber, these screw types could also be used as reinforcements. The purpose of this reinforcement is to significantly improve a structural element. Two examples of structural elements will be discussed in this sub-chapter in which self-tapping screws can be used as reinforcement to improve the structural element. These are a dowel type connection and a notched beam. The goal of the reinforcement in both examples is to prevent splitting of the timber by inserting self-tapping screws in the timber perpendicular to the expected crack. Cracks could be expected generally parallel to the grain.

Reinforced dowel type connection loaded laterally
In previous years research has been done by Bejtka and Blaß [2] to reinforce timber connections such as displayed in figure 1.3: a dowel type connection. The load carrying capacity of such a dowel connection is calculated using the Johansen's yield theory, but full strength will not be reached in reality. The strength is limited by the geometry of the connection, the yield moment of the dowel and the embedding strength of the timber itself.

When the connection is loaded axially like shown in figure 1.3 the timber could split parallel to the grain. The splitting pattern is shown in figure 1.3. According to Bejtka and Blaß [2] the splitting tendency is affected by the spacing of the dowels, showing increasing splitting tendency with decreasing fastener spacing parallel to the grain. Splitting in the timber decreases the effective number of fasteners, which reduces the strength of the connection. The findings by Bejtka and Blaß [2] where based on findings in the dissertation by Schmid [28]. The timber used by Schmid [28] is mainly softwood, only two hardwood species were used namely beech and oak. By using reinforcements such as screws as shown in figure 1.3, the splitting can be prevented when the axial load carrying capacity (withdrawal strength) of each screw in the timber is larger than 30 percent of the lateral load carrying capacity per shear plane of each dowel (Schmid [28]). Then the timber does not split, and the effective number of dowels equals the number of dowels used. The load carrying capacity of the dowel connection can be further improved by placing the screws in contact with the dowels. This combination of using screws and placing them in contact of the dowels could increase the load carrying capacity up to 120 percent (Bejtka and Blaß [2]).

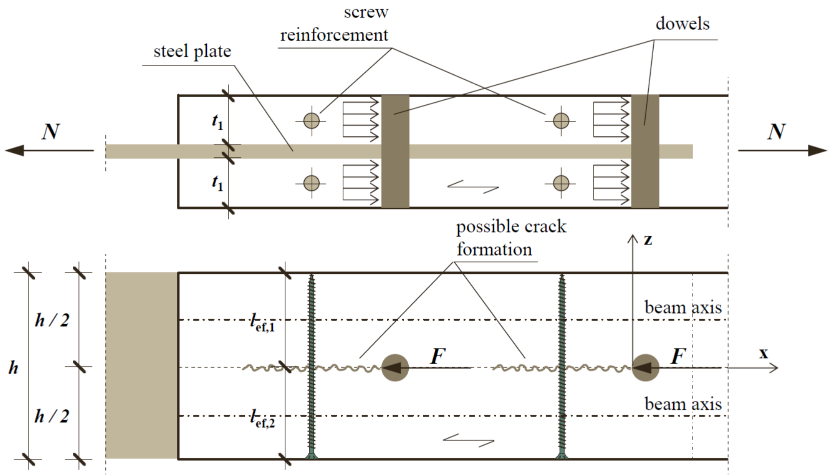

Figure 1.3: Example of dowel type connection with self-tapping screws, showing the splitting pattern parallel to the grain. Top and side view are shown (Ringhofer [21]).

If an engineer wants to reinforce a connection like above with screws perpendicular to the grain it is necessary to know the withdrawal strength of the screw in the timber. Only then screws can be designed to achieve 100 percent effective dowels.

Reinforcing notched beam
The other example is a notched beam. In these beams splitting could be a problem parallel to the grain near the notch as can be seen in figure 1.4. Research done by Oudjene et al. [18] shows that the load carrying capacity of notched beams improve with reinforcements as shown in figure 1.5. The reinforced beams show less brittle failure and research done by Oudjene et al. [18] shows a 34 percent improvement in strength compared to unreinforced beams. These results found by Oudjene et al. [18] are based on tests done on spruce with an average density of 420 kg/m^3.

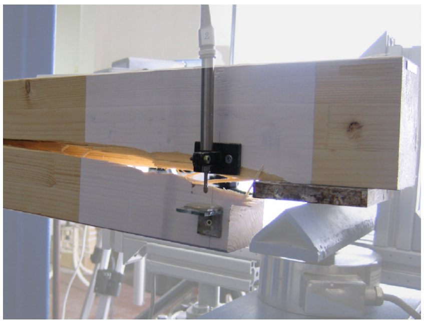

Figure 1.4: Notched beam showing splitting along the grain (Franke, Franke, and Harte [8]).

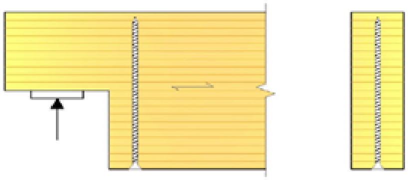

Figure 1.5: Notched beam with self-tapping screws used as reinforcement (Franke, Franke, and Harte [8]).

Research done by Franke, Franke, and Harte [8] states that the most common failure mode in timber beams is cracking in the grain direction. If there is tension in the timber perpendicular to the grain screws can help to prevent splitting if necessary. This would mean that the screws are loaded axially, and the ability to prevent splitting of the timber parallel to the grain depends on the withdrawal strength of the screw in the timber perpendicular to the grain.

1.1.2. Self-tapping screws inserted in tropical hardwood species

For several reasons it could be interesting to use tropical hardwood instead of softwood or temperate hardwoods (for example oak or beech). Tropical hardwoods are known for their durability and strength. Therefore tropical hardwoods are especially interesting for outside and wet conditions. Practical examples are bridges, weirs, jetties and sluice gates.

In the previous sub-chapter two examples were given of structural elements that could be improved using self-tapping screws as reinforcement. The results mentioned in that sub-chapter are not based on tropical hardwoods which could have a very high density, but rather mainly on softwoods with a lower density. It is found that notched beams and dowel connections made out of tropical hardwoods are also prone to splitting. In research done by Kuilen et al. [16] notched beams made out of tropical hardwoods were tested, which showed just like research done on spruce by Oudjene et al. [18] cracking failure starting from the notch along the grain. An example of this can be seen in figure 1.6a. An example of a cracked dowel connection (crack along the grain) can be seen in figure 1.6b.

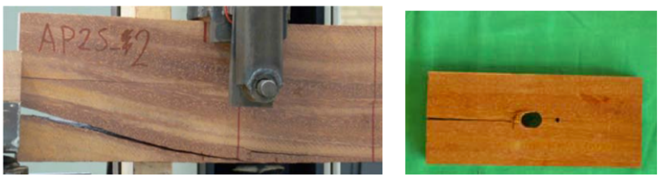

Figure 1.6: (a-left image) Notched beam showing splitting along the grain, with in this case a beam out of tropical hardwood (Ekki) (Kuilen et al. [16]). (b-right image) Dowel connection made out of Ekki showing splitting along the grain after embedment test parallel tot the grain with hss dowels (Sandhaas et al. [26]).

Splitting is a failure mode which does occur in tropical hardwood, and therefore reinforcements perpendicular to the grain with the help of self-tapping screws could be interesting to prevent splitting. There are already a few practical problems, namely that it might be very difficult to insert screws into the tropical hardwoods because of their high density. EN 1995-1-1:2011 states in 10.4.5 (2) that pre-drilling is necessary when the characteristic density of the timber is larger than 500 kg/m^3. This is generally the case for tropical hardwoods. Further, it is important to calculate the withdrawal strength of self-tapping screws in tropical hardwood when using self-tapping screws as reinforcements. Here the next problem comes up because EN 1995-1-1:2011 8.7.2 (4) mentions that the assumed failure mechanism in the provided formula for withdrawal strength of screws in timber is a brittle failure mechanism, meaning little deformations and limited possibilities to redistribute stresses. The formula for withdrawal strength of screws in timber is based on tests on softwoods, not high density wood species such as tropical hardwoods.

1.1.3. Problem definition and thesis focus

A lot of research has been done on the withdrawal strength of self-tapping screws inserted in wood. The majority of these researches are based on tests done on softwoods. Also the formula provided by the Eurocode 1995-1-1:2011 to calculate this withdrawal strength is based on tests done on softwood. Little is known about the withdrawal strength of self-tapping screws in tropical hardwoods. Therefore the focus of this thesis will be on axially loaded self-tapping screws inserted in tropical hardwood. The goal is to learn more about the withdrawal strength of self-tapping screws inserted perpendicular to the grain in tropical hardwood species and to determine if these wood species are usable in engineering applications. The main focus will be on the performance of a single screw.

1.2. Objective

The objective of the thesis is to gain knowledge about the withdrawal strength of self-tapping screws in tropical hardwood species when loaded perpendicular to the grain. This could gain insight if or in what degree the withdrawal properties of tropical hardwoods are applicable in engineering practice.

1.2.1. Research questions

Main question:

- What is the withdrawal strength of self-tapping screws in tropical hardwood species perpendicular to the grain and is it possible to develop a verification model for engineering purposes?

The main question has a very broad scope. To help answering the main question and narrowing down the subject sub questions will be introduced.

Sub-question:

- What are the most common failure mechanisms of withdrawal tests of screws perpendicular to the grain in topical hardwood?
- What is the influence on the strength of parameters such as:
  - Screw diameter
  - Pre-drilling diameter;
  - Effective length of screws;
  - Density of different tropical hardwood species;
  - Moisture content in tropical hardwood species (higher m.c. for lock doors);
- Is it possible to validate the experimental findings using numerical analysis or an empirical formula?
- Is the withdrawal strength of tropical hardwood species applicable in engineering practice?
  - How do withdrawal test results compare to current engineering formula?
  - Could tropical hardwood meet the requirements to make sure 100 percent of the dowels are effective in reinforced dowel type connections?

1.2.2. Project boundaries/ scope/ goals

The project boundaries are set by the sub questions formulated in the previous sub chapter. The goal is to be able to answer all these questions and ultimately give a sufficient answer to the main question.

1.3. Methodology

In this chapter the methodology is explained. First a literature research will be conducted to gather more knowledge about the subject. This will be followed by experiments.

Literature study

- Literature review on the different anatomies of wood species;
- Literature review on the different screw types;
- Existing calculation methods for withdrawal strength and possible drawbacks:
  - Calculation methods from EC5;
  - Calculation methods from screw manufactures;
  - Existing literature on the withdrawal strength of screws in different wood species;
- Withdrawal strength of screws in hardwood literature;

A literature study regarding the practical use of screws in timber has already been done and can be found in the problem analysis.

Experiments

The literature research will be followed by experiments on topical hardwood specimens. Experiments will be carried out on tropical hardwood species by testing their withdrawal strength of screws applied perpendicular to the grain. Experiments will preferably be conducted according to EN 1382:2016. The experiments will take place at the TU Delft.

2 Literature study

Before starting with experiments it is useful to explore the topic in more detail. In this chapter the differences between softwood and hardwood will shortly be addressed, followed by a review of calculation methods regarding the withdrawal strength of screws in timber from design codes and research. Screw insertion into wood with high densities might be difficult so also this topic will be elaborated. And finally, the influence of material properties on the withdrawal strength will be addressed.

2.1. Short introduction to hardwood and softwood

Wood species can be divided into two groups: softwood (gymnosperms) and hardwood (angiosperms). An example of softwood is spruce and an example of hardwood is oak. There are many differences and similarities between the two groups. The terms 'hard' or 'soft' does not have to apply to the density or durability of the two groups.

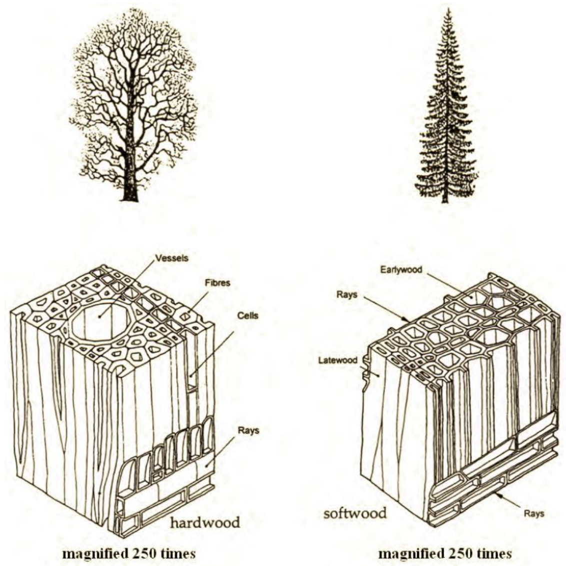

Figure 2.1: Magnified details of hardwood and softwood (Angst et al. [1]).

Softwood

The structure of softwood is build-up from two cell types namely tracheids and parenchyma cells. The tracheids are mostly present and make up about 90 - 95 percent of the softwood. The remaining are rays, longitudinal parenchyma and resin canals (Blaß and Sandhaas [4]).

Hardwood from temperate regions and Tropical hardwood

Hardwood includes much more types of cell compared to softwood, this is dependent on the species. Hardwood is comprised of cell types that are specialised for multiple purposes. For example fibre tracheids transport water but also reinforce the wood, and libriform fibres are exclusively present to provide strength (Blaß and Sandhaas [4]).

Tropical hardwood species are also part of the angiosperms. Among tropical hardwoods there are species with very high wood densities, but there are also species with densities lower than some temperate hardwoods or softwoods. Hardwoods are sometimes also called deciduous. The term deciduous means that a plant loses its foliage during a dry season or winter. This does not apply to most angiosperms from tropical regions. These frost free regions provide that trees in tropical regions do not have to be dormant. Generally tropical hardwood species are not deciduous but evergreen, meaning these species remain their foliage functional throughout multiple growing seasons. We also do not speak of annual rings in tropical hardwood species but rather of growth rings.

2.2. Introduction to axially loaded screws

In this sub-chapter 2.2 information is extracted from a dissertation by Ringhofer [21]. Information from (Ringhofer [21]) relevant for this thesis has been reviewed such as the development of axially loaded screws, the geometry of self-tapping screws and the production of self-tapping screws. The geographical focus of the work done by Ringhofer [21] was in Central Europe (Germany, Austria and Switzerland), so findings in this sub-chapter are mainly based on development in those countries.

2.2.1. Development of axially loaded screws

The use of threaded screws made out of metal is not a new concept. Already in the 18th century these kind of screws were used to connect timber elements. The threads at that time were also already cut or rolled. Up until the 1990s screws were mainly used to take lateral loading in timber engineering. Development of predominantly axially loaded screws and their standardisation started in the beginnings of the 1990s. Together with this, the number of technical approvals for the use of axially loaded screws in wood also rapidly increased.

One of the first application fields around the 1990s of axially loaded self-tapping screws was for timber-concrete composite systems. These screws are placed under an angle in the timber and concrete which results in axial loading of the screws. In figure 2.2 this composite system is shown. In these composite systems rigid connections are important to allow for maximum composite action. When loading screws in timber laterally large deformations and ductility is possible while the failure load is lower compared to axially loaded screws in timber. Compared to laterally loaded screws in timber, axially loaded screws show higher bearing resistance and stiffness. The ductility and maximum deformations are lower compared to laterally loaded screws. So, therefore loading screws axially allows for better composite action in timber-concrete systems. Further, by developing the screws in this structure to be self-tapping this composite system became significantly cheaper, since pre-drilling was not necessary anymore. This timber-concrete composite system is one of the fields where axially loaded screws in timber were developed. It was found very quickly that there was potential for a broader use of axially loaded screws in timber, especially with the economic option of self-tapping screws in timber where pre-drilling was no longer necessary.

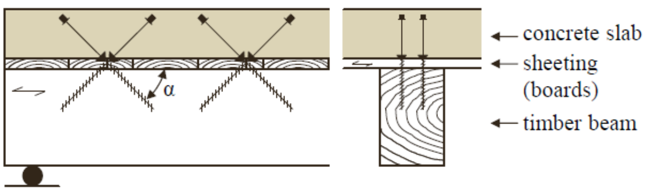

Figure 2.2: Timber-concrete composite connection with the threaded screw part under angle α in the timber and a stud in the concrete part (Ringhofer [21]).

Further development came with the full threaded self-tapping screws which could be used for passive applications (such as reinforcements) or active applications (such as timber to timber connections).

2.2.2. Self-tapping screw geometry

Generally the parts of a self-tapping screw can be divided in 5 components:

- Drive;
- Head;
- Shank;
- Threaded part;
- Tip;

In figure 2.3 these components are displayed. The components described can vary between screw manufacturers. In so called European Technical Assessments (ETA) every manufacturer specifies the geometry of all five components mentioned.

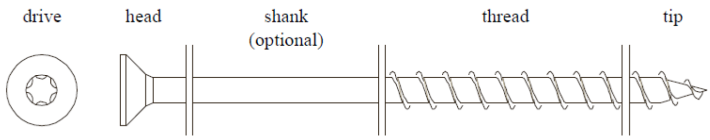

Figure 2.3: Geometrical components of self-tapping screws (Ringhofer [21]).

Screw drive
Beginning with the drive, this is the part or interface between the fastening part and the screw driving tool. Drives are classified in three types: internal drives, external drives and combined forms of internal and external drives. Among these types there is also variation. Figure 2.4 shows some examples of drives.

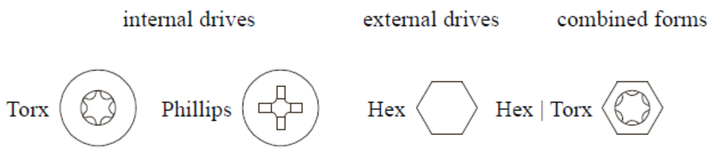

Figure 2.4: Drive classification and some examples (Ringhofer [21]).

Screw head
By looking at current valid ETAs Ringhofer [21] classified screw heads in two categories: sunk heads and non-sunk heads. Sunk heads are designed to easily be inserted into the wood, but because of this this type has a lower head pull-through capacity compared to non-sunk heads. The types are displayed in figure 2.5, the countersunk head should be familiar because this is a very popular type. Non-sunk heads have a larger d_{head}, and the head pull-through resistance is much better compared to the sunk heads.

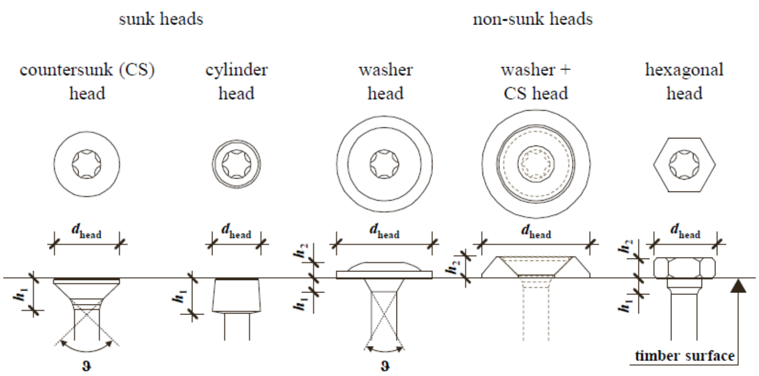

Figure 2.5: Screw head classification and some examples (Ringhofer [21]).

Shank
The screw shank is the part between the head and the threaded part, but could also be between two threaded parts. The only mechanical relevance the steel of the shank has is the torsional resistance and the axial resistance together with the yield moment. Shanks can be produced with cutters as can also be seen in figure 2.6. The goal of adding these cutters is to reduce the insertion moment needed to drive the self-tapping screw into the wood.

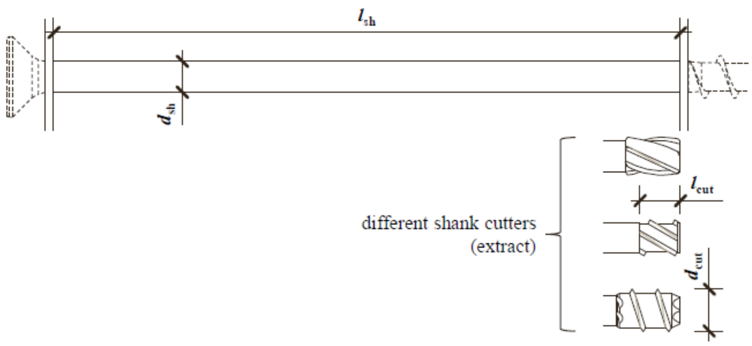

Figure 2.6: Screw shank and some examples of possible cutters (Ringhofer [21]).

Threaded part of the screw

The threaded part of the screw is the most important part of the screw when a screw is loaded axially. The threads transfer the load into the wood. All threads are produced right-handed. In figure 2.7 the geometry of self-tapping screws is shown. With p being the thread pitch, v the thread flank inclination angle, d_c the inner thread diameter and d the outer thread diameter (nominal diameter). These are also parameters used in current valid ETAs.

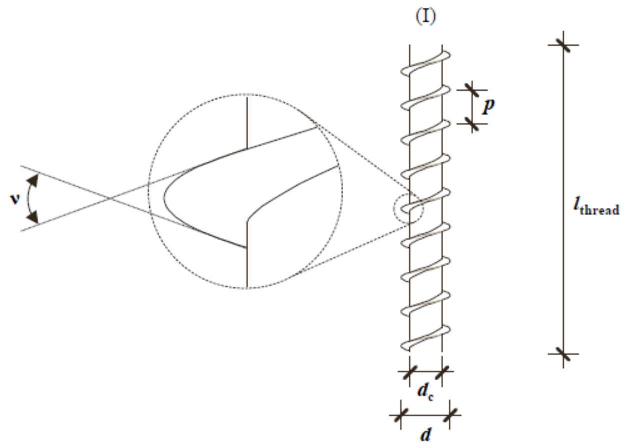

Figure 2.7: Thread geometry of self-tapping screws (Ringhofer [21]).

Screw tip

Screw tips are classified as threaded tips and non-threaded tips by Ringhofer [21]. The types can be seen in figure 2.8. The function of the screw tip is to decrease the insertion moment, to increase the precision of screw placement and to increase the insertion speed of the screw. The tip length l_{tip} is in some cases used to subtract from the threaded length of the screw to define the effective thread length. Further, modifications are possible above the screw tip such as cutters to decrease the insertion moment.

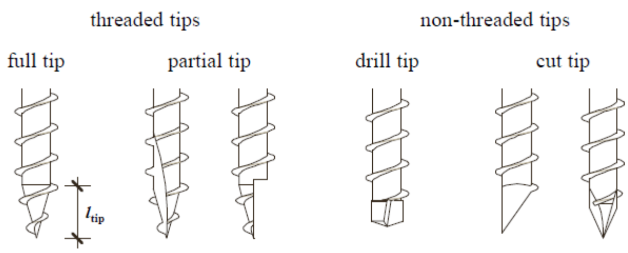

Figure 2.8: Screw tip geometry types (Ringhofer [21]).

2.2.3. Production of self-tapping screws

Self-tapping screws are produced by cold-forming steel wire rods. The steel wire rods consist generally out of low alloy carbon steel. These rods are firstly clamped at one side after which the screw head is stamped on the other end. After this the tip and threaded geometry part are rolled into the steel. In figure 2.9 the negative forms are shown for screw production.

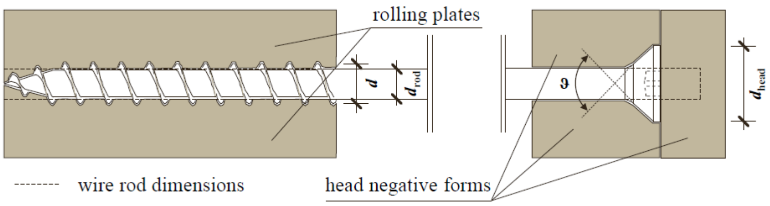

Figure 2.9: On the left the rolling plates are shown to form the threaded part, on the right the part where the screw head is stamped (Ringhofer [21]).

Forming the screws is only one step in the production process, also the hardening process is an important step to improve screw properties. Because of the cold-forming of the self-tapping screws usually already the steel hardness and strength are increased in the tip and threaded part. But also after this the screws are hardened in a separate process. This hardening process is used to increase the tensile and torsional resistance. The steel is hardened by first warming the material up to around 900 °C. This temperature is maintained for a certain time. After this the steel is quenched in water or oil to cause immediate cooling-down of the material to below 300 °C. This process leads to inner lattice stress, leading to increased strength and hardness. This also makes the material much more brittle. In the end the material is again warmed to around 300 °C to reverse some negative effects of the hardening, but also some positive effects.

After the forming of the screw and the hardening the last step is to add a protective coat. This is done for durability reasons and increases the service life. Generally there are two options to increase the service life against corrosion:

- Metallurgical modification;
- Protective coating;

In the case of metallurgical modifications this relates to stainless steels, here the alloy composition of the steel is changed for better corrosion resistance. For protective coating there are many options to choose from. These coatings are used for carbon steel screws if corrosion could be problematic. Coatings are classified in metallic, non-metallic and organic coatings. A well know metallic coating is zinc.

Finally, the self-tapping screws are finished with a coating to reduce the surface friction when inserting the screw into the timber. This is generally a water-based lubricant.

2.3. Existing methods for withdrawal strength of screws in timber

Calculation methods to determine the withdrawal strength of screws in timber are nothing new. EN 1995-1-1:2011 (EC5) gives tools to calculate the resistance of axially loaded screws. Because of the large variety in screws made by commercial manufacturers also screw and timber specific parameters exist per manufacturer to calculate the withdrawal strength of their screws. These parameters can be found in so called ETA (European Technical Assessment) documents. The formulas in EC5 are based on test on softwood, and methods described in the ETA's are according EC5. The available calculation methods lack the availability of models specifically for hardwood. The main focus in this sub-chapter will therefore be on methods based on softwood tests.

2.3.1. Methods in Eurocode 5 version 2011

The methods for the withdrawal strength of screws in wood can be found in EN 1995-1-1:2011 8.7.2. These methods from the Eurocode will be described in this sub-chapter. The Eurocode also describes other failure modes for threaded screws, but the focus of this thesis is on the withdrawal strength of screws in wood. EN 1995-1-1:2011 offers two methods to calculate the withdrawal strength of screws in timber. Which method can be used is governed by dimensional limits that will be explained next. Method 1 is a general approach to determine the withdrawal strength of screws in wood. Method 2 is generally used for manufacturer specific screws, values that have to be used in method 2 can be found in ETAs provided by the screw manufacturers.

Withdrawal strength method 1

For the screw the minimum point side penetration length of the threaded part has to be 6d. In accordance with EN 14592 for connections method 1 can be used if the following conditions are met:

- 6 mm $\leq$ d $\leq$ 12 mm
- 0,6 $\leq$ d_1/d $\leq$ 0,75

Where d is the outer thread diameter and d1 is the inner thread diameter. The characteristic withdrawal capacity should be taken as followed:

$$F_{ax,k,Rk} = \frac{n_{ef} f_{ax,k} d l_{ef} k_d}{1,2cos^2\alpha + sin^2\alpha} \tag{2.1}$$

where:

$$f_{ax,k} = 0,52 * d^{-0,5} l_{ef}^{-0,1} * \rho_k^{0,8} \tag{2.2}$$

$$k_d = min(d/8, 1) \tag{2.3}$$

$F_{ax,\alpha,Rk}$	is the characteristic withdrawal capacity of the connection at an angle α to the grain in N
$f_{ax,k}$	is the characteristic withdrawal strength perpendicular to the grain, in N/mm^2
$n_e f$	is the effective number of screws
$l_e f$	is the penetration length of the threaded part, in mm
ρ_k	is the characteristic density, in kg/m^3
α	is the angle between the screw axis and the grain direction, with $\alpha \geq 30^{\circ}$

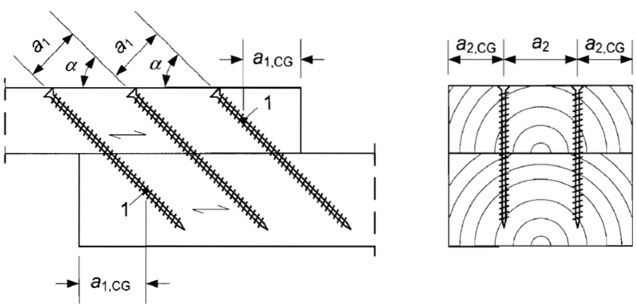

Figure 2.10: Image showing grain-screw axis orientation α and the minimal spacing and edge distances 'a' from EN 1995-1-1:2011.

Withdrawal strength method 2

If the following requirement, 0,6 $\leq$ d_1/d $\leq$ 0,75, can not be satisfied the characteristic withdrawal capacity $F_{ax,\alpha,Rk}$, has to be calculated in a different way:

$$F_{ax,\alpha,Rk} = \frac{n_{ef} f_{ax,k} d l_{ef}}{1,2cos^2\alpha + sin^2\alpha} * \left(\frac{\rho_k}{\rho_a}\right)^{0,8} \tag{2.4}$$

$f_{ax,k}$ is the characteristic withdrawal parameter perpendicular to the grain determined in accordance with EN 14592 for the associated density ρ_a
ρ_a is the associated density for $f_{ax,k}$ in kg/m^3

The values for $f_{ax,k}$ are specified in ETAs provided by screw manufacturers, this will be explained in sub-chapter 2.3.2. For a connection with a group of screws loaded by a force component parallel to the shank, the effective number of screws is given by:

$$n_{ef} = n^{0,9} \tag{2.5}$$

with:

n is the number of screws acting together in a connection
n_{ef} is the effective number of screws

Concluding the Eurocode methods

This is exactly how the withdrawal resistance is formulated in the EN 1995-1-1:2011. To summarize formula 2.1 and 2.4 can be used to calculate the characteristic withdrawal capacity. EC5 also gives methods to calculate other failure modes such as the pull-through capacity and the tensile capacity of the shank of the screw. As described several properties in formula 2.4 have to be found with the help of tests. In EC5 it is also noted that the failure mode is brittle. Further, it is clear that formula 2.1 and formula 2.4 are related to the equation formulated by Hankinson [9], which has been developed to calculate the multi-axial stresses that are caused by the anisotropy of wood. These multi-axial stresses are generated when a load is applied with an angle to the grain. This can be seen in figure 2.11.

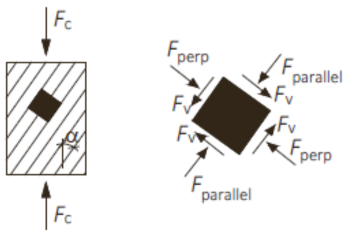

Figure 2.11: Timber element compressed at an angle causing multi-axial stresses (Blaß and Sandhaas [4]).

Hankinson's equation is as followed:

$$f_{t,\alpha} = \frac{f_{t,0}}{cos^2\alpha + \frac{f_{t,0}}{f_{t,90}} sin^2\alpha} \tag{2.6}$$

With:

$f_{t,0}$ Tensile strength parallel to the grain
$f_{t,90}$ Tensile strength perpendicular to the grain

2.3.2. Methods in European Technical assessments

Multiple commercial screw manufactures provide methods to calculate the axial withdrawal capacity of screws they make. The methods have been verified by so called European technical assessments

(ETA). In this sub-chapter the focus will be on the withdrawal strength of screws with the screw axis perpendicular to the grain. The following manufactures have been reviewed:

- ETA-11-0024 Eurotec 2017;
- ETA-11-0027 Fischer 2016;
- ETA-11-0030 Rotho Blaas 2020;
- ETA-11-0190 Wuerth 2018;
- ETA-11-0284 Heco 2019;
- ETA-12-0062 SFS 2019;
- ETA-12-0114 SPAX 2017;
- ETA-12-0197 Timtec 2019;
- ETA-12-0373 Schmid 2017;

The formula that is used in all the assessments named above is the following:

$$F_{ax,\alpha,Rk} = n_{ef} k_{ax} f_{ax,k} d l_{ef} * \left(\frac{\rho_k}{\rho_a}\right)^{0,8} \tag{2.7}$$

k_{ax} Factor for taking into account angle α between screw axis and grain direction
$f_{ax,k}$ is the characteristic withdrawal parameter

Every manufacturer gives their own values for $f_{ax,k}$, this parameter is dependent on the type of wood the screw is applied in and the type of screw that is used. For k_{ax} several factors are specified. For screws with angle α between screw axis and grain direction with: 45° $\leq \alpha \leq$ 90°, k_{ax}=1.0. An alternative for k_{ax} given that: $\alpha \geq$ 15° and $l_{ef} \geq$ min((4*d)/sin(α) ; 20*d) is:

$$k_{ax} = \frac{1}{1,2cos^2\alpha + sin^2\alpha} \tag{2.8}$$

With the use of the factor specified in 2.8 in 2.7 the exact same formula from EC5 can be recognized (2.4). This alternative is only specified by Wuerth and Timtec. Rotho Blaas specifies next to fixed values for certain timber types and screws for $f_{ax,k}$ also a formula in the case of screws in pre-drilled hardwood with a maximum characteristic density of 590 kg/m^3, this is the following:

$$f_{ax,k} = 7 * 10^{-4} * \rho_k^{1,6} * d^{-0,34} \tag{2.9}$$

Most ETA's give options to use wood with higher densities, summarizing all the investigated ETA's the limits fall within: 590 Kg/m^3 $\leq \rho_k \leq$ 750 Kg/m^3. The upper limit of 750 Kg/m^3 often applies to beech LVL members while the lower limits relate to the solid timber.

2.3.3. Other methods from research

In research done by Hubner, Rasser, and Schickhofer [13] the withdrawal capacity of screws and threaded rods in Glue laminated timber (GLT) made of European Ash is investigated. The characteristic density of European Ash is higher than the density of the spruce timber where the EC5 methods are based on. The mean value of the density was ρ_{mean}= 746 kg/m^3 in the research done by Hubner, Rasser, and Schickhofer [13]. The following calculation model followed from the regression analysis of the withdrawal resistance with the screw axis equal or larger than 30 degrees to the grain:

$$R_{ax,\alpha,k} = 1,42 * 10^{-3} * l_{ef}^{0,94} * \rho_k^{1,7} * d^{0,65} \tag{2.10}$$

With in this case for the effective penetration length:

$$l_{ef} = l_{nom} - 1,11 * d \tag{2.11}$$

With l$_{nom}$ being the nominal penetration length.

In bachelor end work done by Kieboom [15] tests were done on two tropical hardwood species (Kanda and Mukulunku). One of the things that was tested was the withdrawal strength of several self-tapping screw types in those woods. The density of Kanda in these tests ranged between 575 kg/m^3 and 719 kg/m^3. The density of the Mukulunku in these tests ranged between 931 kg/m^3 and 1044 kg/m^3. Pre-drilling diameters ranged between 0 and 10 mm, insertion depths ranged between 30 and 100 mm. 5 mm HTS screws, 9 mm VGS and 11 mm VGS screws were used from Rothoblaas. Kieboom [15] developed an empirical formula aiming to best describe the test results on the mentioned tropical hardwoods. This is the following formula:

$$F_{max} = d * l_{eff} * 0,035 * d^{-0,5} * \rho_k^{1,2} \quad (2.12)$$

2.3.4. Comparing different calculation methods

Previously several calculation methods have been discussed, in this chapter these methods will be compared. Two parameters from those previously mentioned calculation methods will be compared with respect to the characteristic withdrawal resistance. The first is the characteristic density which can be seen in figure 2.12(a), the second is the outer thread diameter which can be seen in 2.12(b).

For figure 2.12(a) the outer diameter for all methods was 8 mm, the effective length was 48 mm and the screw-grain angle was 90 degrees. For 2.12(b) the characteristic density has been chosen to be 750 kg/m^3, the effective length was 48 mm and the screw-grain axis was 90 degrees.

Formula 2.1 has been described in this report as method 1 from EN 1995-1-1:2011 to calculate the withdrawal strength of screws in timber and is represented in figure 2.12 in blue. Formula 2.10 is represented in red and was determined by Hubner, Rasser, and Schickhofer [13], this method has been discussed in chapter 2.3.3. The green and the dashed red line represent a calculation method taken from ETA-11-0030 from Rotho blaas, this method is based on method 2 from the Eurocode (formula 2.4). The green line represents a screw type used for pre-drilled LVL with 590 kg/m^3 $\leq \rho_k \leq$ 750 kg/m^3, the characteristic withdrawal parameter $f_{ax,k}$ was specified to be 29 N/mm^2. This screw was available for the outer diameters between 3 mm and 13 mm. The red dashed line represents a screw type that can be used without pre-drilling, also with 590 kg/m^3 $\leq \rho_k \leq$ 750 kg/m^3, this screw is available for outer diameters 6 mm and 8 mm and the characteristic withdrawal parameter $f_{ax,k}$ was specified to be 42 N/mm^2. These self-tapping screws made by Rotho blaas have been chosen for this comparison especially because they can be used for high density timber types.

As can be seen in figure 2.12, method 1 from the Eurocode (in blue) is the most conservative method. The method (formula 2.10) represented in red was developed for hardwood (European ash) instead of softwood, with ρ_{mean}= 746 kg/m^3. As can be seen this already gives higher values for the characteristic withdrawal capacity. The method with the dashed red line from the Rotho blaas ETA shows the highest withdrawal capacity within its given limits. By laboratory tests the characteristic withdrawal parameter has been determined which make it possible to get more accurate and favourable values compared to method 1 in blue. The method in blue is more or less applicable for general use (within its given limits) while the ETAs give a more specialized screw specific determination of the withdrawal capacity.

The yellow line in figure 2.12 shows the formula developed by Kieboom [15], which was already described in formula 2.12. This formula is based on withdrawal tests done on two tropical hardwood species (Kanda and Mukulunku), further background of these tests is described in chapter 2.3.3. The densities in these tests ranged between 575 kg/m^3 and 1044 kg/m^3. It would be expected that the formula developed by Kieboom [15] would give the highest withdrawal capacity compared to all the others. This is not the case, although it gives better results than method 1 from EC5 (in blue). Kieboom [15] states that the developed formula shows a maximum difference of 20 percent if formula 2.12 is compared to the test results. Kieboom [15] also states that some problems occurred during testing which might have influenced the results, this is described in chapter 2.5.3. Therefore the accuracy of formula 2.12 is doubted, but also shows already good withdrawal capacity results for timber species with higher densities.

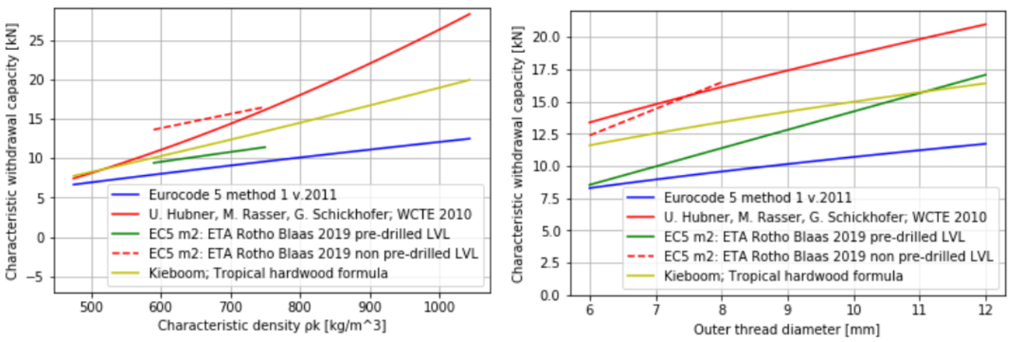

Figure 2.12: (a-left graph) Characteristic withdrawal capacity vs. characteristic density. (b-right graph) Characteristic withdrawal capacity vs. outer thread diameter.

2.4. Calculation methods for self-tapping screws used as reinforcement in timber

In chapter 2.3 the focus was on methods to calculate the withdrawal strength of self-tapping screws in timber. As mentioned in the problem analysis chapter 1.1 self-tapping screws in timber can not only be used as fasteners but also as reinforcements. In this chapter two types will be addressed: reinforcement of notched beams and reinforcement of dowel type connections loaded perpendicular to the grain. The focus will be on calculation methods to improve these details. Most screw manufacturers provide the same calculation methods for these types of reinforcements in their ETA's.

The use of self-tapping screws as reinforcement could also be called a passive application compared to active applications such as fastening. The methods described in this sub-chapter assume that the timber has already been cracked. In other words a cracked tensile zone has been assumed, so the tensile strength of the timber perpendicular to the grain has not been taken into account (Dietsch and Brandner [6]).

2.4.1. Reinforcement of notched beams

In figure 2.13(a) an example is given of the geometry of a notched beam. If the beam is loaded from the bottom or top tensile forces occur in the zone indicated with the dashed line in figure 2.13(a). These tensile forces occur perpendicular to the grain, this could lead to cracking parallel to the grain (Blaß and Sandhaas [4]). This tensile force can be transferred by fully threaded screws to improve this notch, indicated with number 1 in figure 2.13(b). These methods are described in technical reports for self-tapping screws such as ETA's. The calculation method for engineering design is described below in formula 2.13.

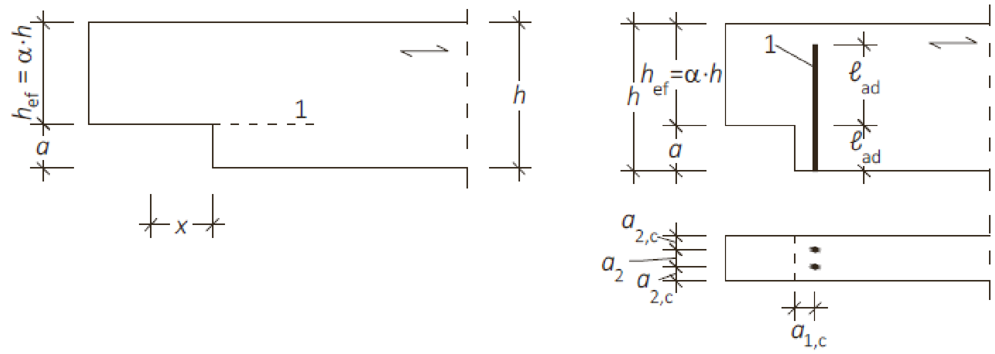

Figure 2.13: (a-left image) Side view of notched beam, tensile stress occurs in zone 1 if the beam is loaded from the top or bottom (Blaß and Sandhaas [4]). (b-right image) Geometry of reinforced notched beam (Blaß and Sandhaas [4]).

$$F_{t,90,d} = 1.3 * V_d * (3 * (1-\alpha)^2 - 2(1-\alpha)^3) \tag{2.13}$$

And:

$$F_{t,90,d} \leq min(F_{ax,Rd}, F_{t,Rd}) \tag{2.14}$$

With:

V_d	Design value of shear force in N
α	h/h_{ef}
$F_{t,90,d}$	Tensile force perpendicular to the grain in N
$F_{ax,Rd}$	Withdrawal capacity of the screw in N, see chapter 2.3
$F_{t,Rd}$	tensile capacity of the screw in N
l_{ad}	Effective anchorage length, corresponds to the smallest value of the penetration depth below or above the possible crack in mm

It is important when calculating the withdrawal resistance of the screw to take the smallest value of the anchorage length and to use fully threaded screws. In figure 2.13-b that would be the l_{ad} on the bottom.

2.4.2. Reinforcement of dowel type connections loaded perpendicular to the grain

In the problem analysis chapter 1.1 research regarding the reinforcement of laterally loaded dowel-type connections was mentioned. By reinforcing this connection type with screws perpendicular to the grain cracking could be avoided and the effective number of dowels increases, thus increasing the load carrying capacity. Rules to reach 100 percent effective dowels have been given in chapter 1.1. These have not yet been implemented in the ETAs when this thesis was written.

Calculation methods for another dowel-type connection have been implemented in the ETAs. This dowel-type connection is loaded perpendicular to the grain and can be seen in figure 2.14. This method does not aim to increase the effective number of dowels but only to avoid cracking, the possible cracking can be seen in figure 2.14. This crack might occur due to the tensile load from the element that is connected perpendicular to the grain to the timber part. The calculation method for engineering design is described below in formula 2.15.

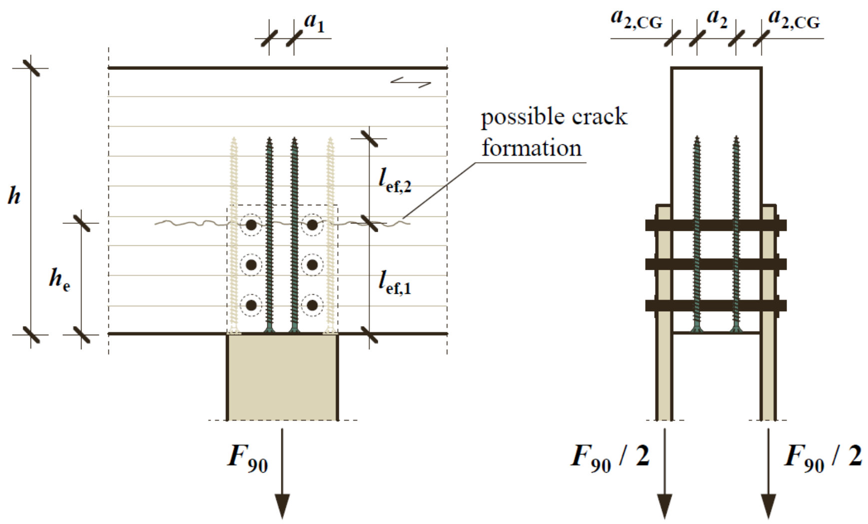

Figure 2.14: Geometry of dowel-type connection loaded perpendicular to the grain (Ringhofer [21]).

$$F_{t,90,d} = F_{90} * (1 - 3 * \alpha^2 + 2 * \alpha^3) \tag{2.15}$$

And:

$$F_{t,90,d} \leq min(F_{ax,Rd}, F_{t,Rd}) \tag{2.16}$$

With:

F_{90}	Design value of the shear force component perpendicular to the grain in N
α	h_e/h
$F_{t,90,d}$	Tensile force perpendicular to the grain in N
$F_{ax,Rd}$	Withdrawal capacity of the screw in N, see chapter 2.3
$F_{t,Rd}$	tensile capacity of the screw in N
l_{ef}	Effective anchorage length, corresponds to the smallest value of the penetration depth below or above the possible crack in mm

2.5. Driving screws into high density woods

It is imaginable that driving a screw in timber with a high density is difficult or even impossible. This subject is therefore very important for this thesis since the focus is on tropical hardwood. Pre-drilling could be necessary in order to insert screws, this does however reduce the economic advantage of screws because now an extra manual handling is introduced namely drilling. Problems that could occur when applying a screw without pre-drilling could be the following:

- Splitting of timber when driving in screw;
- Failure of screw due to insertion moment;

To avoid this in general two things can be done: modifying the timber by pre-drilling or modifying the screw.

2.5.1. Timber modifications for screw insertion

Pre-drilling could help to reduce the insertion moment on the screw, but also helps against splitting because of stresses that develop transverse the screw axis during insertion (Brandner, Ringhofer, and Reichinger [5]).

Pre-drilling in Eurocode 5 version 2011

In chapter 10.4.5 of the EN 1995-1-1:2011 some comments are made on the need for pre-drilling of screws in timber. These are the following:

- Pre-drilling is necessary when the characteristic density of the timber is larger than 500 kg/m^3;
- Pre-drilled hole for the shank has to have the same diameter as the shank;
- Pre-drilled hole has to have the same depth as the length of the shank;
- pre-drilled hole for the threaded part of the screw has to have a diameter of approximately 70 percent of the shank diameter;

Pre-drilling in ETA specifications

Product specific recommendations have been made by screw manufacturers. In all the ETAs mentioned previously specific requirements for pre-drilling can be found for different screw types. The maximum characteristic density does not exceed 750 kg/m^3 in any case.

In ETA-12-0197 (Timtec) and ETA-12-0373 (Schmid) regulations can be found for screw insertion specifically for hardwood. These regulations allow also for screw insertion in hardwood without pre-drilling. The ETA for Schmid allows screw insertion without pre-drilling with no limitations for the full insertion depth while the ETA for Timtec allows screw insertion without pre-drilling for short insertion depths according to Brandner, Ringhofer, and Reichinger [5].

2.5.2. Screw modifications

With increasing timber densities the insertion moment needed for driving a screw into wood also increases. This could be problematic because the screw might fail before it reaches the desired position. The torque resistance of a screw might not be sufficient. Pre-drilling is one way to avoid this problem, but also the screw could be modified/improved.

The steel type used for the screw could be of influence for the torque resistance. In the ETA generally two types of steel are described: carbon steel and stainless steel. The screws made from carbon steel show a higher torque resistance. It has to be noted that stainless steel screws are preferable in the case of some structures made out of tropical hardwood since tropical hardwood is often used in hydraulic structures.

Next to this also these options are possible to make it easier to drive a screw into hardwood.

- Modify the screw tip and other geometric features;
- Use special lubricants on the screws such as slide coatings(Brandner, Ringhofer, and Reichinger [5] and Schiro et al. [27]);

- Use of an impact driver instead of torque drill (Schiro et al. [27]);

Regarding the sliding coatings, this has been researched by Fairchild [7]. It was found that using lubricants (in this case white soap) could be used to make the insertion easier without any great loss of withdrawal strength.

2.5.3. Insertion moment of self-tapping screws into high density timber in literature

In a bachelor end work done by Kieboom [15] the insertion moment of self-tapping screws in tropical hardwood species perpendicular to the grain has been tested. Two tropical hardwood species have been tested: Kanda and Mukulunku. The density of Kanda in these tests ranged between 575 kg/m^3 and 719 kg/m^3. The density of the Mukulunku in these tests ranged between 931 kg/m^3 and 1044 kg/m^3. Pre-drilling diameters ranged between 0 and 10 mm, insertion depths ranged between 30 and 100 mm. 5 mm HTS screws, 9 mm VGS and 11 mm VGS screws were used from Rothoblaas. These screws were inserted and the insertion moment was measured.The maximum insertion moment that could be measured in these tests was 50 Nm. Test showed that increasing insertion depth could be reached with increasing pre-drilling diameter. Maximum insertion depth could be reached with Kanda but this was not possible with Mukulunku with the used drill. The results show as expected that with increasing density, the insertion moment also increased. The tests showed several problems with decreasing pre-drilling diameter, decreasing pre-drilling depth and increasing screw diameter. These are problems such as splitting of the wood and screws getting stuck while not being fully inserted. Also screw failure due to the insertion moment was observed, see figure 2.15. Kieboom [15] does mention that the width of the test specimen was too small according to the Eurocode 5 version 2011 and could therefore have caused the splitting. The author also mentions that not all test results are accurate and reliable because some tests were carried out by hand and because the tool to measure the insertion moment did not work properly. Also every test variation has only been tested once. Results can be found in figure 2.16.

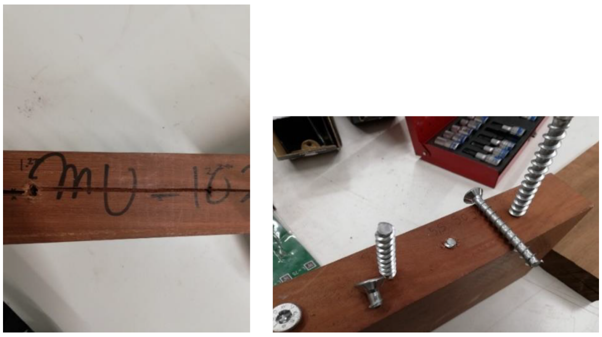

Figure 2.15: (a-left image) Splitting of wood during insertion moment testing. (b-right image) Failure of screw due to insertion moment (Kieboom [15]).

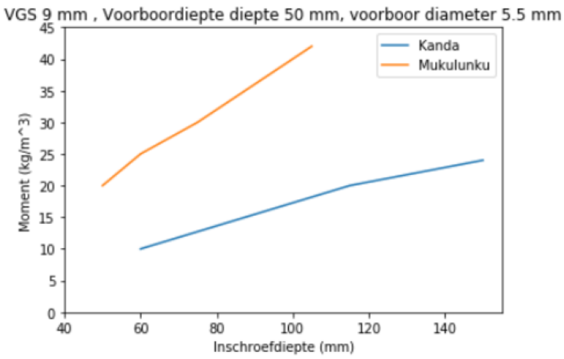

Figure 2.16: Results from Kieboom with on the horizontal axis the screw insertion depth, on the vertical axis the insertion moment (please note unit is in Nm). Results for screws with 9 mm diameter (Rothoblaas VGS 9 mm) pre-drilled depth is 50 mm and pre-drilled diameter is 5,5 mm. (Kieboom [15]).

In (Brandner, Ringhofer, and Reichinger [5]) the insertion moment of screws into hardwood was tested. The hardwoods tested were sweet chestnut, oak, ash, black poplar, birch and beech. Densities of the wood ranged between the 400 kg/m^3 and 800 kg/m^3. Two types of self tapping screws were used, one with an outer diameter of 8 mm and inner diameter 5,2 mm (screw ST1: Schmid RAPID). The other screw (screw ST2: Schmid RAPID Hardwood) has an outer diameter of 8,1 mm and inner diameter of 6,8 mm. Pre-drilling diameters varied between 5,5 mm and 7 mm. In (Brandner, Ringhofer, and Reichinger [5]) it was found that with increasing density the insertion moment increased as well, which was expected. Also with increasing pre-drilling diameters the insertion moment decreased, which is also as expected. For the Schmid RAPID screw the decrease was higher than for the Schmid RAPID hardwood. This was due to the ratio between the pre-drilling diameter and the screw inner thread diameter. In other words, the Schmid RAPID has a smaller inner diameter which made insertion easier with increasing pre-drilling diameter. Also this could be expected and shows that a balance should be found between screw inner diameter and pre-drilling diameter. Results from the research done by Brandner, Ringhofer, and Reichinger [5] can be found in figure 2.17.

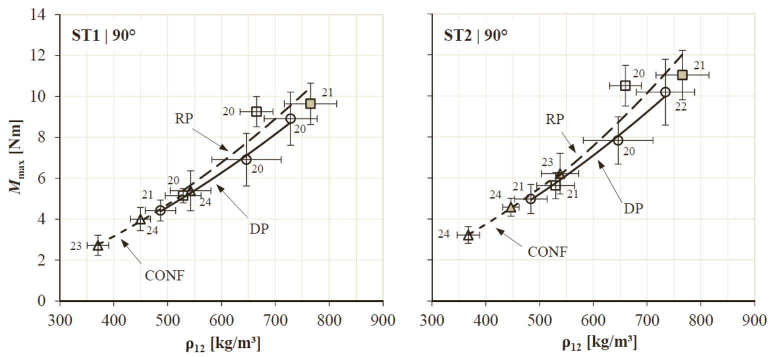

Figure 2.17: Maximum insertion moment vs. density of different wood species (With CONF (coniferous species), RP (ring porous) and DP (diffuse porous deciduous)). (Brandner, Ringhofer, and Reichinger [5])

2.6. The influence of material properties on the withdrawal strength

In the following sub-chapter literature will be reviewed on the influence of material properties on the withdrawal resistance.

2.6.1. Influence of moisture content

Tropical hardwood species are often used in hydraulic structures and outside conditions. Some examples are:

- Sluice gates;
- Weirs;
- Bridges;
- Jetties;

These structures are situated in varying weather conditions. Especially the hydraulic structures will have to deal with a wet environment. Wet conditions could lead to problems with for example fungi. Tropical hardwood species are used for these conditions because some tropical hardwood species can be very durable. One example is Ekki, which is a widely used tropical hardwood species in The Netherlands for hydraulic structures and outside conditions. Ekki is very fungi resistant and can be found in durability class I (very durable against fungi). In terms of resistance against insects and wood pests in sea it is classified as class D in Dutch weather conditions (Durable) [10]. Because of the use of tropical hardwoods in outside conditions it is expected this could change the moisture content of the timber over time. Therefore, the influence of moisture content on the withdrawal strength is investigated in this sub-chapter. The moisture content in wood influences most properties of the wood. When the moisture content increases in timber the stiffness and strength decrease (Blaß and Sandhaas [4]). Because of this it is also important to find out if this is also the case for the withdrawal strength.

Moisture content in timber engineering

The equilibrium moisture content is the state where the moisture absorption of the timber balances the moisture discharge, this corresponds to a combination of surrounding humidity and temperature of the air (Blaß and Sandhaas [4]). According to EN 1995-1-1:2011 the equilibrium moisture content is around 12 percent. In wood technology this is a moisture content generally used for mean values such as the density and relates to an ambient temperature of 20°C with 65 percent relative humidity (indoor room environment, service class 1). All the service classes from EN 1995-1-1:2011 with their corresponding moisture contents are summarized in table 2.1. These service classes are used for the strength modification factor k_{mod}, to include for example the influence of moisture content on the strength.

Table 2.1: Service classes from EN 1995-1-1:2011, values only available for softwoods.

Service class	Moisture content [%]	Relative humidity [%]
1	12	maximum 65, only exceeding for few weeks per year
2	20	maximum 85, only exceeding for few weeks per year
3	more than 20	more than 85

As mentioned before hydraulic structures are placed in wet conditions. Results for the withdrawal strength of tropical hardwoods in wet conditions might be available but could not be found. Sandhaas et al. [26] performed embedment tests on tropical hardwood (Ekki) specimens with a high moisture content of around 43 percent by placing them in a fog chamber. These wet Ekki specimens showed in embedment tests a lower embedment strength compared to Ekki specimens with a lower moisture content.

Results from research
In research done by Ringhofer et al. [22] it was found that if the moisture content increases above 12 percent the withdrawal strength significantly decreases. A comparison between results regarding moisture content variation and withdrawal resistance of self tapping screws has been made by Ringhofer et al. [22]. These results are compiled of literature sources and research done by the author(s) and can be found in figure 2.18.

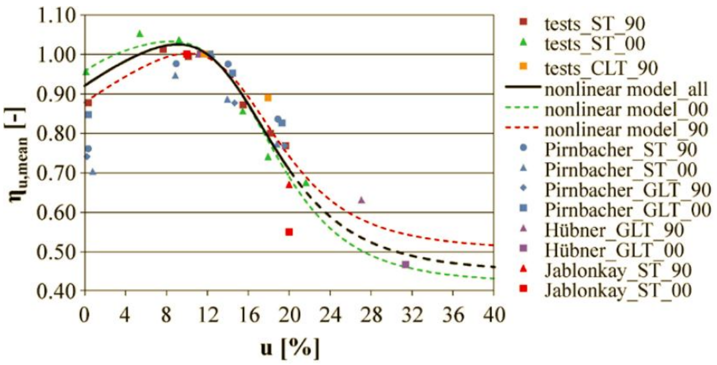

Figure 2.18: Comparison of test results from several literature sources from (Ringhofer et al. [22]).

The horizontal axis in figure 2.18 shows the moisture content u. The vertical axis shows the deviation of mean values:

$$\eta_{u,mean} = \frac{f_{ax,u,mean}}{f_{ax,12,mean}} \tag{2.17}$$

The 12 in the formula above refers to a moisture content of 12 percent. The sources and timber types used in figure 2.2 are summarized in table 2.2.

Table 2.2: Timber types used in figure 2.18.

Name	Timber type	Angle screw axis-grain α
Test ST 90 (Ringhofer et al. [22])	Solid timber spruce (*picea abies*)	90°
Test ST 00	Solid timber spruce (*picea abies*)	0°
Test CLT 90	CLT	90°
Pirnbacher ST 90 ([19])	Solid timber spruce	90°
Pirnbacher ST 00	Solid timber spruce	0°
Pirnbacher GLT 90	GLT spruce	90°
Pirnbacher GLT 00	GLT Spruce	0°
Hübner GLT 90 (Hubner [11])	GLT Ash	90°
Hübner GLT 00	GLT Ash	0°
Jablonkay ST 90 (Jablonkay [14])	Solid timber spruce, douglas fir, beech	90°
Jablonkay ST 00	Solid timber spruce, douglas fir, beech	0°

Especially the data from Joblankay and Hübner are interesting for this report because in those tests also hardwood was used as can be seen in table 2.2. The mean density for the Ash used in the research from Hübner was between 691 kg/m^3 and 760 kg/m^3. Also those results fall within the pattern of withdrawal resistance decrease when the moisture content increases from 12 percent.

2.6.2. Influence of pre-drilling on withdrawal resistance

When a timber section is pre-drilled for the insertion of screws material is removed. With the removal of material a reduction of the withdrawal strength is possible. Research has been done on this topic by Brandner, Ringhofer, and Reichinger [5]. The research shows that no influence from pre-drilling was found on the withdrawal properties if the conditions according to formula 2.18 are met. This is based on tests on softwood species but also on hardwood species such as oak, ash, black poplar and birch. The mean densities of the tests ranged between between 358 kg/m^3 and 848 kg/m^3.

$$d_{PD} \leq 0,8d \tag{2.18}$$

with:

d_{DP}	Pre-drilling diameter
d	Nominal diameter screw

2.6.3. Influence of timber density

Research done by Brandner, Ringhofer, and Reichinger [5] reports that with increasing density of the timber the withdrawal strength f_{ax} also increases. The research also reports that the increase is more pronounced in deciduous timber species compared to coniferous species.

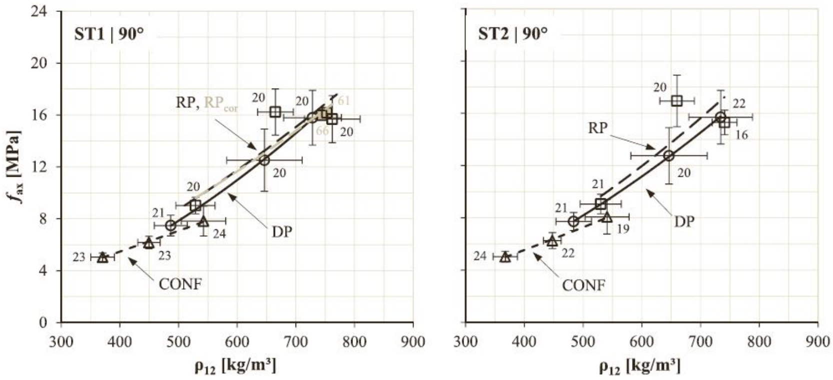

Figure 2.19: Withdrawal strength compared to several wood densities from (Brandner, Ringhofer, and Reichinger [5]).

With in figure 2.19 CONF (coniferous species), RP (ring porous) and DP (diffuse porous deciduous). ST1 (Schmid Schrauben RAPID outer diameter 8 mm) and ST2 (Schmid Schrauben RAPID Hardwood outer diameter 8,1 mm) are screw types. All results shown in figure 2.19 come from withdrawal tests done perpendicular to the grain. Not only the withdrawal strength increases with increasing density as is also shown in figure 2.19, displacements at maximum loading decrease and the softening gradient becomes steeper (gradient softening phase decreases) with increasing timber density.

2.6.4. Influence of the screw diameter

Many variations exist regarding the screw diameter. Two diameters are important: the outer threaded nominal diameter and the inner core diameter. Pre-drilling is also a factor, in formula 2.18 limits were found in order to have no influence on the withdrawal strength from pre-drilling.

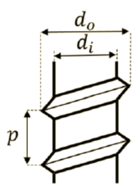

Figure 2.20: Screw geometry with d_o the outer thread diameter, d_i the inner core diameter and with p the pitch (Westermayr and Kuilen [29]).

In research done by Hubner, Rasser, and Schickhofer [13] it is stated that in general the withdrawal strength (N/mm^2) decreases if the screw diameter increases, this can also be seen in figure 2.21. The pre-drilled holes in research done by Hubner, Rasser, and Schickhofer [13] all had a diameter of 0,7*d. It has to be noted that regarding the characteristic withdrawal capacity (kN) the characteristic withdrawal capacity increases with increasing screw diameter. Similar findings regarding the screw diameter have been done by Hubner [12] with tests on beech, ash and black locust.

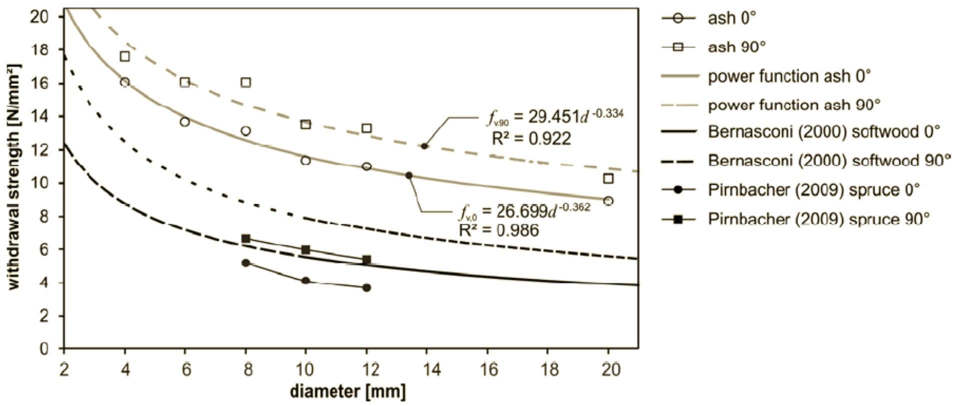

Figure 2.21: Withdrawal strength compared to diameter from (Hubner, Rasser, and Schickhofer [13]). With other sources: (Bernasconi [3] and Pirnbacher, Brandner, and Schickhofer [19]).

In research done by Westermayr and Kuilen [29] several screw types have been tested regarding their withdrawal strength parallel to the grain of beech, ash and spruce. The screws outer thread diameter was in every case the same but the core diameter was different, but no correlation was found between the withdrawal resistance and thread geometry.

2.6.5. Influence of screw tip

The screw tip could influence withdrawal resistance properties in several ways. When the tip is threaded this part could also contribute to the withdrawal resistance. The screw tip is also of importance for insertion into the wood, and might damage the timber in the insertion process decreasing the withdrawal resistance. In research by Westermayr and Kuilen [29] certain types of screws were investigated regarding the withdrawal strength parallel to the grain. The screws were tested with and without tip. A variation in results could be observed, this can also be seen in figure 2.22. Research by Westermayr and Kuilen [29] summarizes that not the thread geometry influences the withdrawal resistance but the different screw tips as a result of pre-damaging during screw insertion. It has to be noted again that this is based on results from withdrawal tests done parallel to the grain.

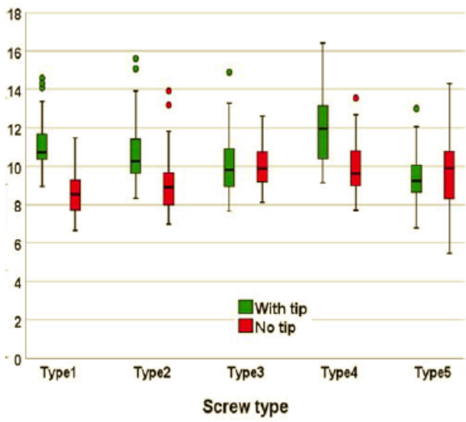

Figure 2.22: Withdrawal resistance of several screw types parallel to the grain in beech (Westermayr and Kuilen [29]), with on the vertical axis the withdrawal strength in N/mm^2 (All outer thread diameter 10 mm; inner shank diameters: type 1: 6,4 mm, type 2: 6,2 mm, type 3: 6,3 mm, type 4: 6 mm, type 5: 6,5 mm and type 6: 6,6 mm).

2.6.6. Influence of effective screw length

In the engineering formula that are used to calculate the withdrawal capacity of self tapping screws generally also the effective penetration length of the threaded part of the screw is included as parameter. In research by Ribeiro et al. [20] the influence of the effective length of the threaded screw length was tested in tropical wood species. Lag screws were used in this study with a diameter of 12,7 mm. Samples with densities up to 520 were pre-drilled with 0,7*d, the samples with higher densities were pre-drilled with 0,85*d. Research done by Ribeiro et al. [20] confirms that with increasing effective length, the withdrawal capacity (kN) increases. Research by Ribeiro et al. [20] notes that with increasing wood density and screw length screw rupture may be problematic. Research by Hubner, Rasser, and Schickhofer [13] notes that because of the high withdrawal strength of European ash (and also higher timber density) compared to softwoods, it is possible to reduce the effective penetration length of the screw to nearly half of what is needed for softwood.

A linear relationship can be noticed between the effective screw length and the withdrawal capacity when looking to design formulas. This linear relationship is reflected in design formulas such as formula 2.4 from EN 1995-1-1:2011 and formula 2.12 by Kieboom [15] (see also chapter 2.3). In formula 2.10 by Hubner, Rasser, and Schickhofer [13] the value of the effective is taken as followed: $l_{ef}^{0,94}$. A comparison between these formulas has been made in chapter 4.1.3 in figure 4.3, also showing a linear relationship between the effective length and withdrawal capacity.

This linearity between the withdrawal capacity and effective length is also confirmed in a study done by Xu et al. [30] as can be seen in figure 2.23. In this study the withdrawal capacity of self-tapping screws in CLT made of Japanese larch was tested. Screw diameters ranged between 6 mm and 11 mm and the density of the CLT ranged between 450 kg/m^3 and 750 kg/m^3. The tested effective lengths were as followed: 48 mm, 72 mm, 96 mm and 120 mm. The lower graph in figure 2.23 shows that the effective length has no significant influence on the withdrawal strength (MPa).

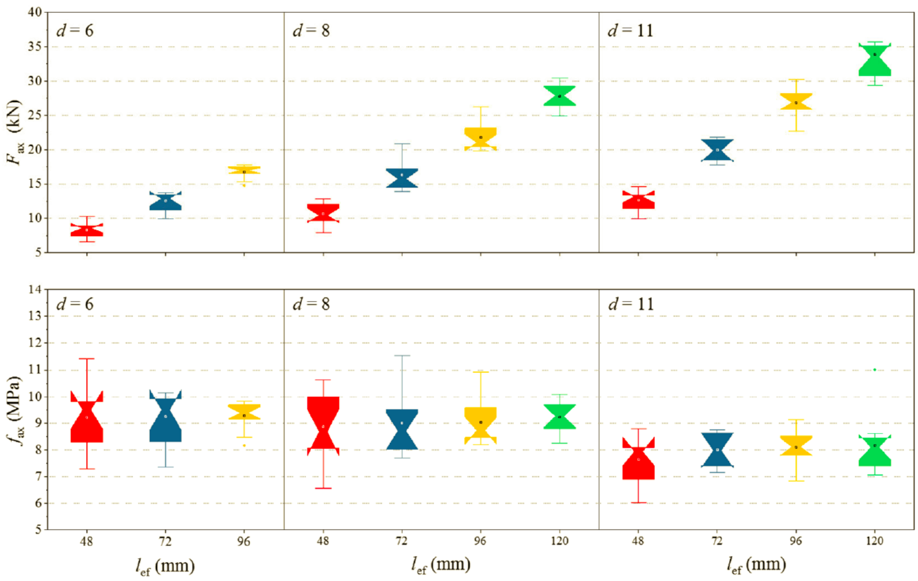

Figure 2.23: Effective length versus withdrawal strength (bottom) and withdrawal capacity (top) of self-tapping screws, in this case in CLT.(Xu et al. [30])

2.6.7. Influence of angle between grain and screw axis

This thesis will mainly be about the withdrawal strength of self-tapping screws with screw axis perpendicular to the wood grain, meaning α= 90°. Still this parameter will be reviewed since it is a parameter in for example the engineering formula from EC5 for the withdrawal resistance as can be seen in formula 2.1. EC5 limits the angle to $\alpha \geq 30^{\circ}$. In figure 2.21 the differences are already made clear, with $\alpha = 90^{\circ}$ giving consistently higher withdrawal strengths compared to $\alpha = 0^{\circ}$. Research by Westermayr and Kuilen [29] reports that a similar trend can be seen for spruce with linearly increasing withdrawal strength with increasing angle between grain direction and screw axis, but in the case of beech no effects of angle between grain direction and screw axis could be found regarding the withdrawal strength.

3
Methods

In the literature study several subjects concerning the withdrawal strength of screws in timber have been discussed. Calculation methods from the Eurocode and the influence of material properties have been reviewed. The available literature is mainly about softwoods, and in some cases about hardwoods from temperate regions. The aim of this thesis is to investigate the withdrawal strength of screws in tropical hardwoods. In this chapter the testing methods that are specified by several codes will be explained to investigate the withdrawal strength. Based on these test methods and together with the available testing materials a research plan will be formulated. This to be able to answer the main research question:

What is the withdrawal strength of self-tapping screws in tropical hardwood species perpendicular to the grain and is it possible to develop a verification model for engineering purposes?

3.1. Testing withdrawal strength

Testing according to EN 1382:2016

An European standard is available providing test methods for determining the withdrawal capacity of fasteners in timber. Using these methods is useful because the testing is then in line with testing that has been done on other wood species, but also because it is required by EC5 for determining the value f_{ax} (withdrawal strength perpendicular to the grain/withdrawal parameter). The timber has to be selected in accordance with EN ISO 8970:2010. After this the conditioning of the test piece is important. These specimens have to be manufactured and stored at 20 +/- 2 degrees Celsius and 65 +/-5 percent relative humidity until it is conditioned. The specimen is conditioned when it attains constant mass. This is determined by measuring the weight of the specimen two times with an interval of 6 hours and the mass of the material does not differ more than 0,1 percent after these two weightings. The specimen that will be tested is also specified by EN 1382. In figure 3.1 the dimensions are given.

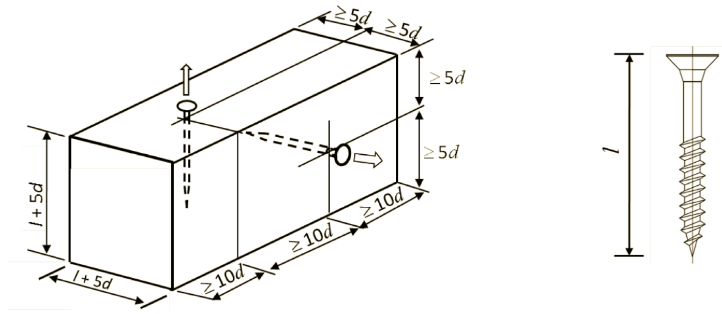

Figure 3.1: (a-left image) Test piece dimensions from EN 1382. (b-right image) Screw dimension.

The apparatus used for testing has to be as required in clause 7 of EN 26891:1991. When testing the depth of penetration l_d has to be determined. A requirement is that any part of the supports shall not be closer to the axis of the fastener than 3d. The loading during testing should be constant. The rate of loading to determine f_{ax} shall be such that the time taken to reach F_{max} is 60 +/-5 seconds. The value F_{max} has to be determined to an accuracy of 1 percent. Then f_{ax} can be determined using the formula below:

$$f_{ax} = \frac{F_{max}}{d * \pi * l_d} \tag{3.1}$$

With symbols according to EN 1382:

d	is the outer thread diameter for screws, the diameter of the smooth plain part of a round nail or for staples the diameter of the wire (transformed to around cross-section)
F_{max}	maximum withdrawal load, in newtons
l	is the screw length, figure 3.1
f_{ax}	withdrawal parameter, in N/mm^2
l_d	effective depth of penetration in mm. For screws only the penetration depth of the profiled part

Test set-up and apparatus

See chapter 5.5.2.

Reason for determining the withdrawal strength

The main topic in this thesis is about the withdrawal strength of self-tapping screws in tropical hardwood. European standards provide this method to find that value.

3.2. Determining stiffness

Testing according to EN 26891:1991

The determination of the joint stiffness has been described in EN 26891:1991. The loading procedure is shown in figure 3.2, the formula 3.2 describes how the slip modulus is calculated. F_{est} will be determine according to EN 1382:2016 as described in chapter 3.1.

First the load has to be applied to 0,4*F_{est}, when this has been reached this load will be maintained for 30 seconds. Then the load will go down to 0,1*F_{est}, which will also be maintained for 30 seconds. After this the loading will be increased again until the ultimate load has been reached or slip of 15 mm. Below 0,7*F_{est} the load has to be constant.

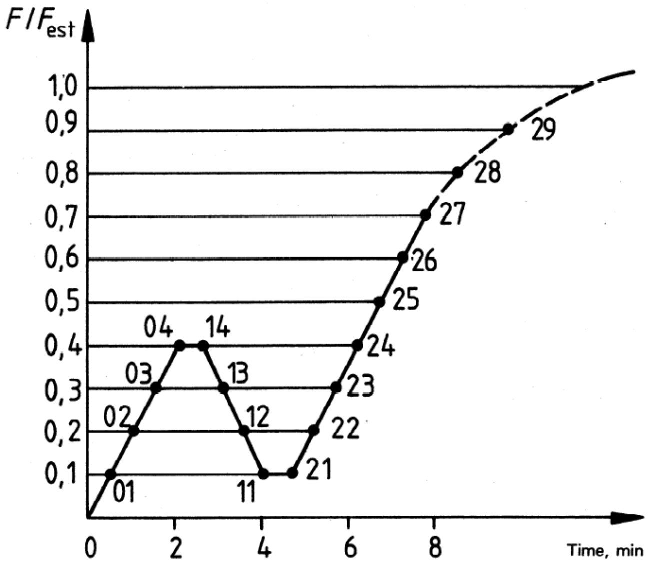

Figure 3.2: Loading procedure from EN 26891:1991.

$$k_s = \frac{0,4 * F_{est} - 0,1 * F_{est}}{(\nu_{04} - \nu_{01})} \tag{3.2}$$

With symbols according to EN 26891:1991:

k_s	Slip modulus, in newtons per millimeter
F_{est}	Estimated maximum withdrawal load, in newtons
ν_{04}	joint slip at 0,4*F_{est}, in millimeters
ν_{01}	joint slip at 0,1*F_{est}, in millimeters

Test set-up and apparatus

Same as for testing the withdrawal strength, see chapter 5.5.2.

Reason for determining the stiffness

Self-tapping screws with high strength and stiffness are excellent to be used in joints. To get to know this it has to be measured. The test procedure for determining the stiffness also goes to maximum loading at the end, so these tests also give withdrawal strength values.

3.3. Determining density

Testing according to NEN-ISO 13910

To determine the density the specimens have to be stored at 20 +/- 2 degrees Celsius and 65 +/-5 percent relative humidity. The specimen has to be free of knots and comprise of the full cross-section of the piece of timber. Further the length of the test specimen for determining the density has to be a minimum of 50 mm. The density values are calculated as followed:

$$\rho_{test} = \frac{m * 10^9}{Lbh} \tag{3.3}$$

The density with moisture content of 12 percent is calculated as followed:

$$\rho_{12} = \rho_{test}[1 - 0,5(w - 0,12)] \tag{3.4}$$

with:

m	mass of specimen in kg
L	Length of timber specimen in mm
b	thickness of a rectangular timber specimen in mm
h	width of a rectangular timber specimen in mm
ρ_{12}	density in kg/m^3 at moisture content 12 percent
ρ_{test}	density in kg/m^3 at time of test
ω	ratio of mass of water to mass of oven-dry wood, equivalent to moisture content

Test set-up and apparatus

See chapter 5.5.4.

Reason for determining the density

The density is a very important parameter in for example calculation methods to determine the withdrawal strength of self-tapping screws. Knowing the density is important to judge mechanical behaviour. The density will also be adjusted to a moisture content of 12 %, which is a common value in timber engineering.

3.4. Determining moisture content

For the determination of the moisture content in timber EN 408 directs to EN 13183-1.

Testing according to EN 13183-1

The test piece has to be conditioned like mentioned before: specimens have to be stored at 20 +/- 2 degrees Celsius and 65 +/-5 percent relative humidity. A slice of timber should be taken from the test piece. The minimal dimension in grain direction has to be 20 mm taken from any point 300 mm from one of the test piece ends. If this is not possible it should be taken from the middle of the test piece. The slice has to be free from knots, bark, resin pockets and resin wood. The taken slice from the test piece has to be weighed immediately after cutting. The test piece now has to be dried at a temperature of 103+/- 2 $^{\circ}$C. The slice has to be weighed every 2 hours until the difference in mass between two successive weighings is 0,1 percent. The dry weight measurement has to be done directly after taking the slice out of the oven. The moisture content now can be calculated in percent as followed:

$$\omega = \frac{m_1 - m_0}{m_0} * 100 \tag{3.5}$$

m_1 mass of the test slice before drying, in grams
m_0 mass of the oven dry test slice, in grams
ω moisture content, in percent

Test set-up and apparatus

See chapter 5.5.4.

Reason for determining moisture content

Timber test pieces in this thesis will be conditioned underwater. To judge the results from testing on these piece it is necessary to know the moisture content. The moisture content can also be used to calculate for example the adjusted density.

3.5. Determining insertion moment

Test method

The insertion moment will be measured using a torque wrench and a force measurement device as shown in figure 3.3. The length between the point of rotation of the wrench and the position of the force measurement device will be measured. This then will be used to calculate the insertion moment by simply multiplying the force times the lever arm. This force will be measured when the self-tapping screw is almost in position. This is the deepest position of the screw and in theory should give the maximum insertion moment.

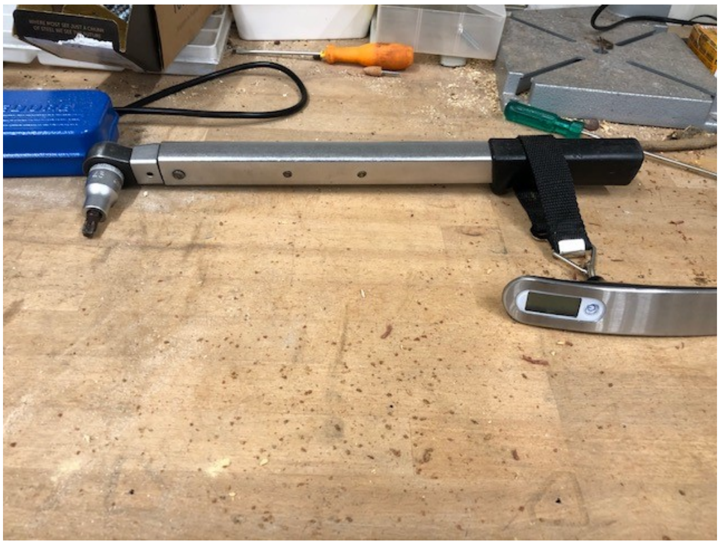

Figure 3.3: Torque wrench shown on the left with the device used to measure the force attached to the handle.

Reason for determining the insertion moment

The insertion moment is measured because it gives an idea of the effort needed to insert a screw into the timber. It also allows to examine if the torque resistance of a screw is reached. Because the method used is done by hand the values from these insertion moment tests should be seen as indicative.

4

Design of test series

In this chapter the process on how the test series was designed is explained. In this thesis tests will be conducted on tropical hardwood species of which the density ranges between 550 kg/m^3 and 1100 kg/m^3. The timber species will be explained in more detail in chapter 5.1.

In chapter 4.1.1 preferred test variations are discussed based on the literature study. In chapter 4.1.2 the available timber specimens are compared to the boundaries in the test regulations from EN 1382:2016 in terms of size. In chapter 4.1.3 estimations are made to find out what screw sizes are usable, the aim is to have screw withdrawal as failure mode so screw steel tensile failure has to be prevented.

In chapter 4.2 a pre-test series has been carried out to get used to the testing machines and to find out what the limits are of the materials. In chapter 4.3 final conclusions are made regarding the final test series.

4.1. Determination test series boundaries

4.1.1. Preferred test variations based on literature study

As has been mentioned several times in the literature study tropical hardwood species in timber engineering are popular for hydraulic structures and outside conditions because of its durability. This means the timber will be wet, and therefore withdrawal strength of screws in wet tropical hardwoods is very interesting.

Because of the fact that the probable application of self-tapping screws in tropical hardwoods is in the field of hydraulic and outside structures, the screw size should also reflect this. Screws will be of a longer category and with a larger diameter. In the master thesis done by Otterloo [17] notched beams used for timber lock gates are tested. In that thesis a notch height of between 100 mm and 120 mm can be found, giving a maximum space of 120 mm effective screw length on either side of the notch. If this is practically possible is investigated in chapter 4.1.3. Longer screws in timber with high densities also asks for screws with a larger diameter to resist the higher insertion moments required, suitable diameters will be investigated in chapter 4.1.3.

EN 1995-1-1:2011 states that timber with a density larger than 500 kg/m^3 has to be pre-drilled with a pre-drilled hole of approximately 70 percent of the shank diameter. In chapter 2.6.2 is was found that 0,8*d pre-drilling does not influence the withdrawal strength of screws in hardwood species such as oak. In this thesis timber species with even higher densities are tested, making screw insertion more difficult. It would be interesting to find out what the effect of an even larger pre-drill hole would be on the withdrawal capacity and insertion moment. So testing with pre-drilled holes of 0,7*d-0,8*d-0,9*d would be interesting.

4.1.2. Applicable screw size based on test piece size

Boundaries of the test piece with inserted screw for withdrawal testing have been given in figure 3.1. The aim is to stay within these limits, and test according to EN 1382:2016. This is done because this gives results which is better comparable with tests done in other research according to EN 1382:2016. The timber sample size that are available for testing have the following dimensions: 300 mm x 45 mm x 145 mm (length x width x height).

In chapter 3.1 the maximum dimension from EN 1382:2016 are explained. Further requirements that are given by EN 1382:2016 are that the fasteners shall be driven to a penetration between 8d and 20d. If tests are done according to EN 1382:2016 it becomes clear that only small diameters are allowed, namely a maximum diameter of 4,5 mm. To increase the screw diameter two other options are proposed which can be seen in figure 4.1. Type 1 on the left is the original board, type 2 in the middle is the original part cut in half and stacked. Type 3 on the right is type 1 cut in three parts and stacked together. It is required that these stacked pieces are cut from the same board to maintain the same material properties. These stacked pieces will be glued together for practical reasons and clamped properly in the test setup for the withdrawal strength, this will be explained later.

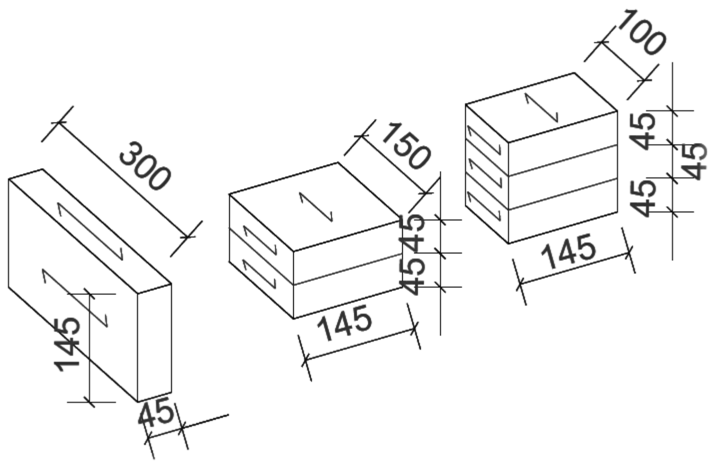

Figure 4.1: Dimensions of the three proposed test piece options. From left to right type 1, 2 and 3.

In table 4.1 the screw limits are displayed for the different test piece types which were shown in figure 4.1. In the first column the type number can be found, in the second column the maximum allowed screw diameter for the respective test type is shown, in the third column a rounded diameter size has been chosen to calculate the maximum allowed screw length in fourth column. Test type 2 gives the largest range of options. For type 2 also some larger diameters are shown because larger diameters are desired for testing due to earlier mentioned reasons.

Table 4.1: Maximum allowed screw diameter and lengths for the 3 piece types.

Type	Max. allowed screw diameter [mm]	Chosen screw diameter [mm]	Max screw length [mm]
1	4,5	5	80
2	7,5	4	70
	7,5	5	65
	7,5	6	60
	7,5	7	55
	7,5	8 (not allowed)	50
	7,5	9 (not allowed)	45
	7,5	10 (not allowed)	40
3	5	4	80
	5	5	100

In table 4.1 maximum screw diameters have been determined according to EN 1382:2016, in research done by Hubner, Rasser, and Schickhofer [13] for example a maximum edge distance of 5*d is taken into account. This would mean in this thesis with the available test pieces that the maximum allowed screw diameter for test piece type 1 is diameter 4,5 mm; for test piece type 2 is diameter 14,5 mm and for test piece type 3 is diameter 10 mm. This would give more room for screw diameter variation, especially in the case of test piece type 2.

4.1.3. Applicable screw size with withdrawal strength as main failure mode

The aim of this thesis is to learn more about the withdrawal strength of screws in tropical hardwood species. In that case it is good to make predictions in advance so screw withdrawal is the dominant failure mode. EN 1995-1-1:2011 describes next to withdrawal strength also another failure mode: tensile steel resistance of the screw. The failure modes is described next, according to EN 1995-1-1:2011. The n_{ef} (effective number of screws) will not be taken into account.

The characteristic tensile resistance is calculated as followed:

$$F_{t,Rk} = n_{ef} f_{tens,k} \tag{4.1}$$

$F_{tens,k}$ is the characteristic tensile capacity of the screw determined in accordance with EN 14592

It becomes clear that the factors needed in the previously mentioned formula have to be provided by screw manufacturers.

Screw comparison with screws applied perpendicular to the grain
Several self-tapping screws from manufacturers mentioned in chapter 2.3.2 have been compared. The full comparison will not be included in this thesis. The comparison resulted in four possible self-tapping screws. These are the screws from Rotho Blaas:

- 6 mm diameter (product name: HBSH7160)
- 8 mm diameter (product name: HBSH9160)
- 11 mm diameter (product name: VGS11150)
- 13 mm diameter (product name: VGS13150)

The HBSH screws are special self-tapping screws developed for hardwoods, with better torque resistance and tensile resistance. These are all galvanized carbon steel self-tapping screws. In table 4.2 the withdrawal strength of these screws in wood is calculated for different densities. 750 kg/m^3 is the maximum density allowed according to ETA-11/0030:2020 from Rotho Blaas, therefore also the withdrawal resistance according to Kieboom [15] and Hubner, Rasser, and Schickhofer [13] is included for the higher densities (described in chapter 2.3.3). These results can also be seen in figure 4.2. 90 mm is used as effective length in these calculations because for this effective length the investigated screws are most likely usable for all densities, this can also be seen in figure 4.3 where 1100 kg/m^3 has been used as characteristic density. All technical details of the screws have been taken from ETA-11/0030:2020, the used f_{ax} (29 N/mm^2) and ρ_a (730 kg/m^3) are normally used for self-tapping screws in pre-drilled LVL or FST with ρ_k between 590 kg/m^3 and 750 kg/m^3. This is used because this is the highest possible density according to ETA-11/0030:2020 for pre-drilled timber. The pre-drilling requirements according to ETA-11/0030:2020 for hardwood is as followed: for outer screw thread diameter 6 mm it is 4 mm, for outer screw thread diameter 8 mm it is 6 mm and for outer screw thread 11 mm it is 7 mm.

It has to be mentioned that the formula used in table 4.2 and figure 4.2 have been used outside their limits regarding the characteristic density parameter. This is done because there are no available methods available to predict the withdrawal strength of self-tapping screws inserted in high density wood species. As mentioned the limits for the characteristic density for the methods from ETA-11/0030:2020 are between 590 kg/m^3 and 750 kg/m^3. The methods developed by Kieboom [15] were based on tests done on wood species with densities between 440 kg/m^3 and 1044 kg/m^3. The methods developed by Hubner, Rasser, and Schickhofer [13] were based on tests done on wood species with densities between 550 kg/m^3 and 900 kg/m^3 with mean density ρ_{mean}=746 kg/m^3.

Table 4.2: Withdrawal capacity predictions of screw types.

Screw dia. [mm]	f_{ax} [N/mm^2]	l_eff [mm]	ρ_k [kg/m^3]	ρ_a [kg/m^3]	$f_{tens,k}$ [kN]	Withdraw. cap. ETA [kN]	Withdraw. Hubner, Rasser, and Schick-hofer [13] [kN]	Withdraw. Kieboom [15] [kN]
6	29	90	750	730	18	16	24,1	21,8
6	29	90	840	730	18	17,5	29,3	24,9
6	29	90	1044	730	18	20,9	42,4	32,4
6	29	90	1100	730	18	21,7	46,3	34,4
8	29	90	750	730	32	21,3	29,1	25,1
8	29	90	840	730	32	23,4	35,3	28,8
8	29	90	1044	730	32	27,8	51,1	37,4
8	29	90	1100	730	32	29	55,8	39,8
11	29	90	750	730	38	29,3	35,8	29,5
11	29	90	840	730	38	32,1	43,4	33,7
11	29	90	1044	730	38	38,2	62,8	43,8
11	29	90	1100	730	38	39,9	68,6	46,6
13	29	90	750	730	53	34,7	39,9	32
13	29	90	840	730	53	38	48,4	36,7
13	29	90	1044	730	53	45,17	70	47,6
13	29	90	1100	730	53	47,1	76,5	50,7

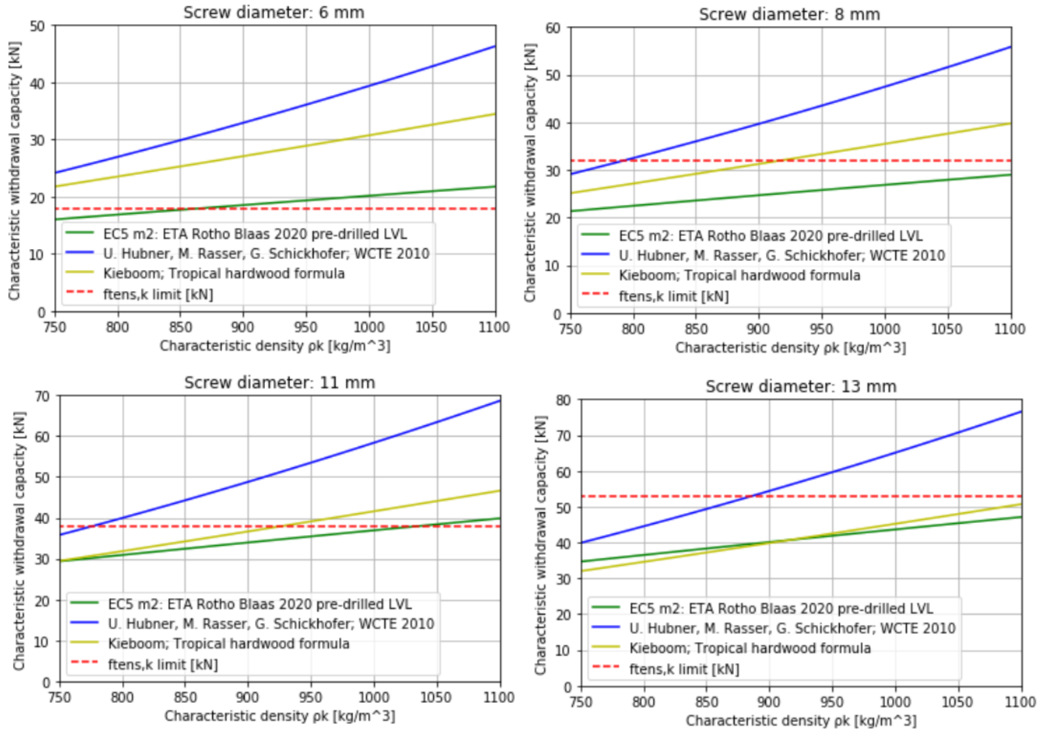

Figure 4.2: Withdrawal capacity predictions of screw types graphically, characteristic withdrawal capacity vs. characteristic density. With effective length (90 mm), f_{ax} (29 N/mm^2) and ρ_a (730 kg/m^3).

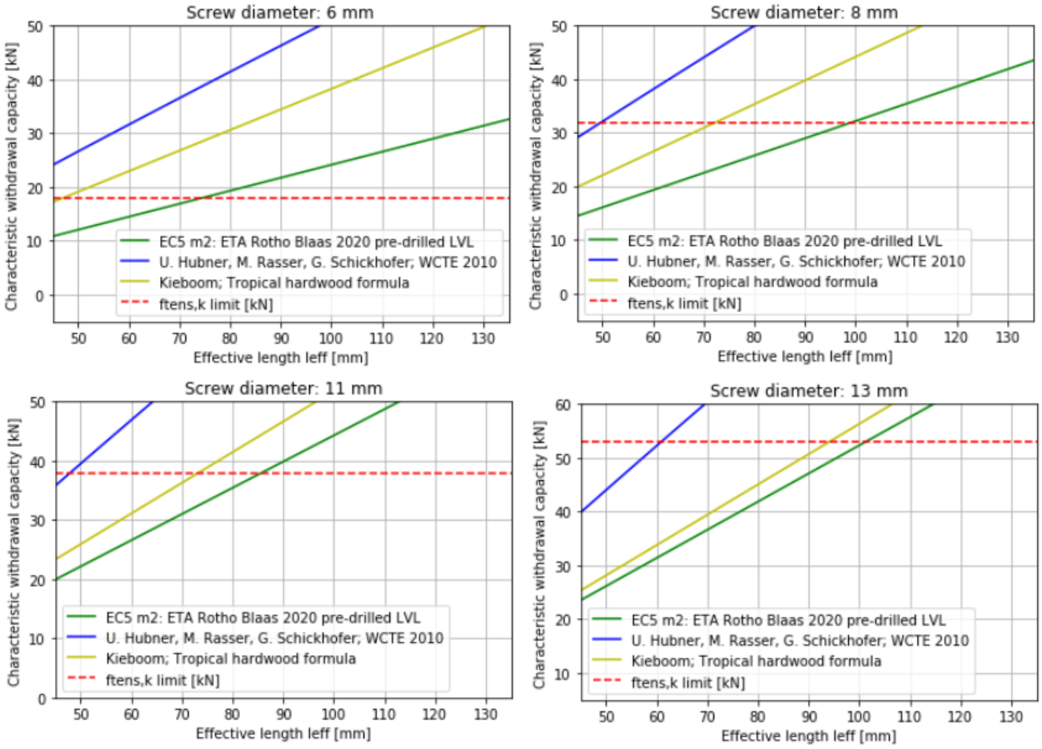

Figure 4.3: Withdrawal capacity predictions of screw types graphically, characteristic withdrawal capacity vs. effective length. With characteristic density (1100 kg/m^3), f_{ax} (29 N/mm^2) and ρ_a (730 kg/m^3).

4.1.4. Provisional conclusion of test series design

In the literature study it became clear that the effective screw length is not the most interesting parameter. Especially not in high density wood species. The longer the effective length, the higher the withdrawal resistance of self-tapping screws in timber. This is a trend observed in all wood species and a very obvious trend as well. Also a linear relationship can be noticed from other research between the effective screw length and the withdrawal capacity (see chapter 2.6.6). With increasing densities high withdrawal capacities can be reached as was already concluded by Hubner, Rasser, and Schickhofer [13] (see chapter 2.6.6). Increasing densities could also lead to screw steel tensile failure instead of withdrawal of the screw. The possible application of self-tapping screws is in hydraulic and outside structures as mentioned before, and as said longer screws and screws with larger diameters are preferred. In table 4.2 using several calculation methods for the withdrawal strength of self-tapping screws in timber a maximum of 90 mm effective length has been found. It is predicted that this length has withdrawal failure as dominant failure mode in all available timber densities. Screw rupture will almost certainly be the dominant failure mode in higher density timber specimens.

Pre-drilling is as mentioned before required by the Eurocode 5 version 2011. This is necessary when the characteristic density is larger than 500 kg/m^3. According to Eurocode 5 version 2011 the pre-drilled hole for the threaded part of the screw has to have a diameter of approximately 70 percent of the shank diameter. In chapter 2.6.2 research done by Brandner, Ringhofer, and Reichinger [5] concludes that no influence from pre-drilling was found on the withdrawal strength of self-tapping screws in timber if the pre-drilling diameter is smaller or equal to 0,8*d (d is the nominal diameter). In this provisional test series two pre-drilled diameters will be tested, 70 and 80 percent of the nominal diameter over the full inserted length. This is done to make sure all screws reach their designated position.

Looking at the predictions in table 4.2 for the 6 mm diameter HSBSH self-tapping screws from Rotho Blaas it already becomes clear that this could be problematic for testing in high density timber types. By using insertion lengths of 25 mm and 50 mm the prediction is that withdrawal of the screw out of the timber will be the dominant failure mode, also in very high density timber species. Therefore these two will types will be included in the provisional test series with pre-drilling diameters 0,7*d-0,8*d.

Kieboom [15] did not do tests with diameter 8 mm screws but with 9 mm VGS screws from Rotho Blaas. Kieboom [15] did reach 70 mm insertion depth with 5,5 mm (0,6*d) pre-drilling and achieved withdrawal failure as dominant failure mode in Mukulungu with density 982,5 kg/m^3. Also this gives confidence that the proposed 8 mm HBSH self-tapping screws from Rotho Blaas will have withdrawal failure as dominant failure mode and will reach the required insertion depth for 90 mm insertion depth and 0,7*d-0,8*d pre-drilled diameter hole. It gives even more confidence since the HBSH is developed for hardwoods and has excellent tensile and torque resistance.

Looking at tests already done by Kieboom [15] insertion depths of 150 mm were reached with pre-drilled holes of 0,8*d and 0,9*d and 80 mm pre-drilling depth in Mukulungu with VGS 11 mm diameter screws from Rotho Blaas. This depth could not be reached for 0,7*d pre-drilling, this only got to 120 mm. Also screw withdrawal failure was achieved for 11 mm diameter screws in Mukulungu with a insertion depth of 90 mm, a pre-drilled hole of 7,5 mm (0,68*d) and a density of 930 kg/m^3. This gives confidence that the required insertion depth and withdrawal failure will be dominant for VGS 11 mm screws with a density of 930 kg/m^3 with pre-drilled holes of 0,7*d-0,8*d.

The VGS diameter 13 mm screw is predicted to give withdrawal failure according to the ETA from Rotho Blaas and the calculation method from Kieboom [15]. The calculation method from Hubner, Rasser, and Schickhofer [13] gives very high values. No practical examples of this screw are available in such high timber densities, so the decision on whether to use this screw diameter is based on the results in table Hubner, Rasser, and Schickhofer [13]. The choice has been made to reject this screw diameter from the test series and reserve it for tests with larger timber specimens in the future. It must also be mentioned that the author of this thesis has most confidence in the ETA provided formula because these are especially calibrated for the calculated screws, although these formula are only valid for wood densities up to 750 kg/m^3.

The test piece configuration that will be used is the type 1 configuration (figure 4.1). This configuration has been chosen because the chosen screw diameters, pre-drilled diameters and insertion depths also did not cause problems in research done by Kieboom [15]. Another reason is the relative small size of the test pieces and the space needed to clamp the test piece in the withdrawal machine. For configuration types 2 and 3 there would be little room to apply screws (figure 4.1). Finally, as has been mentioned before the screws that will be tested are inserted perpendicular to the grain. Everything discussed above is summarized in table 4.3 below.

Table 4.3: Provisional test series. All Variations applied on wet and dry pieces perpendicular to the grain.

Type	Product name	Diameter [mm]	Inserted depth [mm]	Pre-drilled dia. [mm]
1	HBSH7160	6	25	0,7*d
2	HBSH7160	6	50	0,7*d
3	HBSH7160	6	25	0,8*d
4	HBSH7160	6	50	0,8*d
5	HBSH9160	8	50	0,7*d
6	HBSH9160	8	90	0,7*d
7	HBSH9160	8	50	0,8*d
8	HBSH9160	8	90	0,8*d
9	VGS11150	11	50	0,7*d
10	VGS11150	11	90	0,7*d
11	VGS11150	11	50	0,8*d
12	VGS11150	11	90	0,8*d

4.2. Pre-testing

In this sub-chapter a pre-test series is carried out. The goal of pre-testing is to get familiar with the testing equipment and to find the limits of the materials. The most important thing is that it is possible to get the screws in the designated place in the timber and to have withdrawal failure as dominant failure mode during testing.

4.2.1. Pre-testing series

In chapter 4.1.4 table 4.3 a provisional test series has been formulated. In this sub-chapter the extremes from these provisional test series will be tested to find out if it is feasible to get the screws in the desired place and to achieve withdrawal failure as mentioned before. This is done by using the largest diameter from the provisional test series to find out if there are any problems with insertion of the screw into the timber, this would be the 11 mm diameter screw. Also, the 11 mm screw was the most critical screw when looking to predictions made in chapter 4.1.3 figure 4.3 in terms of tensile resistance of the steel screw. The pre-test series will be conducted on the tropical hardwood species with the highest density that is available. This would be the following species: Limbali, Tali and Mukulungu. More on the wood species in chapter 5.1. This then become the following pre-test series as shown in figure 4.4. Details of the used screw can be found in table 4.5.

Table 4.4: Pre-test series. All Variations applied on dry pieces perpendicular to the grain. Test on species: Limbali, Tali, Mukulungu.

Type	Product name	Diameter [mm]	Inserted depth [mm]	Pre-drilled dia. [mm]
1	VGS11150	11	initially 90	0,7*d
2	VGS11150	11	initially 90	0,8*d

Table 4.5: Screw that will be used in pre-testing (from Rothoblaas).

Product name	Diameter [mm]	Threaded length [mm]	$f_{tens,k}$ [kN]	$f_{tor,k}$ [Nm]
VGS11150	11	140	38	61

4.2.2. Configuration pre-testing

In figure 4.4 the pre-test piece configuration is shown with H (height), l (length) and W (width). Also spacing parameters a1 and a2 are included, all values for these parameters can be found in table 4.6.

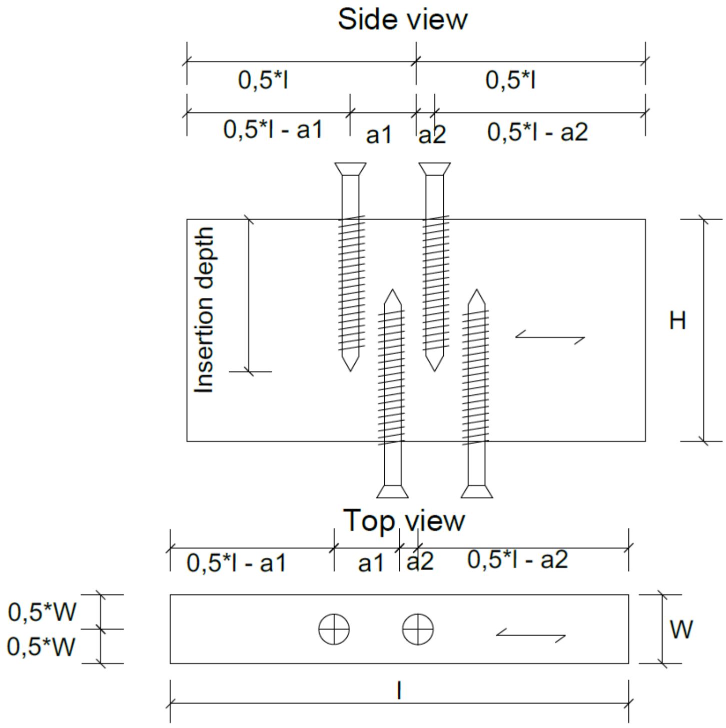

Figure 4.4: Pre-test piece configuration with side view above and the top view on the bottom.

Table 4.6: Dimensions for the pre-test pieces.

l [mm]	H [mm]	W [mm]	a1 [mm]	a2 [mm]	Inserted depth [mm]
≈ 300	≈ 145	≈ 45	43	12	Initially 90 mm

4.2.3. Set-up pre-testing

In this sub chapter the set-up of the pre-testing series is explained. The set-up has been changed over the course of the tests. The change has to do with way the displacement sensors are used, this will be explained.

The block of timber is fixed to the universal testing machine by placing two rectangle hollow steel sections (only one is shown in figure 4.5 for photo purposes) on the top side of the timber block, tightened by threaded steel wire and bolts. The universal testing machine is able to hold on to and pull the self-tapping screw with the help of a small steel block. This steel block has a hole with the diameter of the screw, but smaller than the screw head. This is the basis of the set-up. How the displacement sensors are used has changed during the tests.

Initial set-up sensors

Initially the displacement sensors were attached to the pulling part of the universal testing machine as can be seen in figure 4.5 (right image). Two block are fixed to the sides of the timber piece, from these blocks the displacement sensors take the displacement.

Figure 4.5: Initial pre-test piece setup.

Final set-up sensors

The problem with the set-up in figure 4.5 is that the displacement sensors also measure the influence of the self-tapping screw elongation and the displacement of the timber. In the final set-up these influences are largely taken away. The self-tapping screw is now screwed into the timber through a small green plastic plank as can be seen in figure 4.6. The displacement sensors are now attached on the sides of the timber piece as can be seen in figure 4.6 and the sensors take the displacements from the green plank. The displacement that is measured now is the displacement of the screw out of the timber.

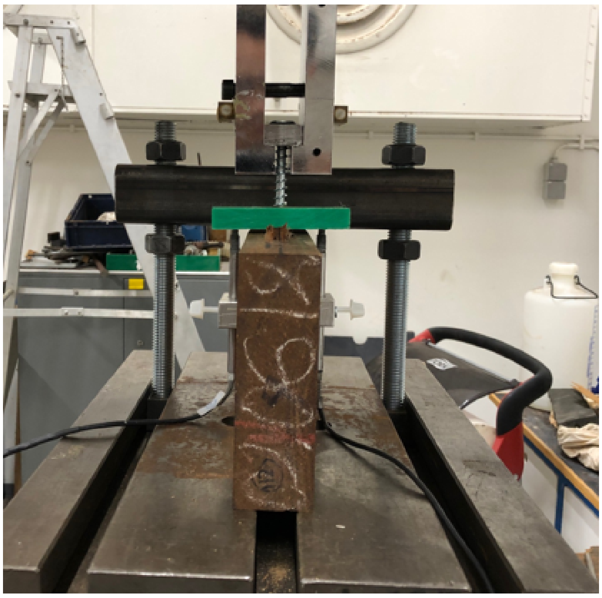

Figure 4.6: Final pre-test piece set-up.

4.2.4. Results pre-testing

Results testing Mukulungu

During these tests the initial set-up of the displacement sensors is used. The effective length that is used is 90 mm. As can be seen in figure 4.7 the measured withdrawal resistance of the self-tapping screws is larger than the characteristic tensile resistance of 38 kN. The pre-drilling diameter does not influence the withdrawal resistance. The withdrawal resistance for the 0,8d tests are even higher than the values for 0,7d pre-drilling as can be seen in figure 4.7, the difference has to do with the difference in density. In figure 4.8 the typical failure of Mukulungu is shown. As can be seen fine splinters are pulled out in fiber direction.

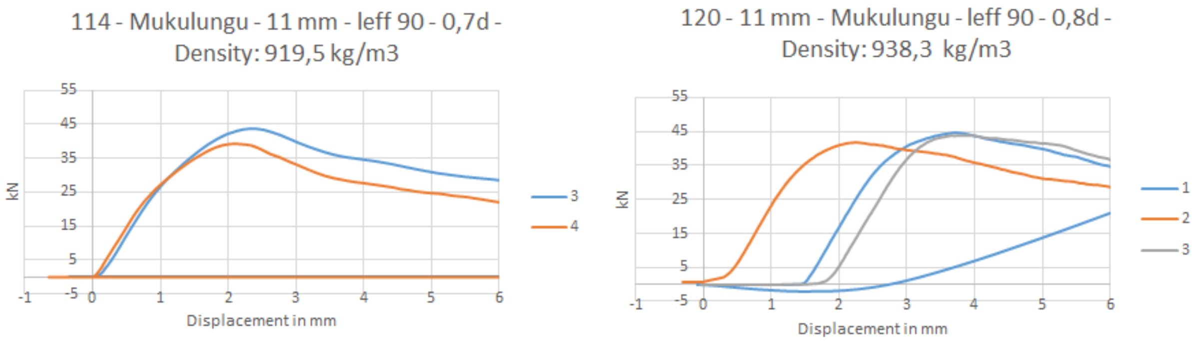

Figure 4.7: (a-left image) Results Mukulungu with 0,7d pre-drilling. (b-right image) Results Mukulungu with 0,8d pre-drilling.

Figure 4.8: Typical failure Mukulungu.

Results testing Tali

The first test done on a Tali piece was with 0,7d pre-drilling and an insertion depth of 90 mm. The initial sensor set-up was used, with the sensors connected to the pulling device of the universal testing machine. As can be seen in figure 4.9(a) a very high withdrawal resistance was measured of around 50 kN. With increasing displacements this self-tapping screw eventually broke as can be seen in 4.9(b).

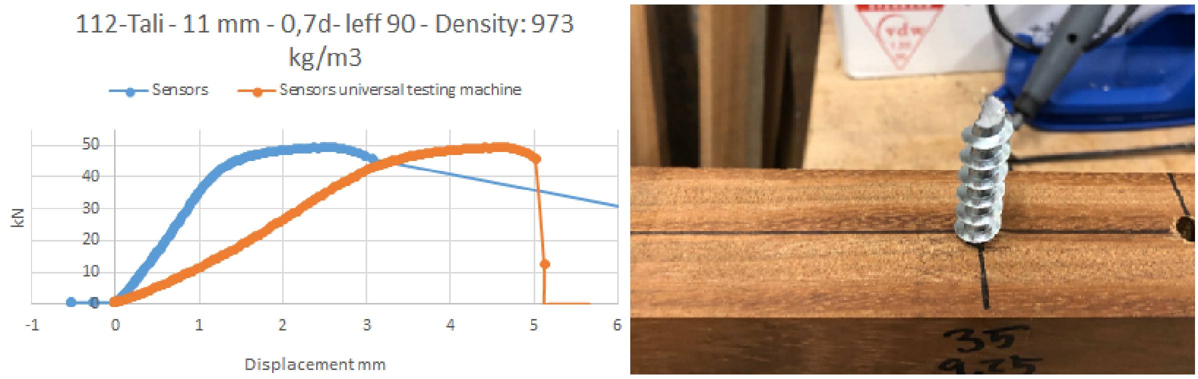

Figure 4.9: (a-left image) Results Tali with 0,7d pre-drilling. (b-right image) Failure of screw.

After the screw failure the set-up was changed to the final set-up as explained in chapter 4.2.3, see figure 4.6. The difference between the initial set-up and the final set-up can be seen in figure 4.10(a). The results of the final set-up is much stiffer, due to the fact that only the displacement of the part that is pulled out of the timber is measured. In figure 4.10(a) and (b) the results for respectively 50 mm insertion length and 80 mm insertion length. This has been done to find the limits. As can be seen in

4.10(b) the results are higher than the characteristic tensile strength of the self-tapping screw (38 kN). The typical failure pattern withdrawal tests on Tali is shown in figure 4.11.

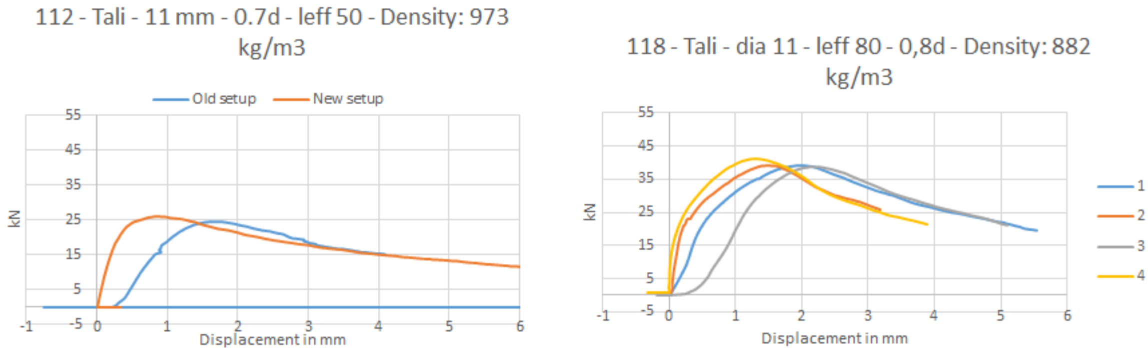

Figure 4.10: (a-left image) Results Tali with 0,7d pre-drilling. (b-right image) Results Tali with 0,8d pre-drilling.

Figure 4.11: Typical failure Tali.

Results testing Limbali

Two pieces of Limbali were tested with a screw insertion depth of 80 mm. The density of the Limbali piece in figure 4.12(a) was 739,1 kg/m^3 and the pre-drilling diameter was 0,8d. The density of the Limbali piece in figure 4.12(b) was 790,8 kg/m^3 and the pre-drilling diameter was 0,7d. Again no clear sign of pre-drilling influence can be seen. The typical failure pattern of withdrawal tests can be seen in figure 4.13

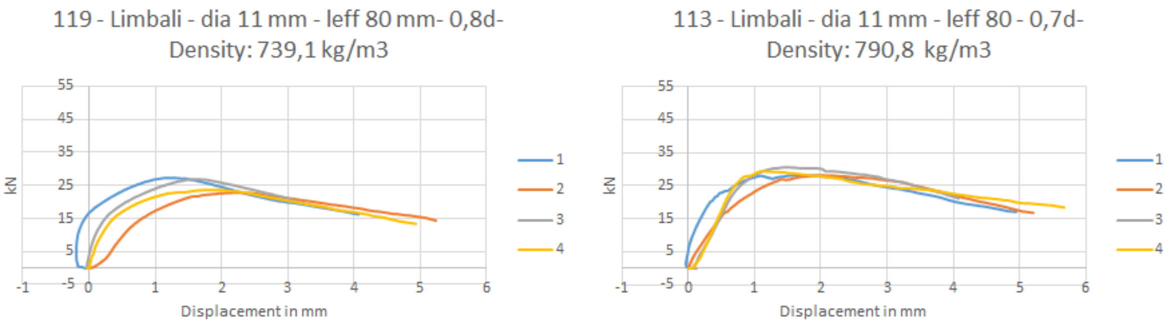

Figure 4.12: (a-left image) Results Limbali with 0,8d pre-drilling. (b-right image) Results Limbali with 0,7d pre-drilling.

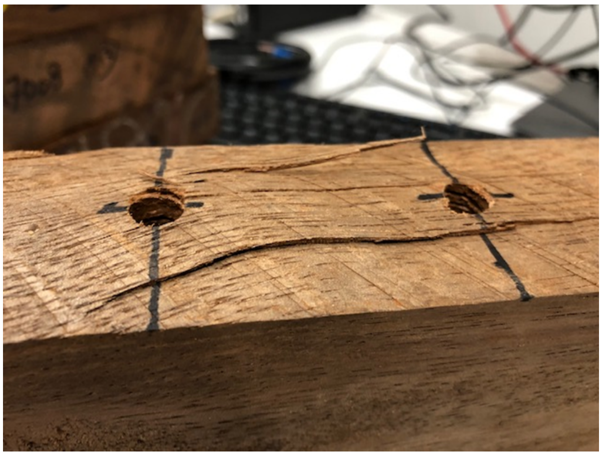

Figure 4.13: Typical failure Limbali.

4.3. Conclusion test design

Self-tapping screw diameters
During pre-testing only the 11 mm diameter (VGS11150) self-tapping screw from Rothoblaas was used. For the full test series also diameters 6 mm (HBSH7160) and 8 mm (HBSH9160) will be used. The last two have been chosen because these are specially designed for use in hardwood species by Rothoblaas. The choice for several screws diameters is made because this is necessary for a good data set to be able to predict the withdrawal resistance of self-tapping screws in tropical hardwood species.

Self-tapping screw insertion depth
To avoid screw tensile failure predictions were made in chapter 4.1.3 to determine what the maximum insertion depth would be. This would be around 90 mm for 11 mm diameter (VGS11150) self-tapping screw from Rothoblaas. During pre-testing however it was found that an insertion depth of 90 mm could lead to screw tensile failure. 80 mm insertion depth has been tried in chapter 4.2.4 on Tali. This resulted in values higher than the characteristic tensile resistance of the screw (38 kN). It has been decided to use 70 mm as the maximum insertion depth to make sure withdrawal of the screw is the dominant failure mode.

In chapter 2.6.6 it was found that the relation between the withdrawal capacity and effective length is linear. Therefore only two insertion depths will be tested for every screw size.

For the 8 mm diameter (HBSH9160) and 11 mm diameter (VGS11150) will be tested with insertion depths of 50 mm and 70 mm. For 6 mm diameter (HBSH7160) the 70 mm could be problematic. It has been chosen to test these with 25 mm and 50 mm insertion depths.

Pre-drilling diameter
In pre-testing 0,7d and 0,8d pre-drilling diameters have been tested. Figures 4.7 and 4.12 show no significant influence of the pre-drilling diameter. It has been chosen to use 0,8d and 0,9d because this might help to insert self-tapping screws in high density hardwood species.

Timber condition
Tropical hardwood species are generally used in hydraulic and outside structures because of their durability. Therefore it would be interesting to find out what the effect of a high moisture content is on the withdrawal capacity of self-tapping screws in tropical hardwoods. So testing will be done on dry and wet timber pieces.

Timber piece size
The test piece configuration shown in chapter 4.2.2 figure 4.4 is not according to EN 1382:2016 (see chapter 3.1). The main concern was that the test piece might crack when inserting the self-tapping screws because of the small width. This was no problem during pre-testing and this configuration will be used in during testing.

5

Experimental research

For good research a plan is needed. In this chapter the course of the experimental research will be elaborated. The used materials will be explained. After this the final test series will be presented. Also the used test piece configuration will be shown and how these will be prepared for testing. Finally the test set-up will be presented together with the positioning and use of sensors to collect the data.

5.1. Wood species

A total of six tropical hardwood species will be tested. In table 5.1 The trade name, botanical name and place of origin of the timber are given. Spruce has been added as a reference material, this is softwood.

Table 5.1: Tropical hardwood species used in testing with botanical name and place of origin

Trade name	Botanical name	Place of origin
Kanda	*Beilschmieda spp.*	Republic of Congo
Lati	*Amphimas pterocarpoides*	Republic of Congo
Longhi	*Chrysophyllum spp*, *Gambeya spp* (synonymous)	Republic of Congo
Tali	*Erythrophleum ivorense*	Republic of Congo
Limbali	*Gilbertiodendron dewevrei*	Republic of Congo
Mukulungu	*Autranella congolensis*	Republic of Congo
Spruce	*Picea abies*	Belgium

5.2. Self-tapping screw types

In table 5.2 the screws used in testing are summarized. The screws are products from Rothoblaas. In the table the product name, nominal diameter, threaded length, characteristic tensile strength $f_{tens,k}$ and characteristic torsional strength $f_{tor,k}$ can be found. All screws are made of galvanized carbon steel. Full product description can be found in ETA-11/0030:2020 or by consulting Rothoblaas.

The HBSH screws are screws especially developed for insertion in hardwoods. This is done by increasing the inner diameter for tightening in high density woods. These screws also have higher values for the characteristic torsional strength and characteristic tensile strength compared to regular screws with similar diameters.

Table 5.2: Screws that will be used in testing

Product name	Diameter (d1) [mm]	Screw length [mm]	$f_{tens,k}$ [kN]	$f_{tor,k}$ [Nm]	l_{tip} [mm]
HBSH7160	6	160	18	18	8
HBSH9180	8	180	32	38	10
VGS11150	11	150	38	61	14

In the analysis the length of the screw tip (l_{tip}) will be subtracted from the insertion depth, this then is the effective screw length from which the withdrawal capacity of the screw is generated. The diameter used to refer to the screws is the nominal diameter (d_{nom}), noted in figure 5.1 and 5.2 as d_1.

The 6 and 8 diameter screws have special ribbed and cutter tips. The 11 diameter screw only has a cutter tip. The geometry of the 6 mm and 8 mm diameter screws can be seen in figure 5.1, geometry values can be found in table 5.3. The geometry of the 11 diameter screw can be found in figure 5.2, geometry values can be found in table 5.3. During testing screws will be reused as much as possible. After each test the screws will be examined to see if there are damages. If there are damages a new screw will be used. To make sure screws are not used to often they are replaced anyway after 12 tests.

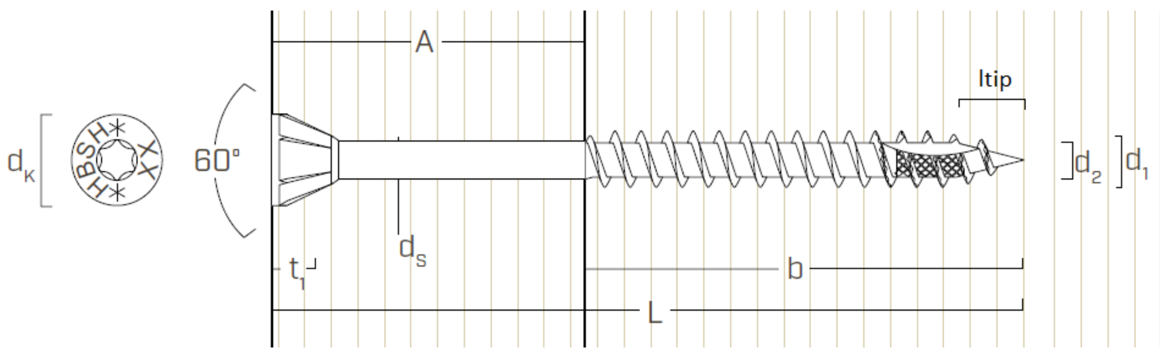

Figure 5.1: Geometry of the HBSH screws Rothoblaas [23].

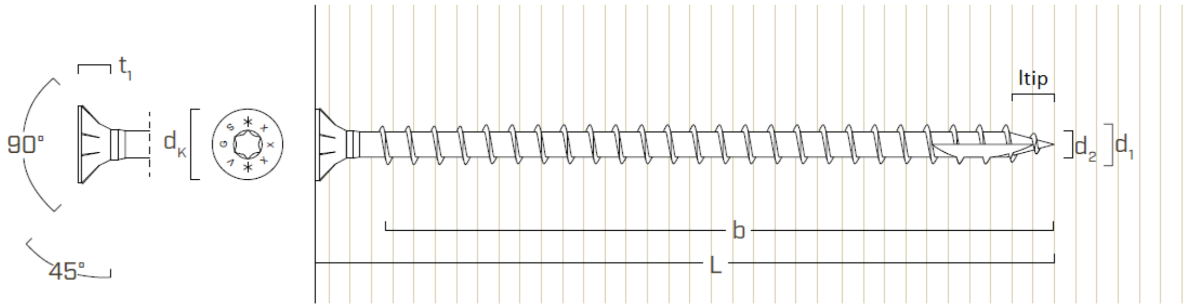

Figure 5.2: Geometry of the VGS screws Rothoblaas [24]

Table 5.3: Screw geometry values.

Product name	Diameter [mm]	L [mm]	b [mm]	d_1 [mm]	d_2 [mm]
HBSH7160	6	160	90	6	4,5
HBSH9180	8	180	100	8	5,9
VGS11150	11	150	140	11	6,6

5.3. Test series

The test series are as followed:

- All test variations in table 5.4 will be applied to timber species described in table 5.1
- Timber condition: every type in table 5.4 will be tested in dry condition and wet condition. The wet pieces have been placed in water. Spruce pieces will not be tested in wet conditions.
- Varying screws and diameters, see table 5.4
- All screws are applied perpendicular to the grain

Figure 5.3 shows a flowchart of the test series.

Table 5.4: Test series. All Variations applied on wet and dry pieces, and on all 6 timber species (see table 5.1)

Type	Product name	Diameter [mm]	Inserted depth [mm]	Pre-drilled dia. [mm]
1	HBSH7160	6	25	0,8*d $\approx$ 5
2	HBSH7160	6	50	0,8*d $\approx$ 5
3	HBSH7160	6	25	0,9*d $\approx$ 5,5
4	HBSH7160	6	50	0,9*d $\approx$ 5,5
5	HBSH9160	8	50	0,8*d $\approx$ 6,5
6	HBSH9160	8	70	0,8*d $\approx$ 6,5
7	HBSH9160	8	50	0,9*d $\approx$ 7
8	HBSH9160	8	70	0,9*d $\approx$ 7
9	VGS11150	11	50	0,8*d $\approx$ 9
10	VGS11150	11	70	0,8*d $\approx$ 9
11	VGS11150	11	50	0,9*d $\approx$ 10
12	VGS11150	11	70	0,9*d $\approx$ 10

Numbering of the test specimens is done from 1 to 156. Reference will be made to those numbers in this thesis and the exact test specification for every number can be found in annex A. In annex A also codes have been reported for every test piece. All pieces were labeled with these codes and relate to earlier bending tests outside this thesis.

It has to be noted that although all tropical hardwood species in this project will also be subject to wet conditioning, only Tali and Mukulungu are usable in hydraulic and outside structures. But to get a good idea of the behaviour of all tropical hardwood species in this project to higher moisture content all of them will be used in wet testing.

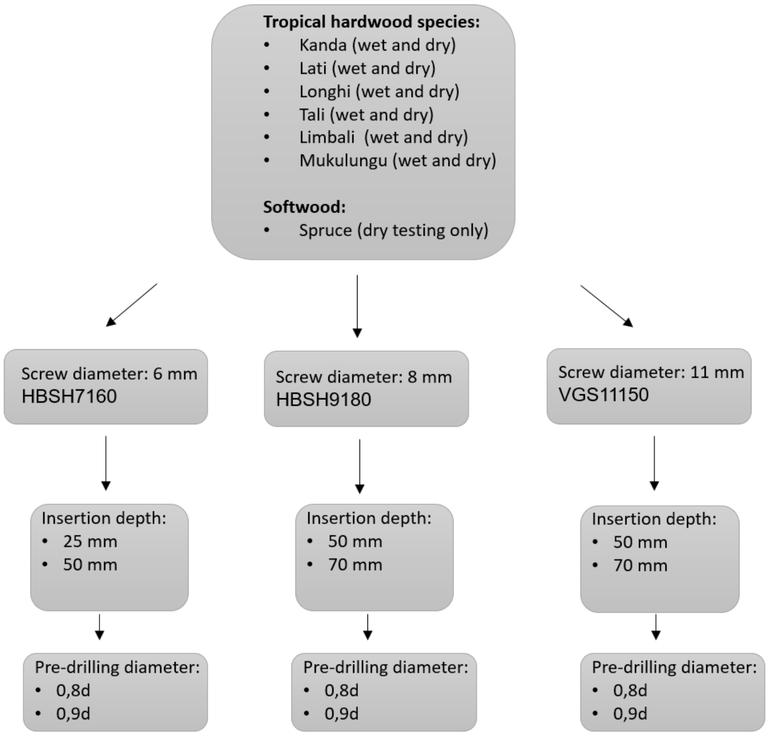

Figure 5.3: Test series flowchart. All species will be tested in 'dry' testing, only the tropical hardwood species will also be used in bot 'wet' and 'dry' tests.

5.4. Test piece configuration

In figure 5.4 the test piece configuration is shown. As can be seen 4 screws will be inserted in one test piece. Dimensions a1 and a2 shown in figure 5.4 have to be taken from the middle of the test piece. The numerical values of a1, a2, the length l, the width w and the height H can be found in table 5.5. The dimensions for the screws on the bottom side are the same as on the top, but mirrored. The values for the insertion depth varies per test series, these can be found in table 5.4.

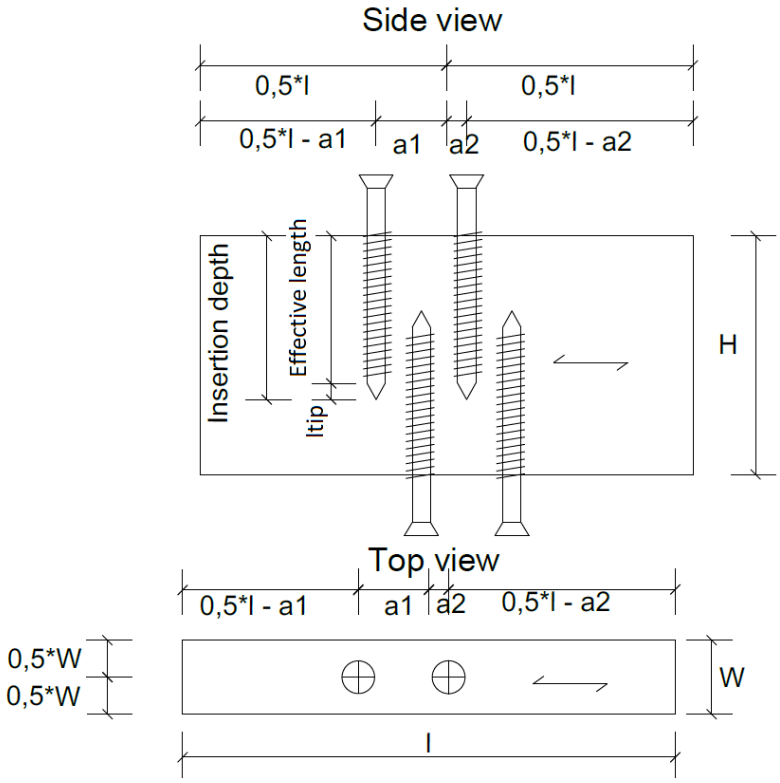

Figure 5.4: Test piece configuration with side view above and the top view on the bottom.

Table 5.5: Dimensions for the test pieces.

l [mm]	H [mm]	W [mm]	a1 [mm]	a2 [mm]	Inserted depth [mm]
≈ 300	≈ 145	≈ 45	48	16	See table 5.4

5.5. Testing

5.5.1. Test piece preparation

Test piece size

The length of all pieces was on average 300 mm, the width on average 45 mm and the height was on average 145 mm. The tropical hardwood pieces have been sawn years before, since these piece were part of bending tests. The spruce has been sawn for the purpose of this project at the TU Delft. An example of the test pieces is shown in figure 5.5.

Figure 5.5: Example of a test piece, in this case Limbali.

Pre-drilling of test pieces

Pre-drilling has been done at the TU Delft. The wet pieces were stored underwater between 25 and 40 days. For practical and planning reasons the pieces have been pre-drilled on the 20th day in the water and afterwards put back in the water.

Conditioning test pieces

The timber species used in this project were not stored in a climate room, except for the Spruce and Mukulungu pieces. These were stored in a 20/65 climate at the TU Delft. The rest of the pieces were stored in the basement of the TU Delft Stevin II lab. All pieces have remained at the same place for years. Also wet pieces will be used. A portion of every tropical hardwood species shown in table 5.1 has been stored underwater except for the Spruce, no wet Spruce pieces were tested. The wet pieces were stored underwater as said between 25 and 40 days. The wet pieces have been pre-drilled on the 20th day in the water and afterwards put back in the water. Figure 5.6 shows the storage of the wet pieces.

Figure 5.6: Storage of tropical hardwood species underwater, blocks of concrete prevent the pieces from floating.

5.5.2. Test set-up

Figure 5.7 shows how the displacement sensors are positioned on the test pieces. Figure 5.7 shows the sensor fix, which is a small metal block which is drilled onto the test piece. The sensor fix holds the displacement sensor in place. The sensor support is fixed to the self-tapping screw and supports the displacement sensor. When the self-tapping screw is pulled out of the timber this support will move, which will be measured by the displacement sensor. The force over the course of every test is measured by the universal testing machine.

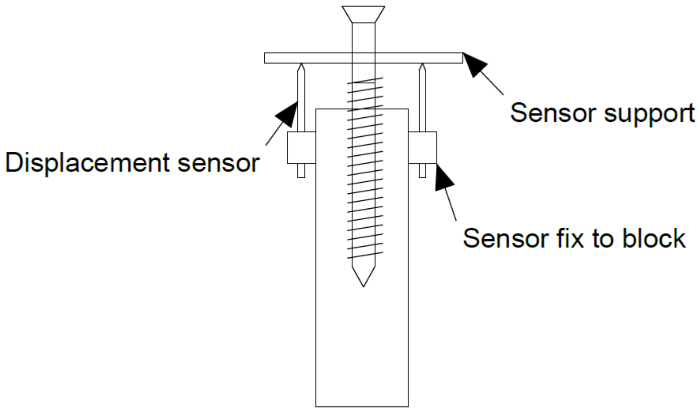

Figure 5.7: Cross section of the test piece showing the positioning of the displacement sensors. View is in grain direction (transverse plane).

In figure 5.8(a) the set-up is shown as used during testing. The test piece is fixed with hollow core steel beams and threaded rods to the universal testing machine. The upper part of the machine remains in the same position the lower part goes down, causing the tension in the self-tapping screw.

Figure 5.8(b) shows the set-up from up close. As can be seen are the displacement sensors fixed onto the timber piece and supported by green plastic pieces. The self-tapping screws are inserted into these plastic pieces.

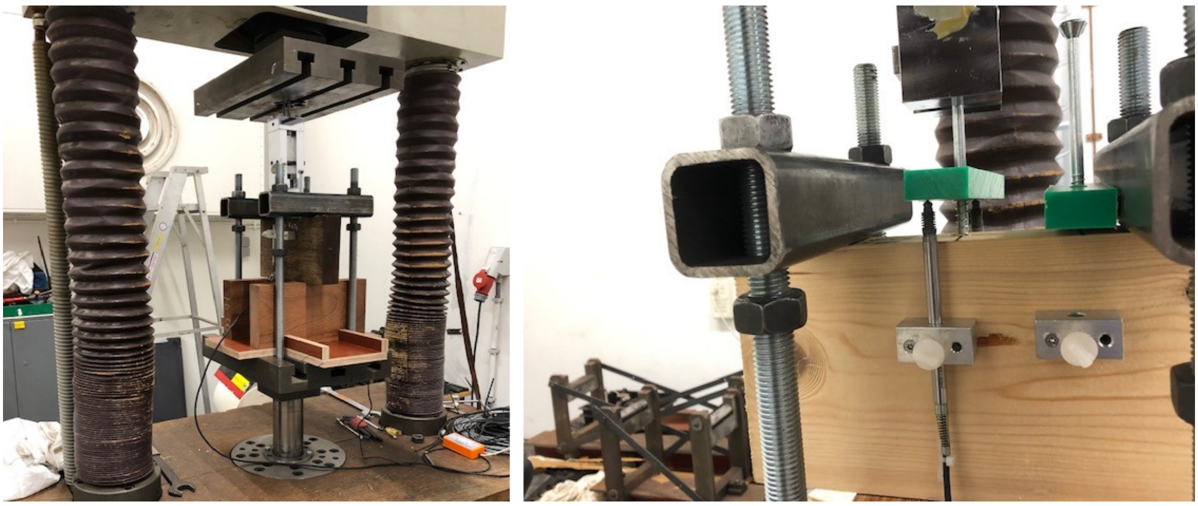

Figure 5.8: (a-left image) Overview of the universal testing machine and the test piece. (b-right image) Test set-up showing the timber, the hollow core steel beams to fix the timber to the machine and the displacement sensors.

The universal testing machine is able to hold on to the screw with the help of a steel piece. This piece is shown in figure 5.9(a). The hole of in the steel piece is tapered in the shape of the screw head. As can be seen in figure 5.9(a) one side of the steel piece is cut open to be able to hang the self-tapping screw in the machine. The steel piece is placed into a mounting piece. Figure 5.9(b) shows the screw as used during testing, the screws are inserted into green plastic pieces which are used to support the displacement sensors.

Figure 5.9: (a-left image) Steel piece used to hang the screws in, the tapered hole has the shape of the screw head. (b-right image) Self-tapping screws used in testing; The self-tapping screws are inserted into plastic green parts which are used to support the displacement sensors.

5.5.3. Test procedures

On every test piece four (also see figure 5.4) tests will be performed. Two tests will withdrawal strength tests according to EN 1382:2016 (see chapter 3.1), the other two tests will be stiffness tests according to EN 26891:1991 (see chapter 3.2). The two withdrawal strength tests will be done first, the maximum of these two will be used for the stiffness tests. The stiffness test will in the end also go to the maximum loading, so these tests also give values for the maximum withdrawal strength. So in the end per test piece there will be four withdrawal strength results and two slip moduli, averages will be taken from these results.

5.5.4. Determining properties

After testing a small piece will be cut out of the tested timber specimen. This piece will taken from the timber close to the tested hole, with a size of approximately 25 mm in length (figure 5.10(a and b)). In case of the wet timber pieces this small piece of 25 mm will also include one pre-drilled hole. This is done because the wet pieces have been taken out of the water, have been pre-drilled and put back into the water. Water will also enter these holes and the moisture content might be higher in those regions.

After sawing the pieces, the small piece of 25 mm will be weighed, measured and put in a dry oven. The density will be determined from the first weighing. The determination of the moisture content will be done according to chapter 3.4 (EN 13183-1).

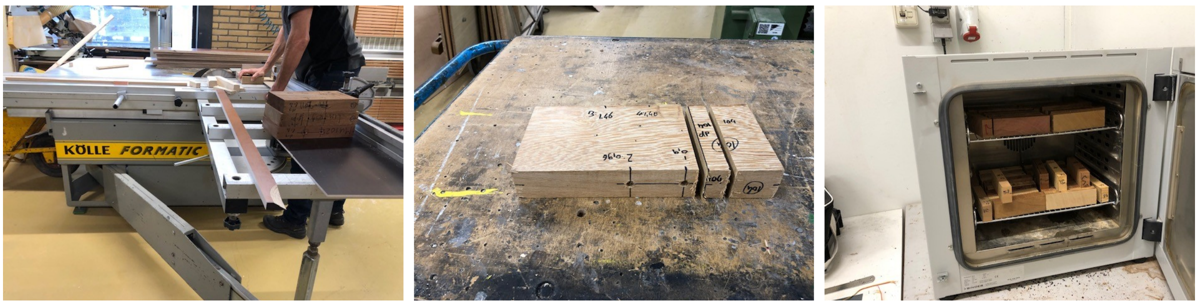

Figure 5.10: (a-left image) Pieces being sawn in the timber workshop. (b-middle image) Original tested specimen cut in pieces. (c-right image) Sawn pieces in dry oven.

6
Experimental results

In this chapter the results from testing will be presented. There is a large variation in results, because of this the results will be presented in groups. A total of 156 timber pieces have been tested. Four maximum withdrawal strength values, four maximum insertion moment values and two slip moduli values have been measured per test piece. resulting in a total of 624 tests.

A broad range of values has been tested and measured, these are the following:

- Density;
- Moisture content;
- Withdrawal capacity;
- Insertion moment;
- Slip modulus;

All results from testing can be found in annex A, and have been corrected for the sensor in-balance. In this chapter the results will be presented. First the density and moisture content of the tested specimens will be presented, followed by withdrawal testing results.

6.1. Measured timber density

6 species of tropical hardwood were used during testing and one softwood species. An overview of the measured (uncorrected) timber densities can be seen in figure 6.1. The average density per species is presented in table 6.1 for the dry specimens and table 6.2 for the wet specimens. Of every species 12 samples were used, and on every sample 4 tests were done.

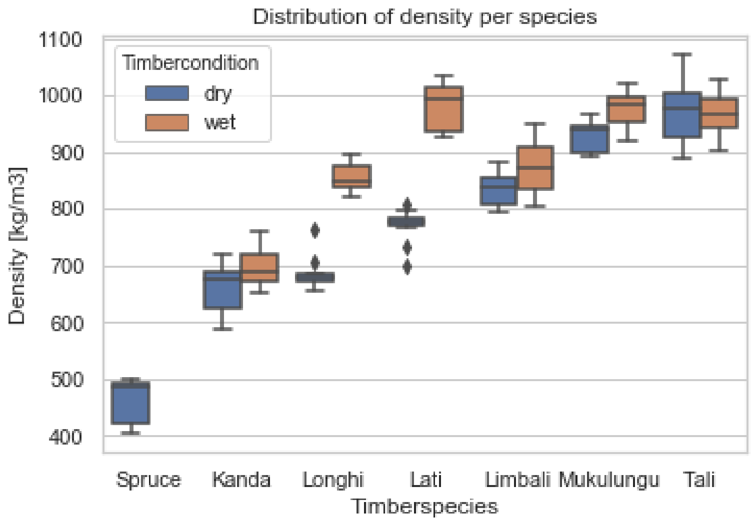

Figure 6.1: Density measured per tested species from dry and wet testing, density not adjusted to 12 % moisture content.

Table 6.1: Average densities of the used timber species (dry, not adjusted to 12 % moisture content).

Trade name	n samples	Av. density [kg/m^3]	Av. density COV [%]
Kanda	12	658	7
Lati	12	771	4
Longhi	12	683	4
Tali	12	973	6
Limbali	12	834	4
Mukulungu	12	931	3
Spruce	12	465	8

Table 6.2: Average densities of the used timber species (wet, not adjusted to 12 % moisture content).

Trade name	n samples	Av. density [kg/m^3]	Av. density COV [%]
Kanda	12	697	5
Lati	12	982	4
Longhi	12	855	3
Tali	12	967	4
Limbali	12	872	6
Mukulungu	12	976	3

6.2. Moisture content

6.2.1. Moisture content dry specimens

The moisture content per species is presented in table 6.3 for the dry specimens. As can be seen in table 6.3 the Mukulungu and Spruce have a moisture content around 12/13 %, these have been stored in a 20/65 climate. The other specimens have been stored in the basement of the TU Delft Stevin II lab. The relative humidity of the basement was apparently lower causing a lower moisture content in those specimens.

Table 6.3: Moisture content (M.C.) of the used timber species (dry).

Trade name	n samples	Av. M.C. [%]	Av. M.C. COV [%]
Kanda	12	8,9	2
Lati	12	9,6	3
Longhi	12	9,8	3
Tali	12	9,0	3
Limbali	12	9,5	3
Mukulungu	12	13,1	3
Spruce	12	12,3	2

6.2.2. Moisture content wet specimens

The increase of mass of the specimens that have been put underwater has been monitored a couple of times during a period of 18 days. 3 pieces of every species have been weighed and an average of the increase in mass compared to the first weighing is shown in figure 6.2. In the legend of figure 6.2 can the average densities be found of every sample before the samples were put underwater. Figure 6.2 shows that the tropical hardwood species with the highest densities have the slowest moisture uptake. But figure 6.2 also shows that the density is not necessarily a factor in the moisture uptake rate. This is also species dependent. Table 6.4 presents the average moisture content of the wet pieces during testing. The wet pieces were stored underwater as said between 25 and 40 days. The wet pieces have been pre-drilled on the 20^{th} day in the water and afterwards put back in the water.

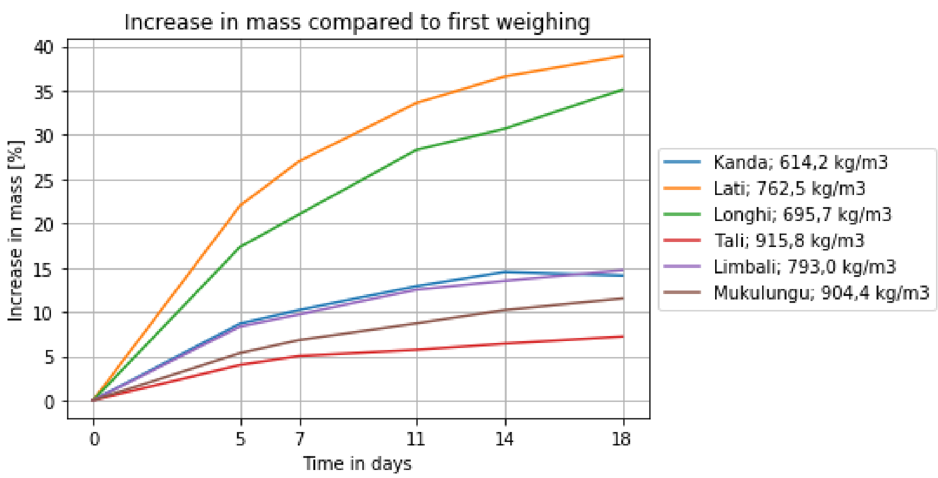

Figure 6.2: Increase of mass versus the days that the timber is underwater. Increase is compared to the weight of the timber block at day zero.

Table 6.4: Moisture content (M.C.) of the used timber species (wet).

Trade name	n samples	Av. M.C. [%]	Av. M.C. COV [%]
Kanda	12	27	25
Lati	12	577	9
Longhi	12	48	12
Tali	12	19	19
Limbali	12	25	19
Mukulungu	12	29	8

6.2.3. Visual effect of higher moisture content in timber

In figure 6.3 cross-sections are shown from every tropical hardwood species used. In table 6.5 the moisture content of the specific cross-section is reported. Also the average density has been reported in table 6.5, this relates to the overall average densities per species from table 6.1 and gives an idea of the density of the timber before being put underwater.

As can be seen in the figure 6.3 has the moisture not penetrated very deep into the wood in the case of Kanda and Tali. Lati had a very high moisture uptake as well as Longhi. Especially in the image of Longhi the moisture content is clearly visible. Also the moisture entered through the pre-drilled hole as can be seen, this is also the case for the Limbali piece where the pre-drilled hole is cut open. This shows that the moisture uptake through the inner surface of the pre-drilled hole was also significant. It has therefore been decided to include a pre-drilled hole in the dry oven slices.

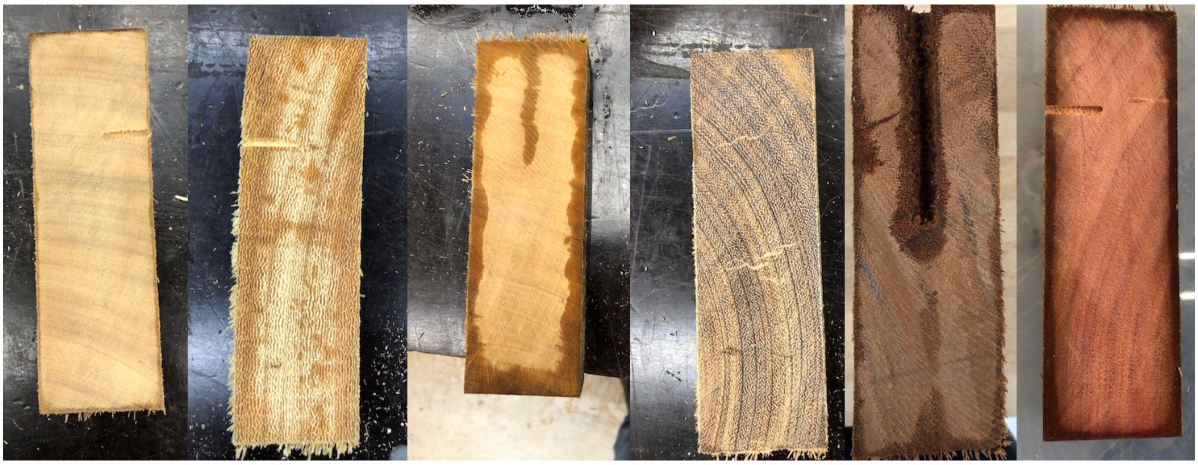

Figure 6.3: Cross-section of wet specimens from left to right: Kanda, Lati, Longhi, Tali, Limbali and Mukulungu.

Table 6.5: Test number, days under water and moisture content of the specimens shown in figure 6.3.

Trade name	Test number	days under water	M.C. [%]	Av. density (before conditioning) [kg/m^3]
Kanda	37	26	20	658
Lati	38	26	53	771
Longhi	45	27	38	683
Tali	40	26	17	973
Limbali	143	40	34	834
Mukulungu	36	30	31	931

6.3. Overview results

In this sub-chapter an overview of the test results will be presented. The main topic of this thesis is the withdrawal strength of self-tapping screws in tropical hardwood species. The results will be presented with plots of the density versus the withdrawal capacity, the slip modulus and the insertion moment. In chapter 7 the results will be examined more closely. All results from testing can be found in annex A.

In figure 6.4 examples are given from testing. The figure shows the displacement versus the withdrawal capacity, all four tests that were performed on one piece have been combined in one graph. As said, the first two tests are withdrawal strength tests the last two are stiffness tests. In figure 6.4(a) the results are shown from testing on dry lati, with self-tapping screw diameter 8 mm and insertion depth 70 mm. The density and moisture content are reported in the sub-title. The same results are shown in figure 6.4(b) but then for wet timber. The insertion moment values reported in this chapter are the values of the maximum measured insertion moments per test piece. The stiffness reported in this chapter are the mean values measured per test piece, further all data points are for the withdrawal capacity are plotted in the graphs in this chapter.

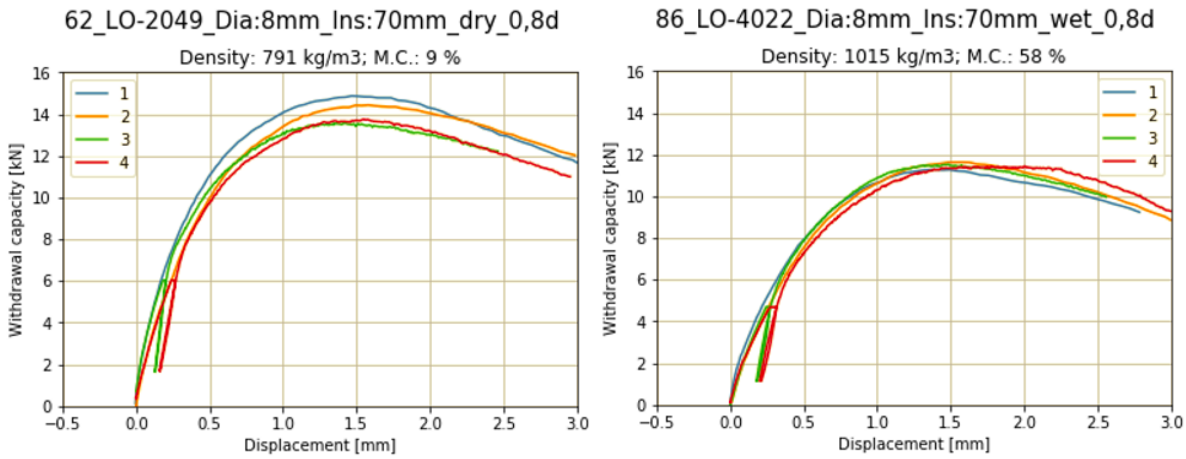

Figure 6.4: (a-left image) Results for withdrawal testing with dry lati, self-tapping screws diameter 8 mm, insertion depth 70 mm and pre-drilling diameter 0,8d. (b-Right image) Same series as in (a) but now with wet timber.

6.3.1. Results withdrawal capacity

Results diameter 6 mm

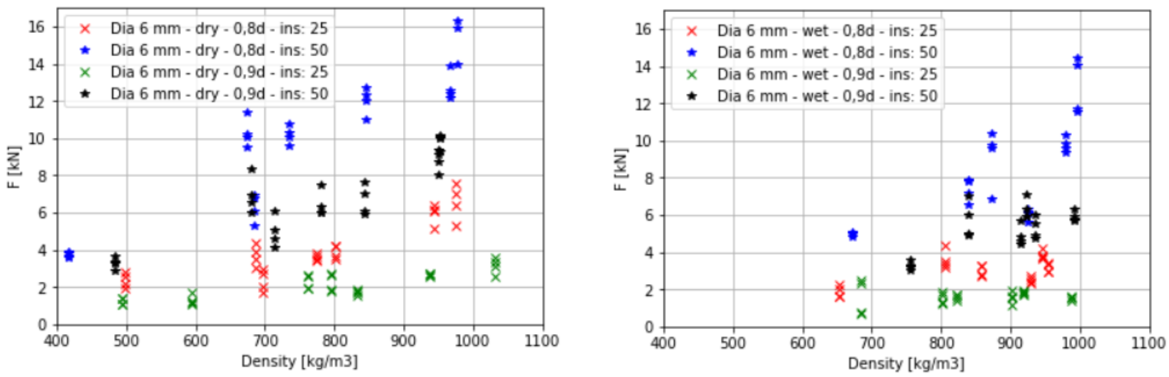

Figure 6.5: (a-left image) Density in kg/m^3 versus the withdrawal capacity in kN of dry timber, for diameter 6 mm, insertion depths 25 mm and 50 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 8 mm

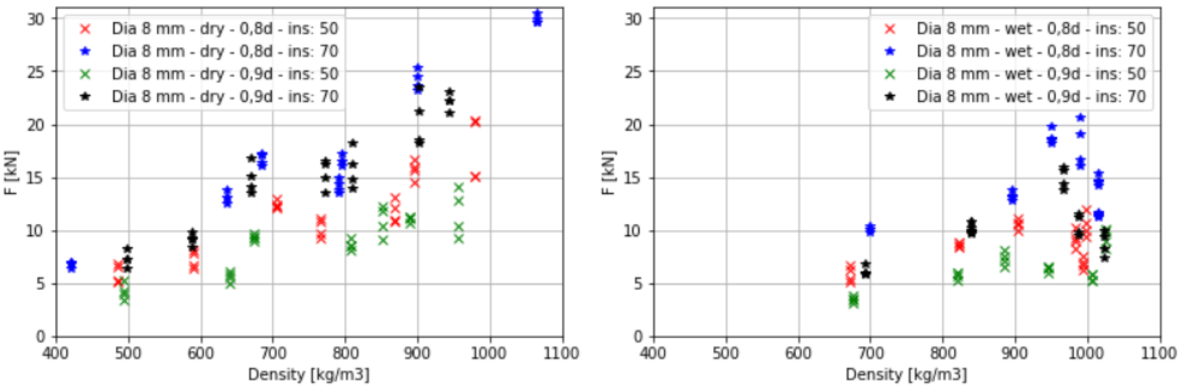

Figure 6.6: (a-left image) Density in kg/m^3 versus the withdrawal capacity in kN of dry timber, for diameter 8 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 11 mm

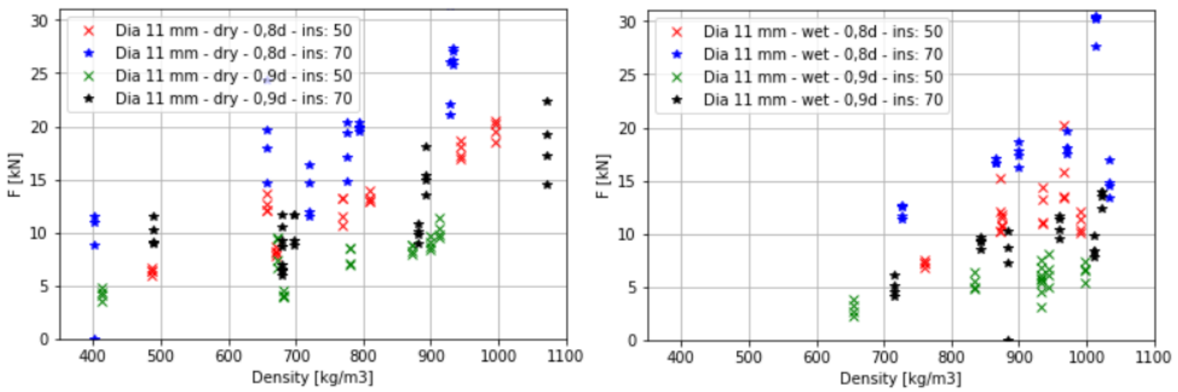

Figure 6.7: (a-left image) Density in kg/m^3 versus the withdrawal capacity in kN of dry timber, for diameter 11 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

6.3.2. Results insertion moment

Results diameter 6 mm

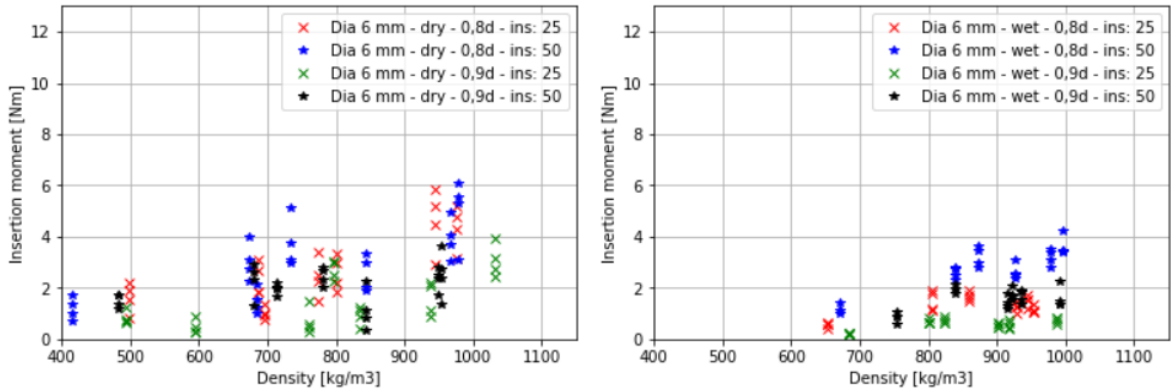

Figure 6.8: (a-left image) Density in kg/m^3 versus the insertion moment in Nm of dry timber, for diameter 6 mm, insertion depths 25 mm and 50 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 8 mm

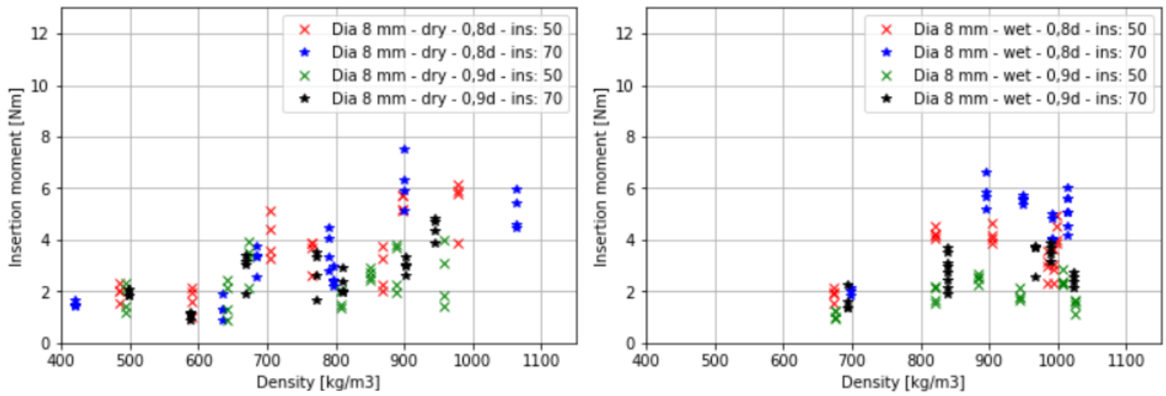

Figure 6.9: (a-left image) Density in kg/m^3 versus the insertion moment in Nm of dry timber, for diameter 8 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 11 mm

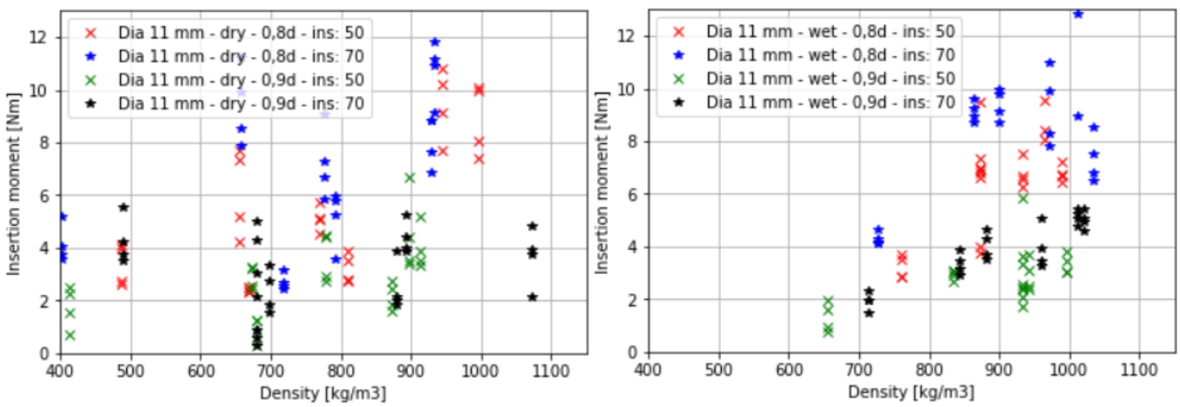

Figure 6.10: (a-left image) Density in kg/m^3 versus the insertion moment in Nm of dry timber, for diameter 11 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

6.3.3. Results slip modulus

Results diameter 6 mm

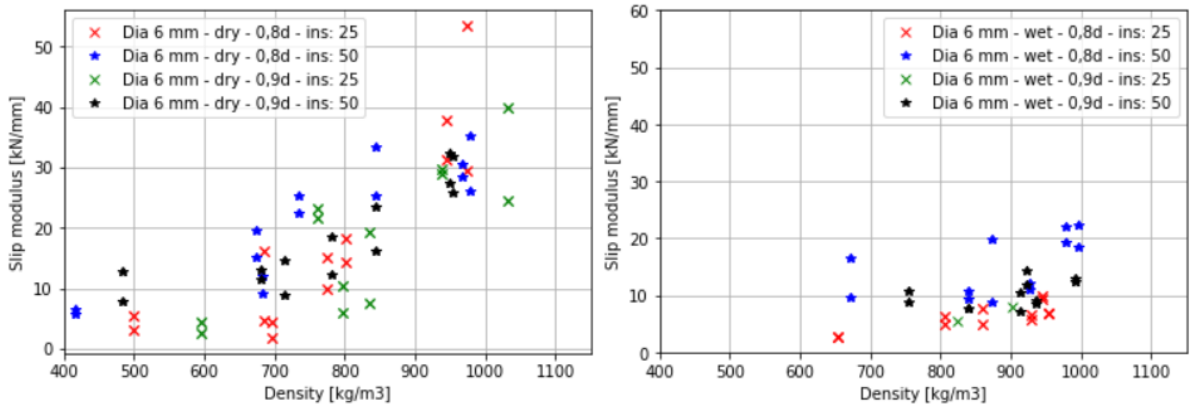

Figure 6.11: (a-left image) Density in kg/m^3 versus the slip modulus in kN/mm of dry timber, for diameter 6 mm, insertion depths 25 mm and 50 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 8 mm

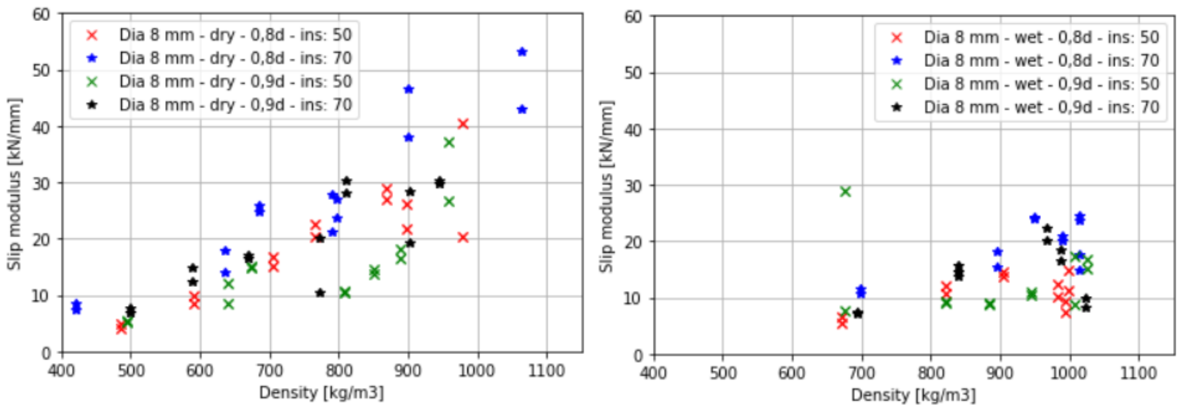

Figure 6.12: (a-left image) Density in kg/m^3 versus the slip modulus in kN/mm of dry timber, for diameter 8 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

Results diameter 11 mm

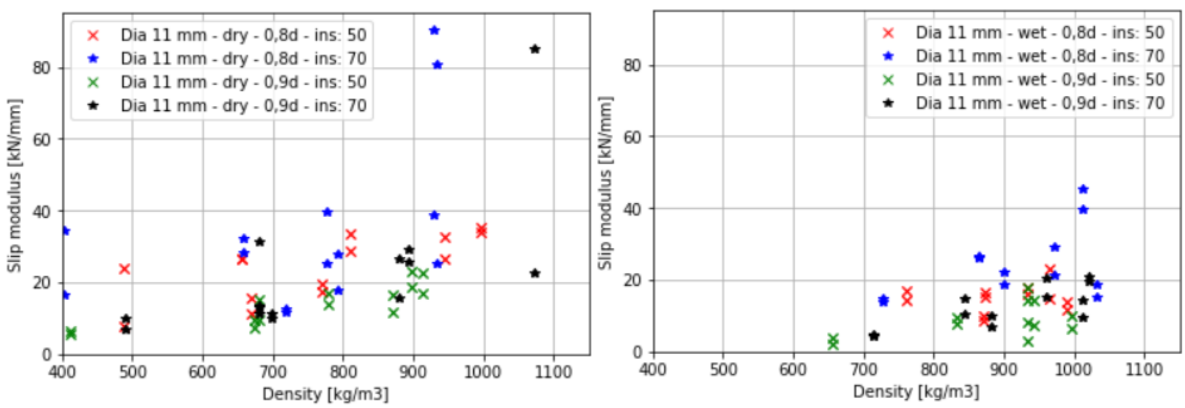

Figure 6.13: (a-left image) Density in kg/m^3 versus the slip modulus in kN/mm of dry timber, for diameter 11 mm, insertion depths 50 mm and 70 mm and pre-drilling diameters 0,8-0,9d. (b-Right image) Same results for wet timber.

7 Analysis

In chapter 6 the experimental results were presented. In this chapter these results will be analyzed. First of all will physical observations that were done during or after testing be analyzed. After this the following subjects will be elaborated:

- Analysis of the measured withdrawal strength;
- Analysis of the measured insertion moment;
- Analysis of the measured slip modulus;

A complete overview of every test can be found in annex A. To determine the withdrawal strength (fax) from the withdrawal capacity (Fax) in this chapter the following formula has been used:

$$f_{ax} = \frac{F_{ax}}{d * \pi * l_{eff}} \tag{7.1}$$

How the slip modulus was determined can be found in chapter 3.2 and how the insertion moment was determined can be found in chapter 3.5.

7.1. Observed failure modes

Since the distance between the test piece edge and the self-tapping screw was not according to EN 1382:2016 (chapter 3.1), problems could occur such as cracking of the timber during screw insertion or during testing. It turned out that this was not a problem and that the edge distances were sufficient for these tests. During pre-testing (chapter 4.2) the main failure that could be observed was withdrawal failure, and in one case screw steel tensile failure. During pre-testing it could be observed that splinters were pulled out in fiber direction. For the main test series only withdrawal failure was observed, no steel tensile failure. This mainly has to do with the fact that the insertion depth was reduced for the main test series compared to the pre-test series.

7.1.1. Observed timber defects - surface

For the majority of the main tests little to no defects could be observed on the timber after testing. For the tropical hardwood species with high densities like Tali and Mukulungu in some cases failure modes as shown in figure 7.1 were observed. In those cases fibres were separated from each other due to the withdrawal of the self-tapping screw and caused cracking in fiber direction.

Figure 7.1: Cracks around pre-drilled hole.

In very rare cases large cracks could be observed in fibre direction on the side of the test pieces. In figure 7.2 an example of this is shown. This usually happened in the case of the largest self-tapping screw that was used (diameter 11 mm) and very high timber densities. In the case of the Tali timber in figure 7.2 the density was 995,3 kg/m^3.

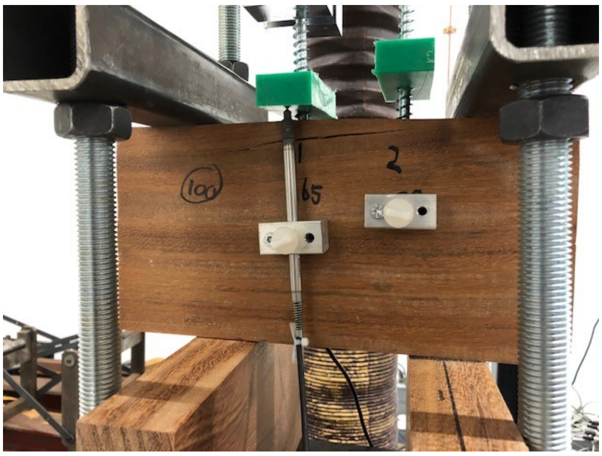

Figure 7.2: Cracking of Tali piece during testing visible above the mounting piece of the displacement sensor, on the side of the timber block. Cracking is in fibre direction.

7.1.2. Observed timber defects - cross-section of pre-drilled hole

From every test series the timber specimen with the highest and the lowest density have been sawn open to see what the effect of withdrawal tests was on the timber inside the pre-drilled hole. The most commonly observed cross-section was the one shown in figure 7.3(a). In figure 7.3(a) the thread in the timber is visible and is slightly expanded upwards due to tensile loading of the screw. In some specimens with a lower density and generally when the pre-drilled hole was 0,9d the screw thread pulverised the pattern the thread made into the pre-drilled hole, this can be seen in figure 7.3(b).

In extreme cases the screw completely pulled out a part of the timber, separating the timber fibres in fibre direction. This is clearly visible in figure 7.3(c-d). In figure 7.3(c) the pulled out timber is very clearly shown, the pulled out part had a length similar to the effective length of the screw.

The observed failure patterns can be grouped in:

- Screw slipping out of pre-drilled hole (figure 7.3(a) and (b));
- Screw pulling out the timber (figure 7.3(c) and (d));

Figure 7.3: (a-first image) Test 136 Kanda with screw diameter 11 mm, insertion depth 70 mm and pre-drilled hole 0,8d. (b-second image) Test 139 Tali with screw diameter 11 mm, insertion depth 70 mm and pre-drilled hole 0,8d. (c-third image) Pre-test 112 with screw diameter 11 mm, insertion depth 50 mm and pre-drilled hole 0,7d; the image shows the other side of the cut. (d-fourth image) Also pre-test 112 but now the full pre-drilled hole is visible.

7.1.3. Observed self-tapping screw defects

In rare cases defects were visible on the self-tapping screws after testing, an example is shown in figure 7.4. The figure shows the thread of the screw being bend opposite to the withdrawal direction. Figure 7.4 shows the defects of the screw used on specimen 106 which was a tali specimen with a density of 913 kg/m^3. The used diameter was 11 mm, the insertion depth was 50 mm and the pre-drilled hole was 0,9d. This defect was only observed on screws used in very high density timber (above 900 kg/m^3), but not in every case. This was also only observed on the 11 mm VGS screws not on the HSBH screws. This might be due to the fact that the ratio between the outer thread diameter and inner diameter is smaller for the HSBH screws.

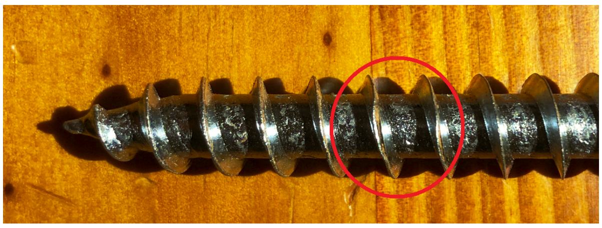

Figure 7.4: Defects on screw after testing - test piece 106.

7.2. Analysis of the withdrawal strength of self-tapping screws in tropical hardwood

In figure 7.5 the measured withdrawal strength for screw diameter 8 mm is plotted in data points versus the adjusted timber density. Fit lines are plotted through these data points and a distinction has been made for different pre-drilling diameters and insertion depths. The same has been done for screw diameter 8 mm in figure 7.6 and for screw diameter 11 mm in figure 7.7. Figure 7.5, 7.6 and 7.7 show that with increasing density also the withdrawal strength increases. This is as expected and was also found in the literature study. Figure 7.5, 7.6 and 7.7 also show that using a 0,9d pre-drilling diameter decreases the withdrawal strength significantly and that there is no clear difference in the withdrawal strength for varying insertion depths when looking at the 0,8d pre-drilling results. A difference can be seen in the case of pre-drilling 0,9d in withdrawal strength results for varying insertion depths.

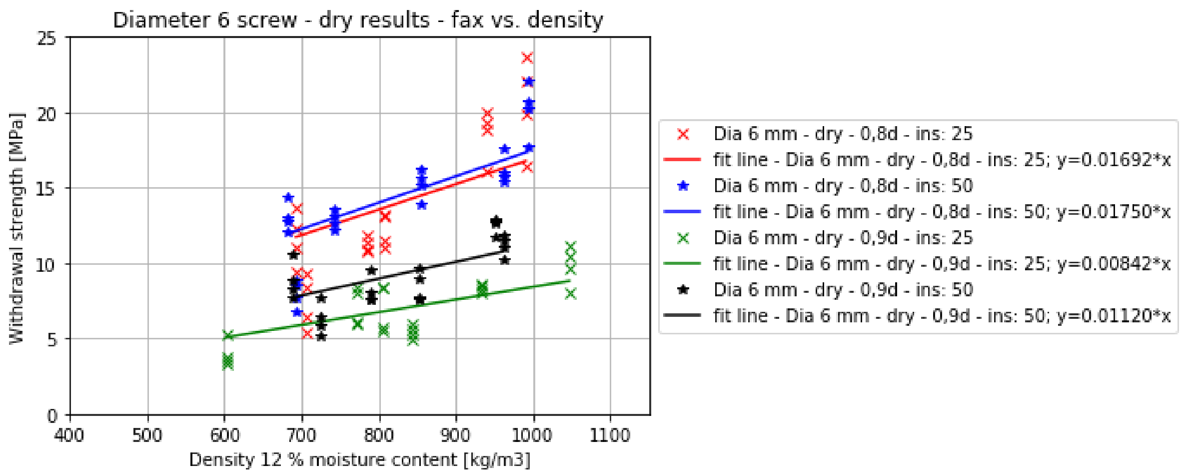

Figure 7.5: Withdrawal strength vs. adjusted timber density to 12 % moisture content for screw diameter 6 mm.

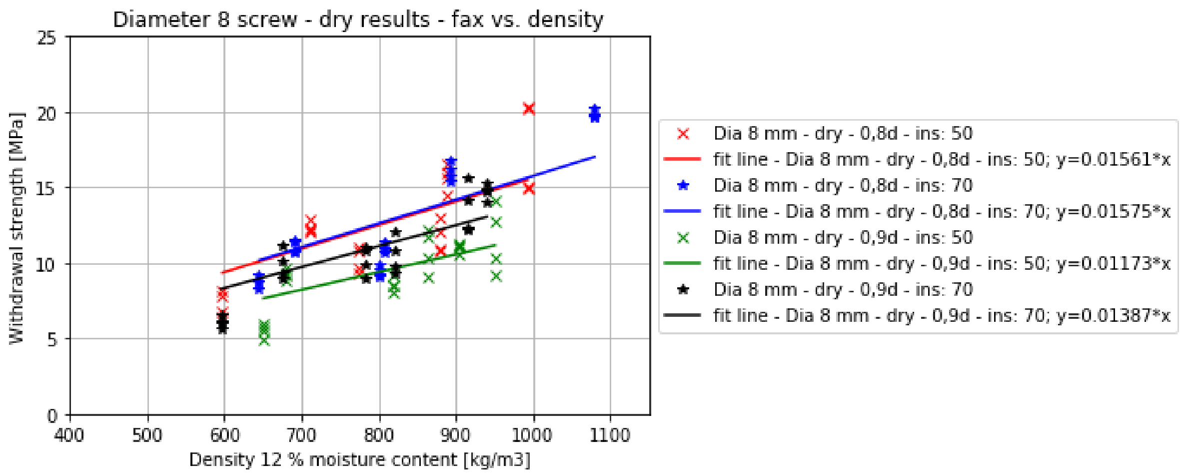

Figure 7.6: Withdrawal strength vs. adjusted timber density to 12 % moisture content for screw diameter 8 mm.

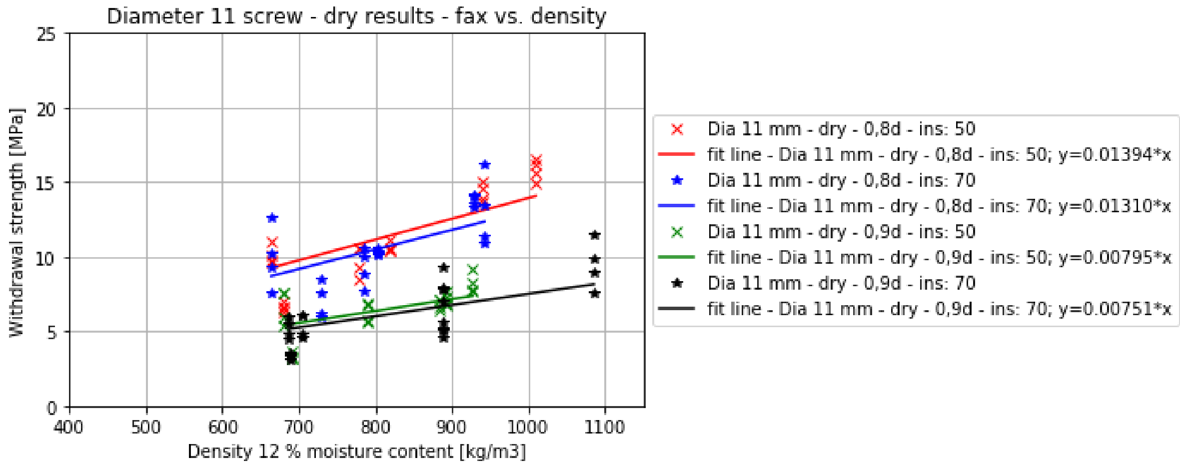

Figure 7.7: Withdrawal strength vs. adjusted timber density to 12 % moisture content for screw diameter 11 mm.

7.2.1. Influence of timber density on the withdrawal strength

The variation in timber density during testing has been achieved by using different timber species as has been mentioned before. It is important to find out what the influence of the timber species is on the withdrawal strength to make good comparisons. Figure 7.8 shows a box plot of the various timber species used during dry testing.

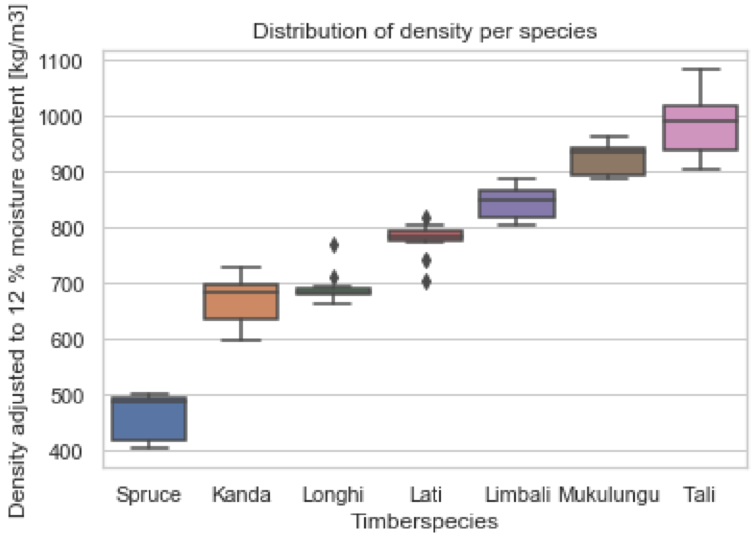

Figure 7.8: Density measured per tested species.

In figure 7.9 a box plot is shown of the measured average withdrawal strength from dry testing per species, a distinction has been made between pre-drilling 0,8d and 0,9d. Again, in figure 7.9 the difference between the pre-drilling diameters is clear. Mean withdrawal strengths related to figure 7.9 can be found in table 7.1. By comparing figure 7.8 and figure 7.9 it is again clear that with increasing density the withdrawal strength increases, but the influence of every species is not very clear. This is made clear in figure 7.10.

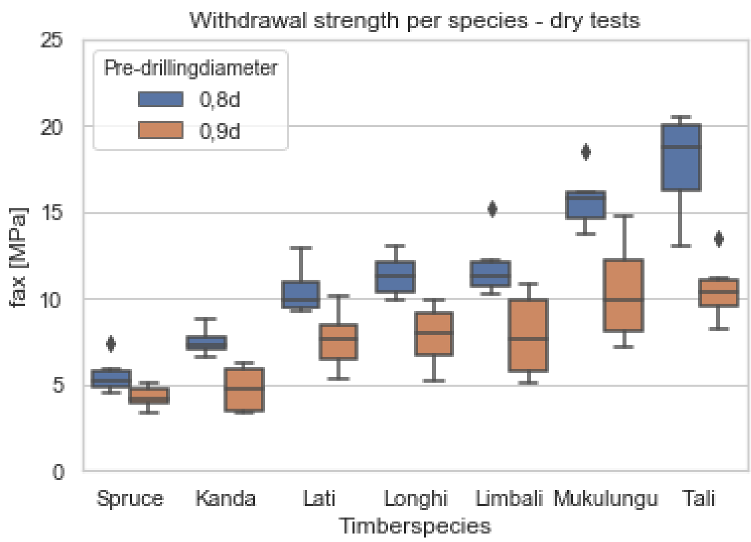

Figure 7.9: Withdrawal strength vs. timber species for pre-drilling 0,8d and 0,9d.

Table 7.1: Mean withdrawal strengths per species divided for pre-drilling 0,8d and 0,9d from dry testing.

Species	fax mean [MPa]	COV fax mean [%]	5^{th} percentile [MPa]
Spruce 0,8d	5,51	19	4,55
Spruce 0,9d	4,28	15	3,53
Kanda 0,8d	7,49	10	6,71
Kanda 0,9d	4,74	29	3,33
Lati 0,8d	10,44	13	9,29
Lati 0,9d	7,57	23	5,57
Longhi 0,8d	11,34	11	9,96
Longhi 0,9d	7,81	23	5,54
Limbali 0,8d	11,83	15	10,37
Limbali 0,9d	7,85	31	5,20
Tali 0,8d	17,82	14	16,72
Tali 0,9d	10,53	17	8,55
Mukulungu 0,8d	15,73	11	13,89
Mukulungu 0,9d	10,37	29	7,39

In figure 7.10 the average withdrawal strength per test piece has been divided by the timber density per test piece. Mean values relating to figure 7.10 can be found in table 7.2. As can be seen although Spruce had on average the lowest density and withdrawal strength, Spruce does not have the lowest withdrawal strength to density ratio. Kanda has the lowest withdrawal strength to density ratio with a mean of 0,011 for pre-drilling 0,8d, while the average density of Spruce was 465 kg/m^3 and for Kanda was 657 kg/m^3. Tali and Mukulungu have on average the highest density and withdrawal strength and also the highest withdrawal strength to density ratio. The withdrawal strength to density ratio of Limbali also stands out which is lower than the withdrawal strength to density ratio compared to Longhi, while Longhi has an average density of 683 kg/m^3 and Limbali an average density of 833 kg/m^3. This shows that the timber species does have influence on the withdrawal strength and it is important to keep this in mind during further analysis.

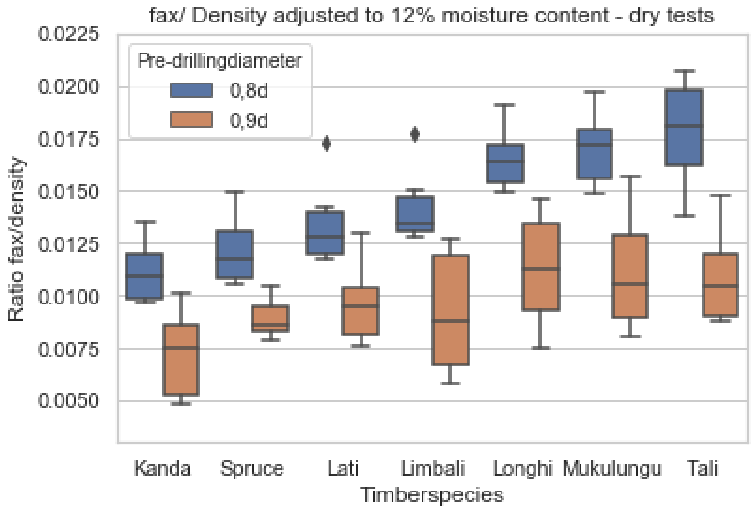

Figure 7.10: Withdrawal strength divided by density adjusted to 12 % moisture content vs. timber species for pre-drilling 0,8d and 0,9d.

Table 7.2: Mean withdrawal strengths divided by adjusted density to 12 % moisture content per species, for pre-drilling 0,8d and 0,9d.

Species	fax/dens. mean *10^{-2} [MPa/(kg/m^3)]	COV fax/dens. mean [%]
Spruce 0,8d	1,22	14
Spruce 0,9d	0,89	11
Kanda 0,8d	1,11	14
Kanda 0,9d	0,72	30
Lati 0,8d	1,35	16
Lati 0,9d	0,97	21
Longhi 0,8d	1,66	9
Longhi 0,9d	1,12	25
Limbali 0,8d	1,43	13
Limbali 0,9d	0,92	33
Tali 0,8d	1,76	15
Tali 0,9d	1,09	22
Mukulungu 0,8d	1,70	11
Mukulungu 0,9d	1,11	27

7.2.2. Influence of screw diameter on the withdrawal strength

In this sub-chapter the influence of the screw diameter on the withdrawals strength is analyzed. In research described in chapter 2.6.4 it was found that the withdrawal strength decreases with increasing screw diameter. All data shown in this sub-chapter is from dry testing.

Figure 7.11 shows a box plot of the withdrawal strength versus the tested screw diameters, mean values can be found in table 7.3. Figure 7.11 shows that on average the withdrawal strength decreases with increasing diameter as was found in research in the case of 0,8d pre-drilling. This is not the case when looking at the results for 0,9d pre-drilling. In this case the diameter 8 mm screw has on average a higher withdrawal strength compared to the diameter 6 mm screw which is 0,9d pre-drilled.

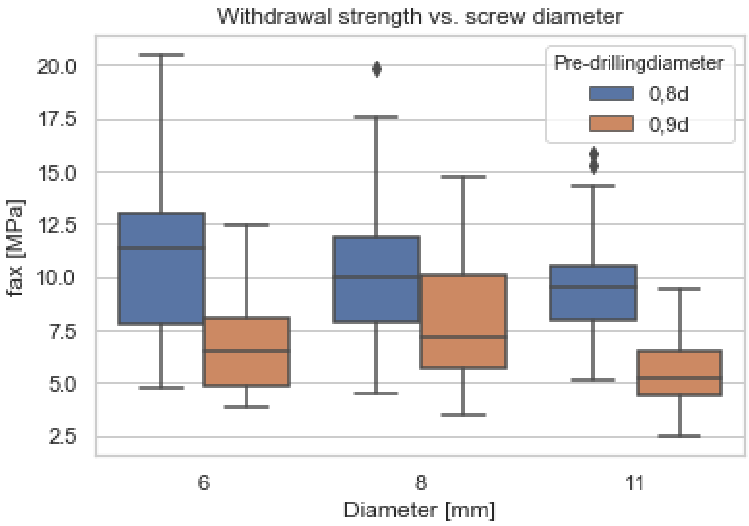

Figure 7.11: Withdrawal strength vs. screw diameter.

Table 7.3: Mean values from the withdrawal strengths shown in figure 7.11.

Screw diameter [mm]	fax mean value [MPa]	COV fax mean [%]
6 - 0,8d	12,78	39
6 - 0,9d	7,49	35
8 - 0,8d	11,50	39
8 - 0,9d	9,33	34
11 - 0,8d	10,07	33
11 - 0,9d	5,96	32

In this sub-chapter ratio's have been calculated, where the diameter 6 mm screw is the reference. The withdrawal strength of the diameter 8 mm or 11 mm screw has been divided by the reference withdrawal strength of the diameter 6 mm screw. In this comparison all other parameters are the same, so for example the withdrawal strength result from test 106 (Tali; diameter 11 mm screw; pre-drilling 0,9d; timber condition: dry) has been divided by the withdrawal strength result from test 10 (Tali; diameter 6 mm screw; pre-drilling 0,9d; timber condition: dry). The ratio's from these comparisons can be found in figure 7.12 where the ratio's are grouped by species and diameter and in figure 7.13 where the ratio's are grouped by diameter, mean values from figure 7.13 can be found in table 7.4.

Again in oppose to literature described in chapter 2.6.4 is the withdrawal strength of the diameter 8 mm screw (0,9d pre-drilling) higher while it would be expected that this value would be lower compared to the diameter 6 mm screw. A reason for this could be that the diameter 6 mm and 8 mm screws are special hardwood screws with a larger inner diameter compared to the diameter 11 mm screw which is a regular screw. Another reason could be the precision of pre-drilling, because it is not possible to make a pre-drilled hole which is exactly 0,9d or 0,8d. In the case of 0,8d pre-drilling the results are again as expected: decreasing withdrawal strength with increasing diameter.

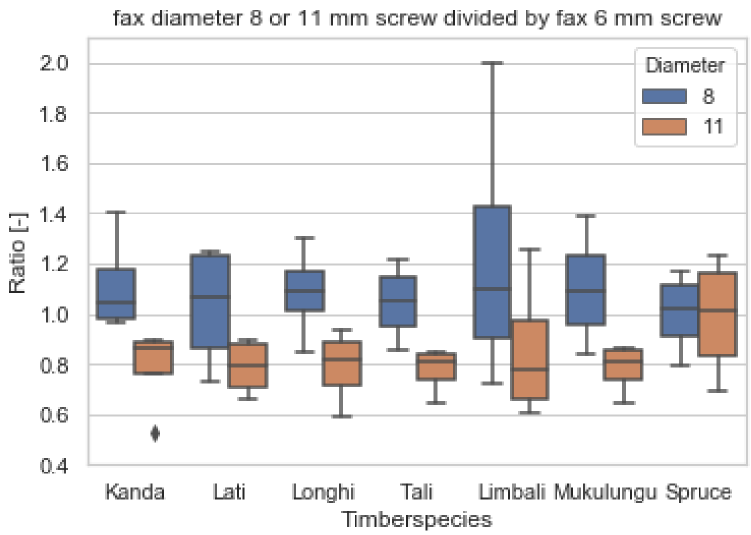

Figure 7.12: Withdrawal strength of 8 mm and 11 mm diameter screws divided by the withdrawal strength of 6 mm screws from the same species, effective length and pre-drilling diameter.

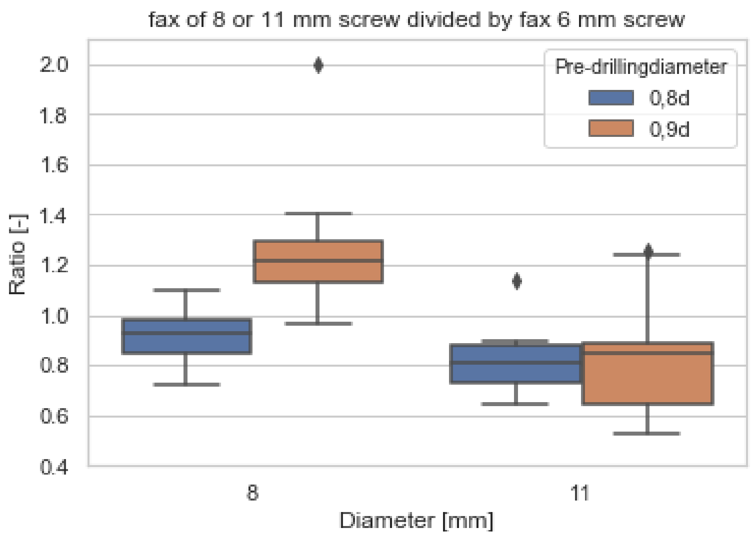

Figure 7.13: Same results as in figure 7.12 but now grouped by diameter.

Table 7.4: Mean values from the ratios shown in figure 7.13, except for screw diameter 6 mm which is the reference for these ratios.

Screw diameter [mm]	fax own/ fax dia. 6 mm mean value [-]	COV fax own/ fax dia. 6 mm [%]
6 0,8d and 0,9d	1 (reference)	-
8 - 0,8d	0,91	13
8 - 0,9d	1,26	19
11 - 0,8d	0,82	16
11 - 0,9d	0,83	26

7.2.3. Influence of pre-drilling diameter on the withdrawal strength

Figure 7.14 shows the difference in displacement versus withdrawal capacity between 0,8d pre-drilling (figure 7.14(a)) and 0,9d pre-drilling (figure 7.14(b)). In this case tests done on Kanda with screw diameter 8 mm and insertion depth 70 mm (effective length 60 mm). Both graphs show 2 withdrawal test results and two stiffness test results. As can be seen the results for 0,9d pre-drilling are lower compared to 0,8d pre-drilling, note that the density in the case for 0,9d is also slightly lower. As is also made clear in figure 7.14(b) the maximum withdrawal capacity is lower but is reached around the same displacement as for 0,8d pre-drilling. The 0,9d displacement curve has a less steep way to the maximum capacity compared to 0,8d.

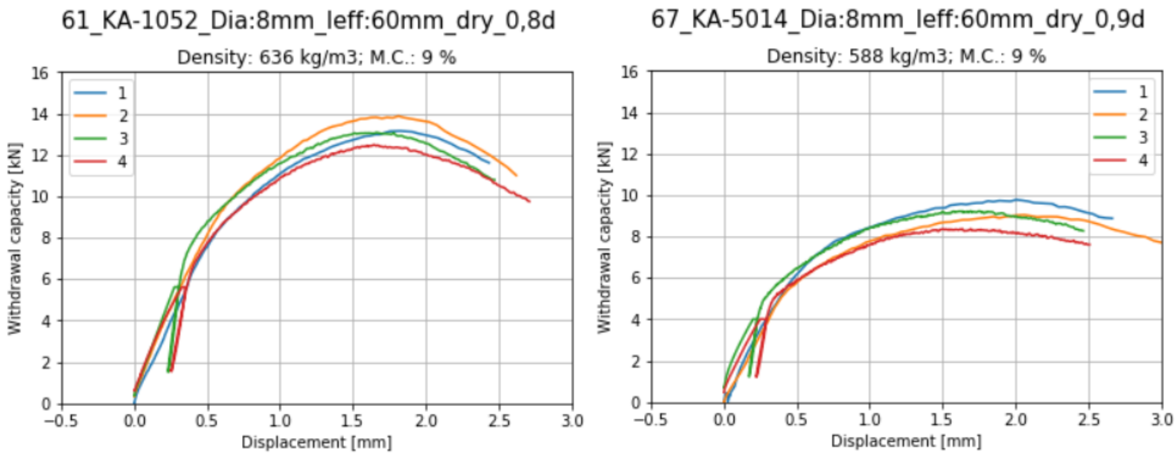

Figure 7.14: (a-left image) Displacement versus withdrawal capacity for dry specimen Kanda with pre-drilling diameter 0,8d, screw diameter 8 mm and insertion depth 70 mm resulting in effective length 60 mm. (b-right image) Same graph for 0,9d.

In this sub-chapter the influence of pre-drilling on the withdrawal strength is investigated. Ratio's have been calculated where the withdrawal strength of a 0,9d pre-drilled specimen is divided by the withdrawal strength of a 0,8d pre-drilled specimen. An example is that the average maximum withdrawal strength of test 67 is divided by the average maximum withdrawal strength of test 61 (see figure 7.14), so in these ratios only the pre-drilled hole varies and all other parameters are the same (species, insertion depth, screw diameter and timber condition). All values mentioned in this sub-chapter are taken from dry tests.

Figure 7.15 shows the ratio's grouped per species. Mean values from figure 7.15 can be found in table 7.5. Looking at the mean values in table 7.5 big differences between the species can not be observed.

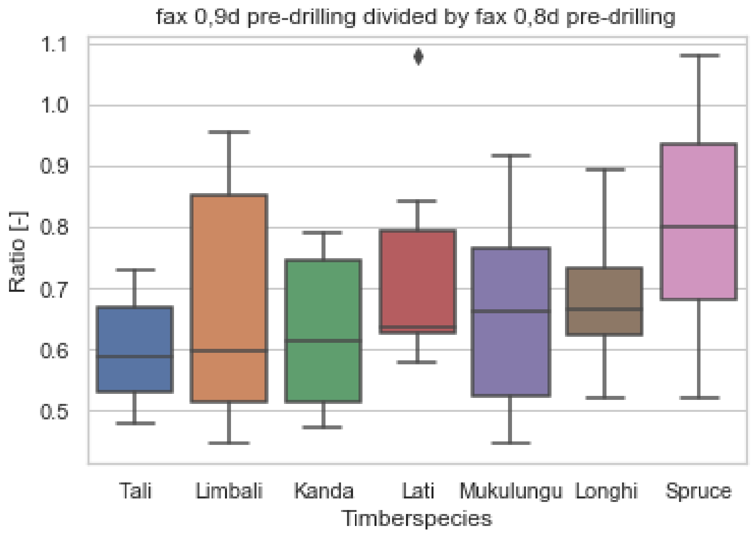

Figure 7.15: Mean withdrawal strength results for 0,9d testing divided by results for 0,8d testing, the boxplot shows the ratios per species.

Table 7.5: Mean values from the ratios shown in figure 7.15.

Species	fax0,9d/fax0,8d mean value [-]	COV fax0,9d/fax0,8d [%]
Spruce	0,80	25
Kanda	0,63	22
Lati	0,73	26
Longhi	0,69	19
Limbali	0,67	33
Tali	0,60	16
Mukulungu	0,66	27

Figure 7.16 shows the 0,9d pre-drilling to 0,8d pre-drilling ratio's grouped by screw diameter. Figure 7.17 shows all values combined, table 7.6 shows the mean values of the ratio's shown in figure 7.16 and 7.17. As can be seen is the influence of pre-drilling very similar for screw diameters 6 mm and 11 mm. The diameter 8 mm screw yields on average higher results when pre-drilled 0,9d when compared to the other diameters. This was also already observed in chapter 7.2.2 regarding the influence of the screw diameter on the withdrawal strength. The reason for this is unknown since both the 6 mm and 8 mm screws are special hardwood screws while the 11 mm screw is a 'regular' screw. Differences could be the result of rounding off the pre-drilled hole diameter, since drill sizes are not available all sizes precise. If the actual pre-drilled ratio is calculated for every screw diameter that should be pre-drilled 0,9d this would be: 0,92d for diameter 6 mm; 0,88d for diameter 8 mm and 0,91d for diameter 11 mm. This shows that the actual pre-drilled hole in the case of the diameter 8 mm screw is the smallest and might be the reason for the higher withdrawal strength. It can be concluded that pre-drilling with 0,9d has a negative effect compared to pre-drilling 0,8d.

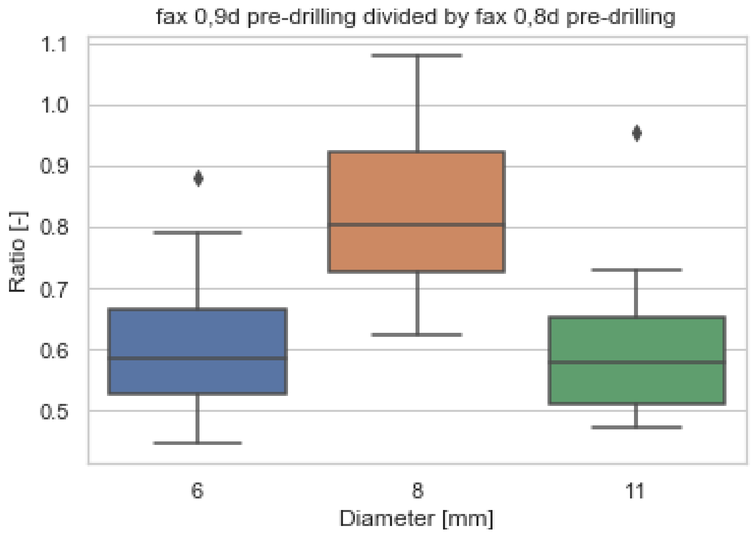

Figure 7.16: Mean withdrawal strength results for 0,9d testing divided by results for 0,8d testing, the boxplot shows the ratios per screw diameter.

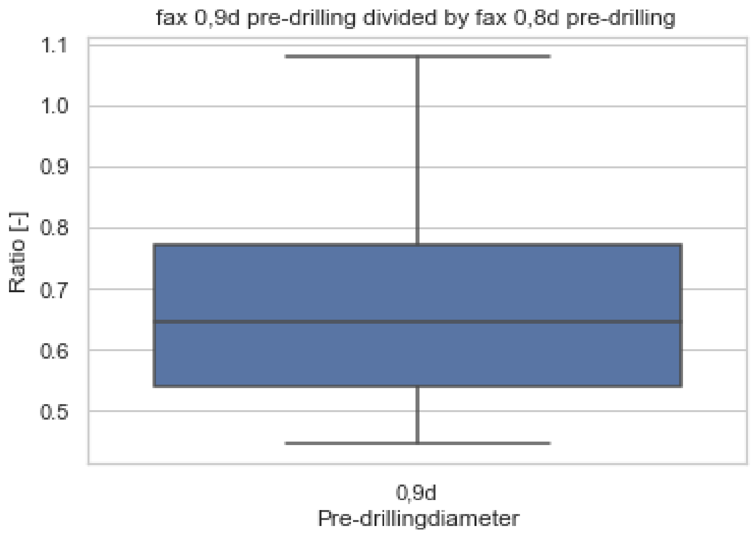

Figure 7.17: Mean withdrawal strength results for 0,9d testing divided by results for 0,8d testing, the boxplot shows the ratio of all results combined. The results for 0,8d pre-drilling are the reference and therefore has a value of 1.

Table 7.6: Mean values from the ratio shown in figure 7.16 and figure 7.17.

Diameter	fax0,9d/fax0,8d mean value [-]	COV fax0,9d/fax0,8d [%]
6	0,61	21,70
8	0,83	17,44
11	0,60	21,02
All	0,68	24,97

7.2.4. Influence of effective length of screws on the withdrawal strength

The displacement-withdrawal capacity curve shown in figure 7.18 are the results from withdrawal testing done on dry Lati specimens with 0,8d pre-drilling and diameter 8 mm. The difference is the insertion depth which is for figure 7.18(a) and figure 7.18(b) respectively 50 mm (effective length 40 mm) and 70 mm (effective length 60 mm). Figure 7.18 is an example to show the effect of less insertion depth on the displacement-withdrawal capacity curve. As could be expected yields the shorter insertion depth lower results in terms of withdrawal capacity (kN).

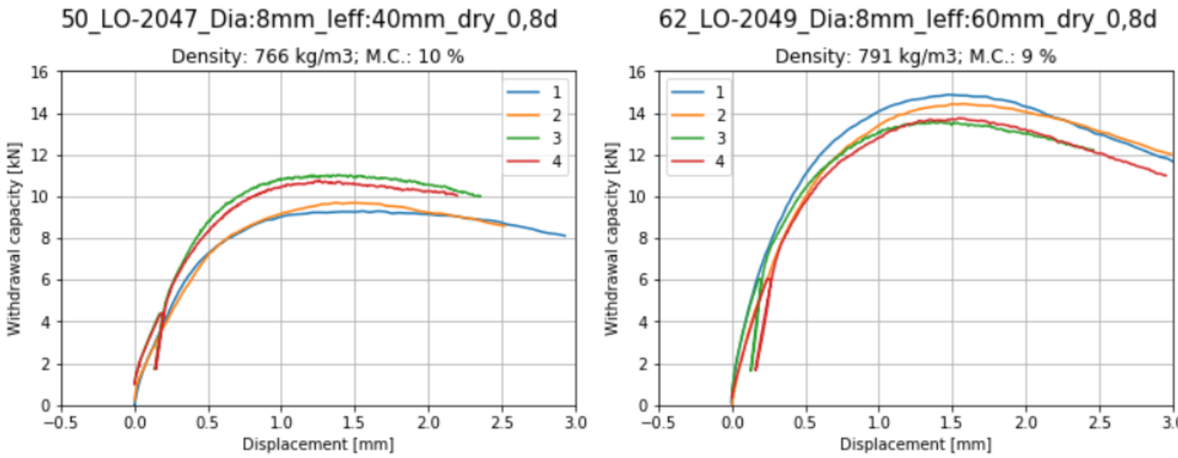

Figure 7.18: (a-left image) Displacement versus withdrawal capacity for tests done on dry Lati with screw diameter 8 mm, pre-drilling diameter 0,8d and insertion depth 50 mm. (b-right image) Same results but then for insertion depth 70 mm.

In research described in chapter 2.6.6 it was found that the effective length has no influence on the withdrawal strength. Figure 7.19 shows a box plot of the withdrawal strength of every effective length measured from dry testing grouped by screw diameter. Figure 7.20 shows a box plot where for every screw diameter the withdrawal strength of the shortest effective length has been divided by the longest effective length, so for example the withdrawal strength from test number 50 (Diameter: 8 mm; effective length: 40 mm; Species: Lati; pre-drilling diameter: 0,8d) was divided by the withdrawal strength of test number 62 (Diameter: 8 mm; effective length: 60 mm; Species: Lati; pre-drilling diameter: 0,8d). Mean values corresponding to figure 7.20 can be found in table 7.7. From figure 7.20 and table 7.7 it can be observed that there is no clear influence of the effective length on the withdrawal strength in the case of 0,8d pre-drilling. Also for pre-drilling 0,9d in the case of the diameter 11 mm screw there if no clear influence that can be observed. In the case of the diameter 6 mm screw and 8 mm screw with 0,9d pre-drilled holes there is some influence that can be observed. The 6 mm and 8 mm screw are different types of screws, these are HSBH hardwood screws with an increased inner diameter while the 11 mm screw is a regular VGS screw. It might be that the withdrawal strength is not optimal with a larger pre-drilling diameter. What exactly the reason is for these differences remains inconclusive.

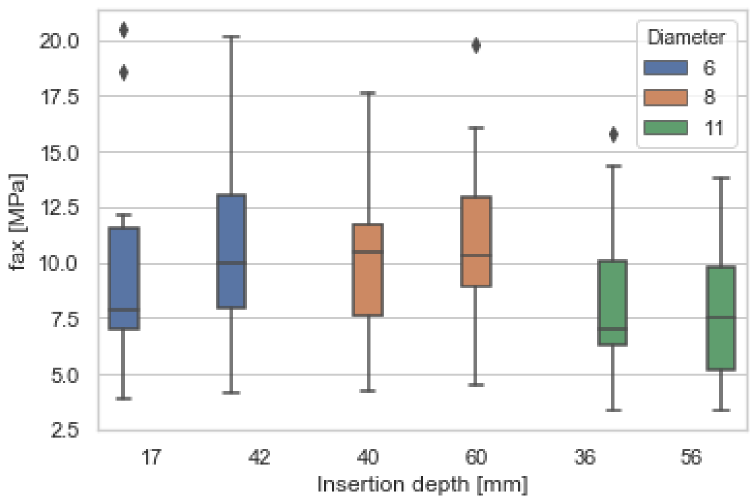

Figure 7.19: Boxplot of the withdrawal strength vs. the effective screw length grouped by diameter.

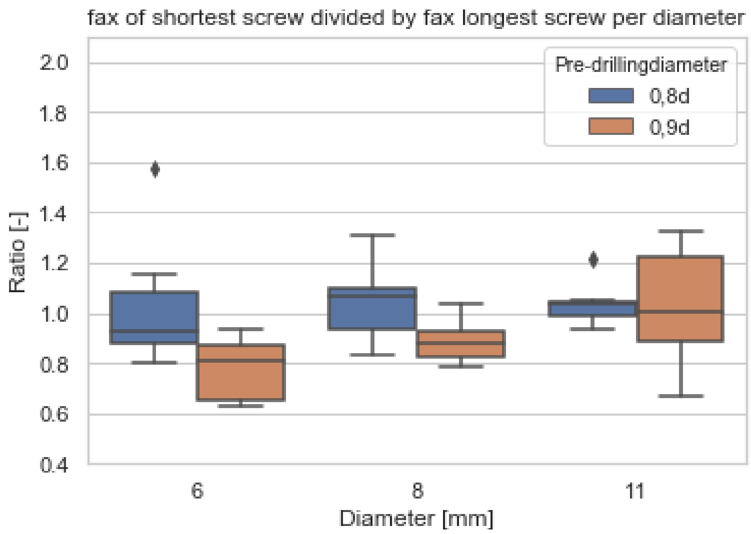

Figure 7.20: Boxplot where for every screw diameter the withdrawal strength of the shortest effective screw length is divided by the withdrawal strength of the longest effective screw length; where all other parameters such as timber species and pre-drilling diameter (and also the diameter of course) are the same.

Table 7.7: Mean ratio values corresponding to figure 7.20.

Diameter	fax short/fax long mean value [-]	COV fax short/fax long [%]
6 - 0,8d	1,03	25
6 - 0,9d	0,77	16
8 - 0,8d	1,04	15
8 - 0,9d	0,89	10
11 - 0,8d	1,04	9
11 - 0,9d	1,03	23

7.2.5. Influence of moisture content on the withdrawal strength

In figure 7.21 results are shown of tests done on Lati specimens with screw diameter 8 mm, insertion depth 70 mm and pre-drilling diameter 0,8d. Figure 7.21(a) shows the results from dry tests, figure 7.21(b) shows the results from wet tests. In the sub-titles of figure 7.21(a) and figure 7.21(b) the density is not adjusted to 12 %. Figure 7.21(b) clearly shows the effect of a higher moisture content, in this case 58 %. The maximum withdrawal capacity is significantly reduced.

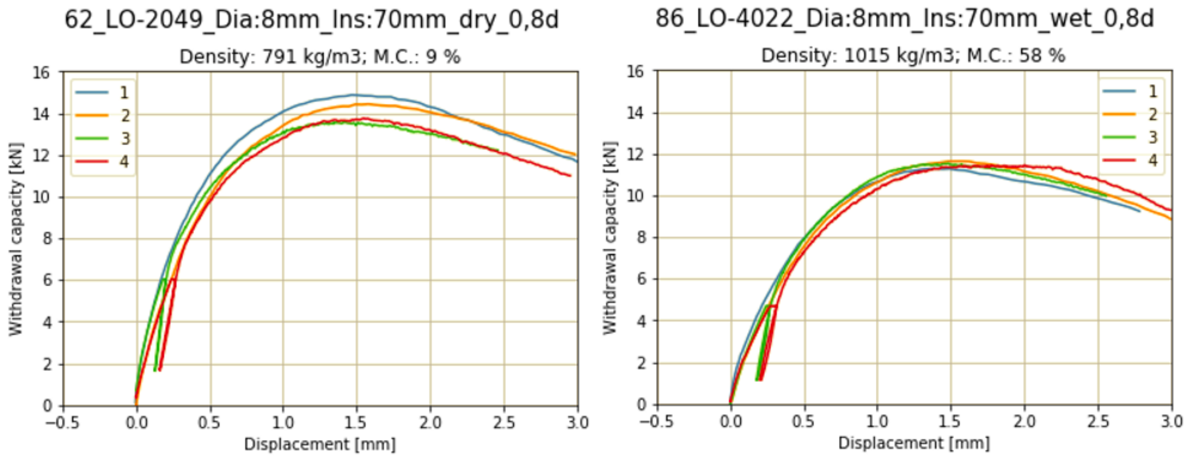

Figure 7.21: (a-left image) Displacement versus withdrawal capacity for tests done on dry Lati with screw diameter 8 mm, pre-drilling diameter 0,8d and insertion depth 70 mm. (b-right image) Same results but then for wet specimens.

Figure 7.21 all ready showed the influence of an increased moisture content on the withdrawal capacity. In the following graphs the influence of the moisture content is visualized by plotting the withdrawal strength versus the moisture content per tested species.

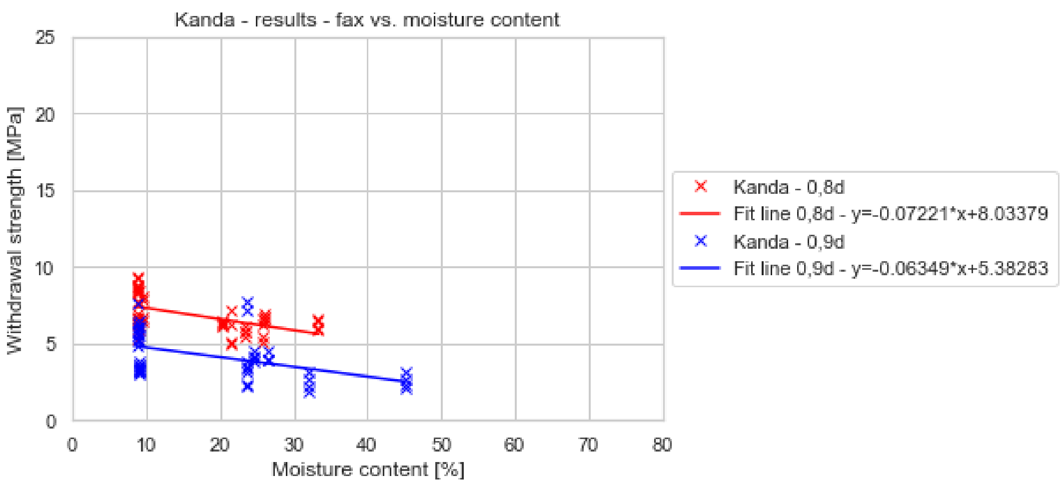

Figure 7.22: Withdrawal strength vs. moisture content from Kanda test specimens.

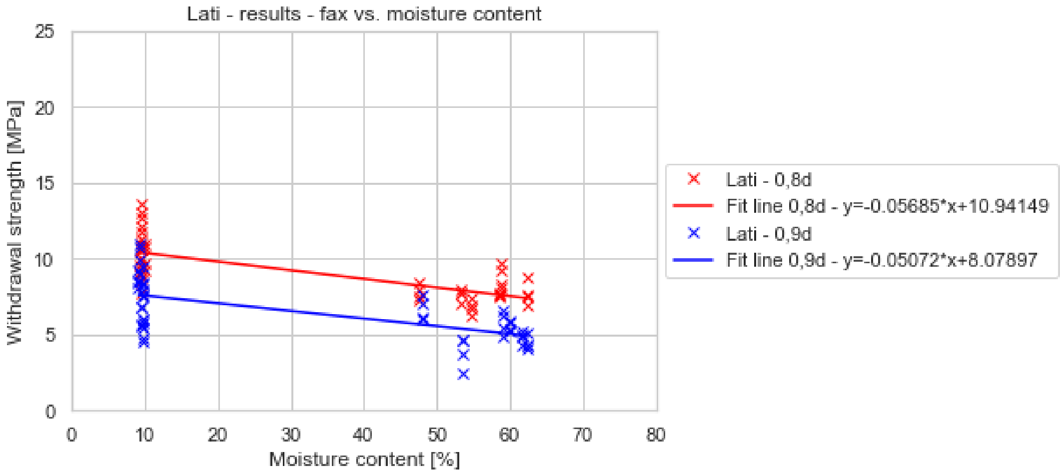

Figure 7.23: Withdrawal strength vs. moisture content from Lati test specimens.

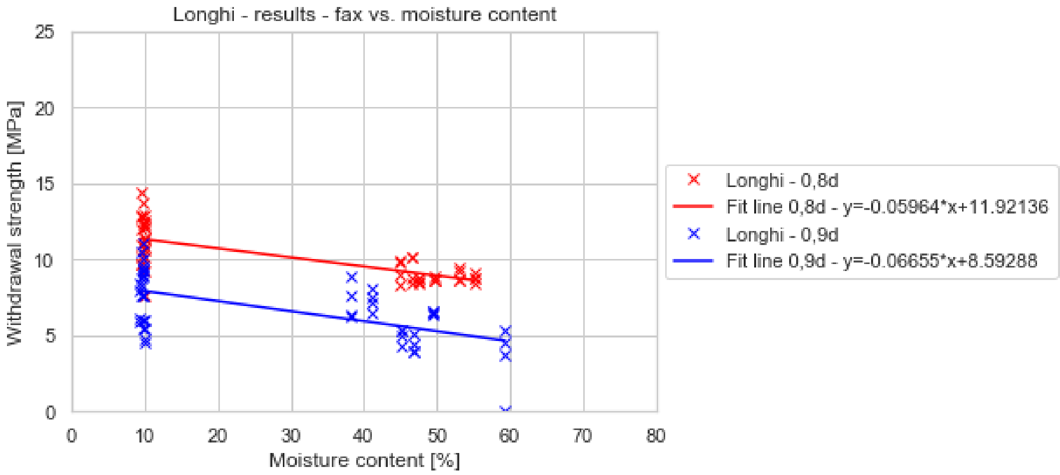

Figure 7.24: Withdrawal strength vs. moisture content from Longhi test specimens.

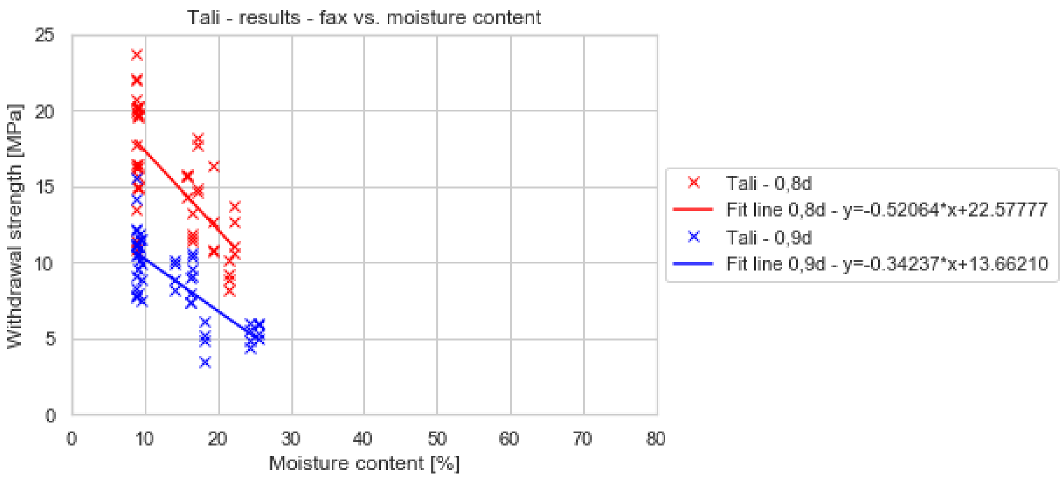

Figure 7.25: Withdrawal strength vs. moisture content from Tali test specimens.

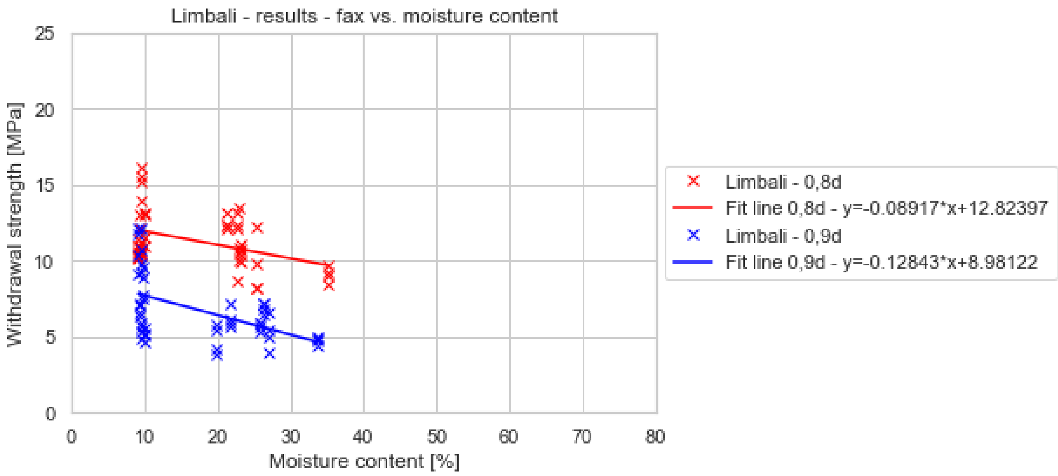

Figure 7.26: Withdrawal strength vs. moisture content from Limbali test specimens.

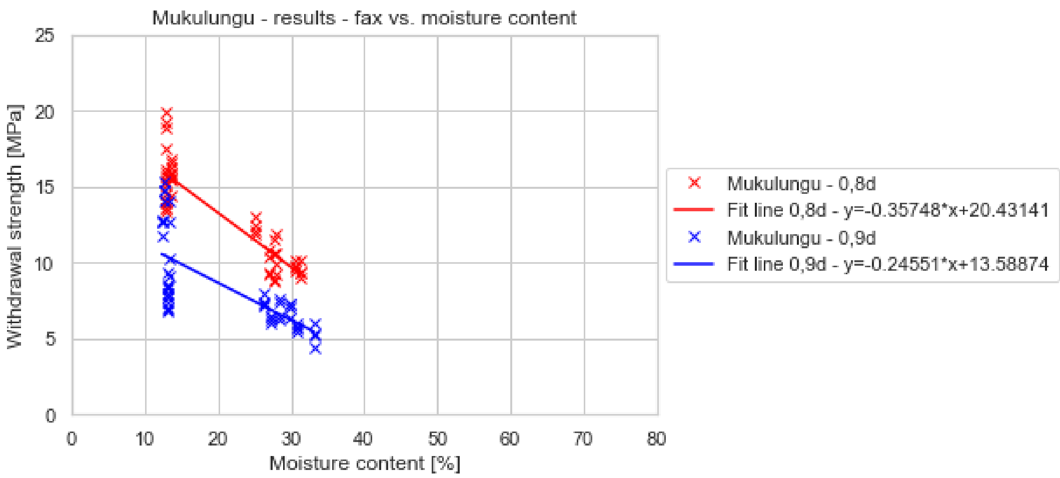

Figure 7.27: Withdrawal strength vs. moisture content from Mukulungu test specimens.

The previous graphs show that the influence of an increased moisture content is very different per species. In figure 7.22, 7.23, 7.24, 7.25, 7.26 and 7.27 fit lines are plotted. But as can be seen in for example figure 7.23 showing the moisture content versus the withdrawal strength for Lati, there is quite a difference between 'dry' and 'wet' results. It is difficult to say something about the withdrawal strength between the dry and wet specimens, linear interpolation is not an option. Therefore withdrawal strength values have been determined per species and per pre-drilling diameter in 'wet' condition. These can be found in table 7.8 and are also visualized in figure 7.28. Not only is the influence of the moisture content different per species, also the moisture content measured from testing is different per species. The corresponding mean moisture content for each species can be found in table 6.4 in chapter 6.2.2, or can be found in table 7.10 in this chapter.

Table 7.8: Mean withdrawal strengths per species divided for pre-drilling 0,8d and 0,9d from wet testing.

Species	fax mean [MPa]	COV fax mean [%]	5^{th} percentile [MPa]
Kanda 0,8d	6,12	6	5,81
Kanda 0,9d	3,59	27	2,48
Lati 0,8d	7,72	8	7,01
Lati 0,9d	5,19	20	4,00
Longhi 0,8d	8,96	4	8,62
Longhi 0,9d	5,81	24	4,38
Limbali 0,8d	10,74	12	9,19
Limbali 0,9d	5,59	15	4,77
Tali 0,8d	12,92	20	9,84
Tali 0,9d	7,13	31	4,99
Mukulungu 0,8d	10,31	10	9,53
Mukulungu 0,9d	6,44	13	5,35

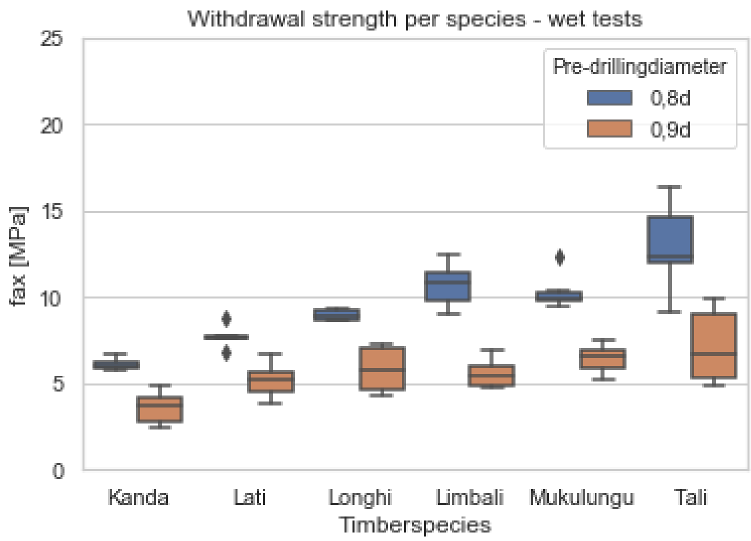

Figure 7.28: Withdrawal strength vs. timber species for pre-drilling 0,8d and 0,9d from wet testing corresponding to table 7.8.

In figure 7.29 a box plot is shown where the withdrawal strength of a wet test piece is divided by the withdrawal strength of a dry test piece. All other parameters are the same, so for example the withdrawal strength results from test 86 (wet, Longhi, diameter 8 mm, insertion depth 70 mm and pre-drilling diameter 0,8d) are divided by the withdrawal strength results from test 62 (dry, Longhi, diameter 8 mm, insertion depth 70 mm and pre-drilling diameter 0,8d). Mean values from figure 7.29 can be found in table 7.9.

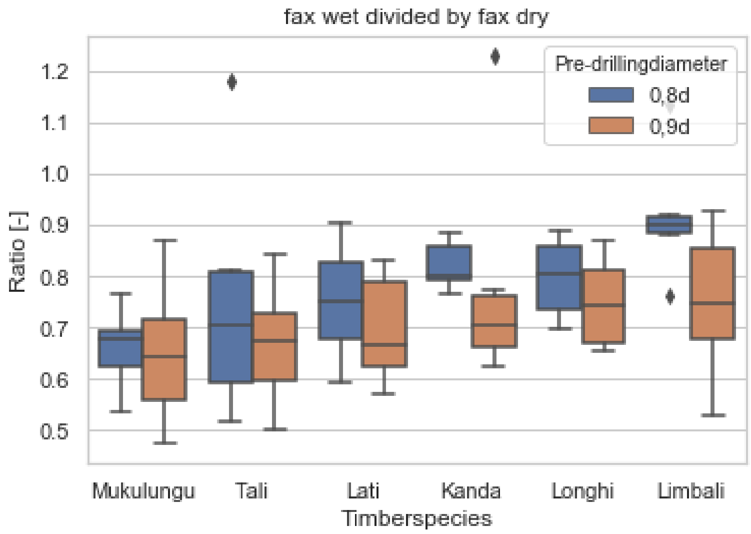

Figure 7.29: Withdrawal strength results from wet testing divided by withdrawal strength results from dry testing, grouped per species and pre-drilling diameter.

Table 7.9: Withdrawal strength results from wet testing divided by withdrawal strength results from dry testing, plotted in figure 7.29.

Species	fax mean ratio wet/dry [-]	COV fax mean ratio wet/dry [-]
Kanda 0,8d	0,82	6
Kanda 0,9d	0,78	29
Lati 0,8d	0,75	16
Lati 0,9d	0,70	16
Longhi 0,8d	0,80	10
Longhi 0,9d	0,75	12
Limbali 0,8d	0,92	13
Limbali 0,9d	0,75	20
Tali 0,8d	0,75	32
Tali 0,9d	0,67	18
Mukulungu 0,8d	0,66	12
Mukulungu 0,9d	0,65	22

Table 7.10: Moisture content (M.C.) of the used timber species (wet).

Trade name	n samples	Av. M.C. [%]	Av. M.C. COV [%]
Kanda	12	27	25
Lati	12	57	9
Longhi	12	48	12
Tali	12	19	19
Limbali	12	25	19
Mukulungu	12	29	8

7.3. Analysis of the insertion moment

During the experiments the insertion moment was measured, this has been done as described in chapter 3.5. The insertion moment values that are presented in figure 7.30, 7.31 and 7.32 are all values measured on each dry test piece. The values represent the value measured at the last turn during screw insertion. Figure 7.30, 7.31 and 7.32 show the insertion moment versus the timber density. All measured results can be found in annex A.

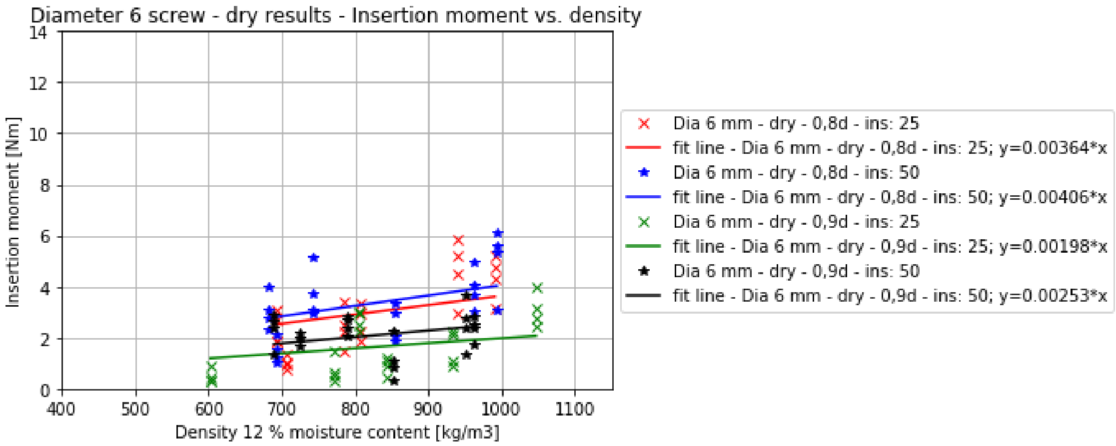

Figure 7.30: Insertion moment versus adjusted density to moisture content 12%. Results from dry testing on diameter 6 mm.

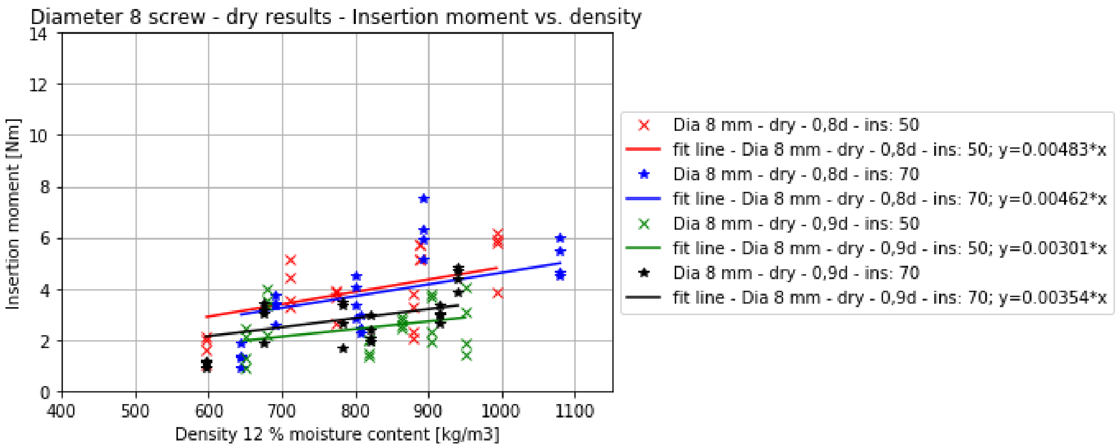

Figure 7.31: Insertion moment versus adjusted density to moisture content 12%. Results from dry testing on diameter 8 mm.

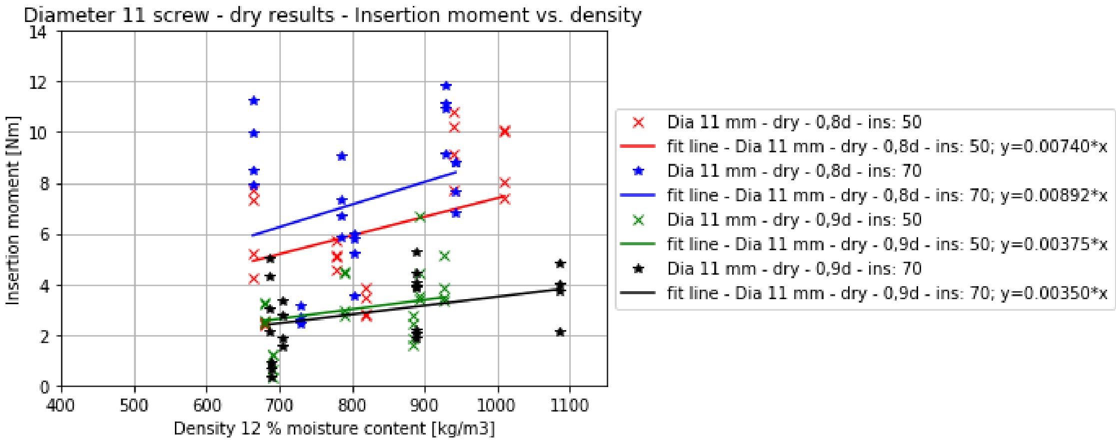

Figure 7.32: Insertion moment versus adjusted density to moisture content 12%. Results from dry testing on diameter 11 mm.

As can be seen in figure 7.30, 7.31 and 7.32 increases the insertion moment with increasing density as expected. With increasing screw diameter and insertion depth also the insertion moment increases. Also the effect of pre-drilling can be observed from figure 7.30, 7.31 and 7.32, where pre-drilling 0,9d reduces the insertion moment compared to pre-drilling 0,8d.

The main reason for measuring the insertion moment is because it gives an indication of the effort needed to insert screws in high density timber such as tropical hardwood and to see what the effect is of an increased pre-drilling hole. As can be seen are the insertion moments relatively low in all cases and can be inserted with a commercial screw driver. Inserting screws was not a problem at all in this project, also no damages occurred because of screw insertion on the screw or the timber. The characteristic torque resistance was not reached, tested values did not even come close as can be seen in table 7.11.

Table 7.11: Characteristic torque resistance of screws used during testing.

Product name	Diameter [mm]	Screw length [mm]	$f_{tor,k}$ [Nm]	Max. measured insertion moment [Nm]
HBSH7160	6	160	18	6
HBSH9180	8	180	38	8
VGS11150	11	150	61	12

7.4. Analysis of the stiffness of self-tapping screws in tropical hardwood

The stiffness has been measured as described in chapter 3.2. Together with the withdrawal strength the stiffness gives a good indication of the performance of a screw when used in a joint. In figure 7.33, 7.34 and 7.35 the measured slip modulus is plotted versus the adjusted density to moisture content 12%. All measured results can be found in annex A.

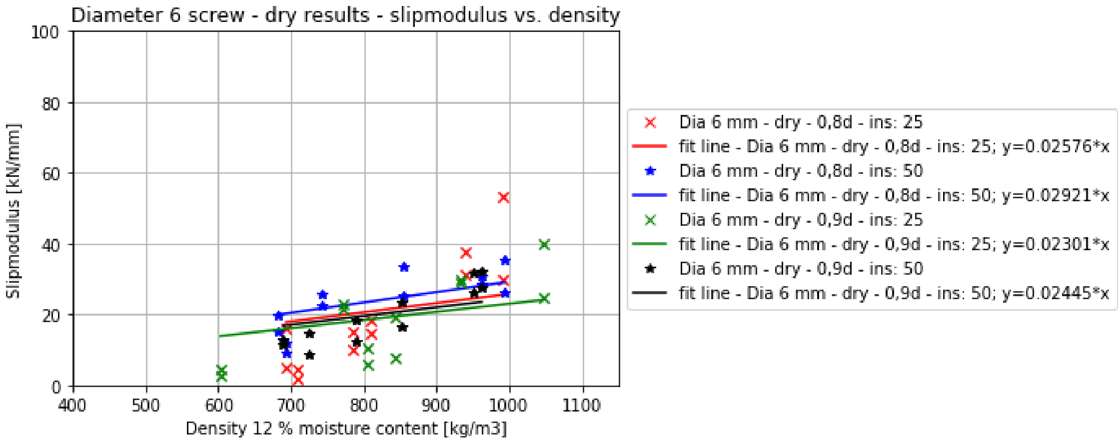

Figure 7.33: Average measured slip modulus versus adjusted density to moisture content 12%. Results from dry testing on diameter 6 mm.

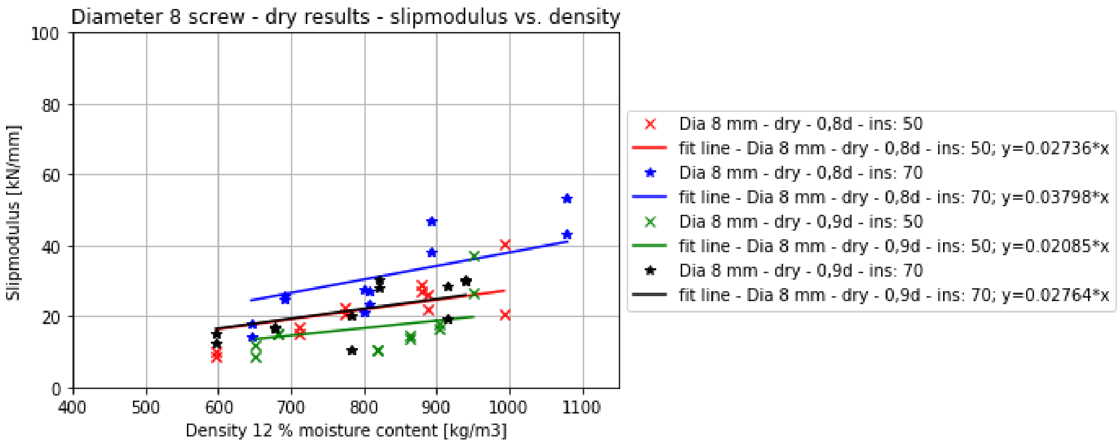

Figure 7.34: Average measured slip modulus versus adjusted density to moisture content 12%. Results from dry testing on diameter 8 mm.

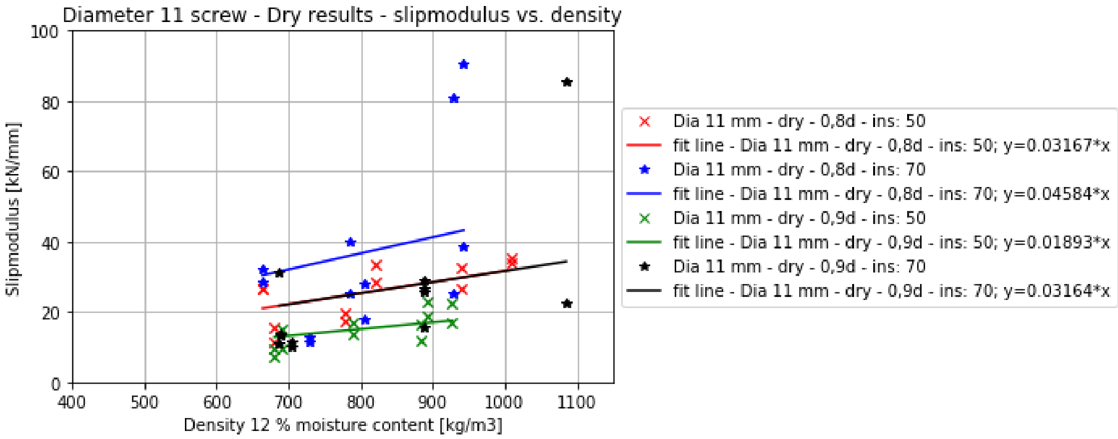

Figure 7.35: Average measured slip modulus versus adjusted density to moisture content 12%. Results from dry testing on diameter 11 mm.

In figure 7.33, 7.34 and 7.35 it can be observed that with increasing density also the stiffness increases. Further with increasing insertion depth and screw diameter also the stiffness increases as expected. And also as could be expected decreases the stiffness with increasing pre-drilling diameter. The highest stiffness was observed for test number 112 on Tali with screw diameter 11 mm, insertion depth 70 mm, dry testing and pre-drilling diameter 0,8d with a average slip modulus of 64,64 kN/mm.

7.4.1. Influence of wood density on the stiffness

In figure 7.8 in chapter 7.2.1 all ready a box plot was shown of the adjusted density versus the different tested tropical hardwood species. In figure 7.36 the species are arranged from left to right from lowest density to highest density. As can be seen, and as could be seen in the previous sub-chapter increases the stiffness with increasing density. Values corresponding to figure 7.36 can be found in table 7.12.

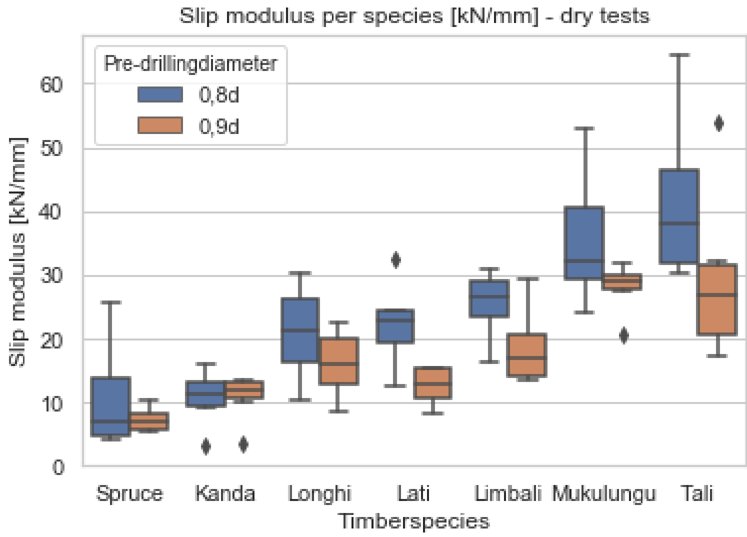

Figure 7.36: Slip modulus measured per tested species (dry results).

Table 7.12: Mean slip modulus per species divided for pre-drilling 0,8d and 0,9d from dry testing.

Species	Slip modulus mean [kN/mm]	COV Slip modulus mean [%]	5^{th} percentile [kN/mm]
Spruce 0,8d	10,68	79	4,33
Spruce 0,9d	7,42	27	5,50
Kanda 0,8d	10,76	41	4,67
Kanda 0,9d	10,82	36	5,26
Lati 0,8d	22,26	30	14,04
Lati 0,9d	12,58	25	8,81
Longhi 0,8d	20,98	36	11,85
Longhi 0,9d	16,01	33	9,42
Limbali 0,8d	25,46	21	17,93
Limbali 0,9d	18,68	33	13,66
Tali 0,8d	41,68	31	30,49
Tali 0,9d	29,50	45	17,92
Mukulungu 0,8d	35,47	30	25,38
Mukulungu 0,9d	28,10	14	22,47

In figure 7.37 the mean slip modulus of a test piece has been divided by the adjusted density for that respective test piece. As can be seen is there some evidence of species influence on the stiffness.

Again Kanda has the lowest ratio, and Tali the highest. This was also observed in chapter 7.2.1 where the withdrawal strength was divided by the adjusted density. Also the difference between pre-drilling diameters can be seen, with 0,9d pre-drilling showing the lowest ratios. Mean values from figure 7.37 can be found in table 7.13.

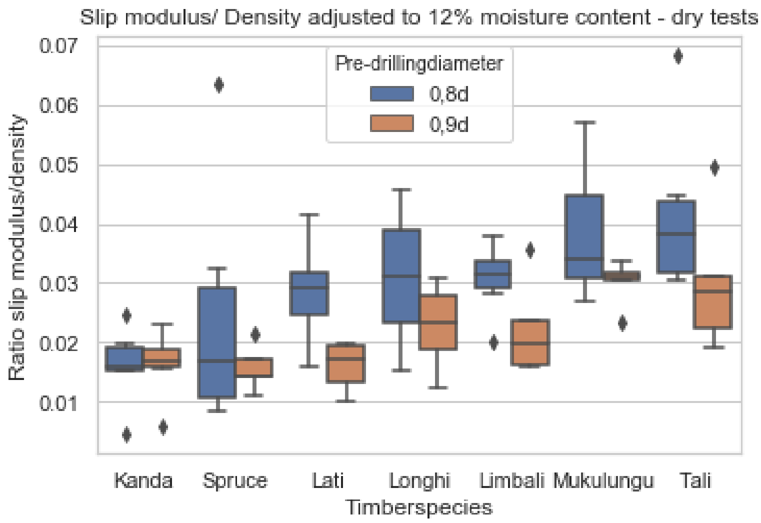

Figure 7.37: Slip modulus results divided by the timber density per species from dry testing.

Table 7.13: Mean slip modulus divided by adjusted density to 12 % moisture content per species, for pre-drilling 0,8d and 0,9d.

Species	Slip mod. /dens. mean*10^2 [(kN/mm) /(kg/m^3)]	COV Slip mod./dens. mean [%]
Spruce 0,8d	2,45	85
Spruce 0,9d	1,56	25
Kanda 0,8d	1,60	42
Kanda 0,9d	1,63	35
Lati 0,8d	2,86	30
Lati 0,9d	1,61	25
Longhi 0,8d	3,09	38
Longhi 0,9d	2,28	30
Limbali 0,8d	3,06	20
Limbali 0,9d	2,19	35
Tali 0,8d	4,18	34
Tali 0,9d	2,97	37
Mukulungu 0,8d	3,84	30
Mukulungu 0,9d	3,03	12

7.4.2. Influence of screw diameter on the stiffness

In figure 7.38 ratios have been calculated between the slip modulus results of the diameter 6 mm screw and the 8 mm or 11 mm screw. The results from the diameter 6 mm screw were used as reference, so all parameters were the same except for the diameter. To give an example: the mean slip modulus results from test 10 (Tali; diameter 6 mm screw; pre-drilling 0,9d; timber condition: dry) has been divided by the mean slip modulus results from test 106 (Tali; diameter 11 mm screw; pre-drilling 0,9d;timber condition: dry). In figure 7.38 it is clear that the influence on average of the screw diameter is not very pronounced. It can also be observed that the pre-drilling 0,9d test results are on average slightly higher in the case of the diameter 11 screw compared to the diameter 6 screw. All values from figure 7.38 can be found in table 7.14.

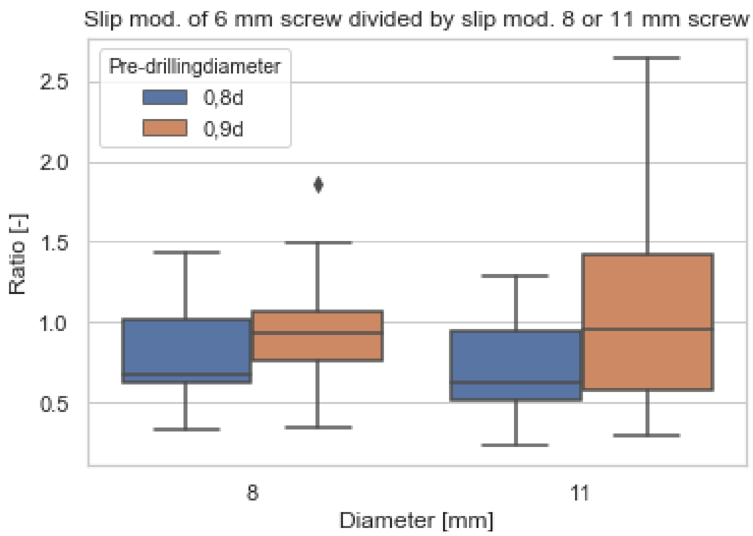

Figure 7.38: Slip modulus results from diameter 6 mm divided by slip modulus results from diameter 8 mm or 11 mm.

Table 7.14: Mean values from the ratios shown in figure 7.38, except for screw diameter 6 mm which is the reference for these ratios.

Screw diameter [mm]	slip mod. 6 mm/ slip mod. own mean value [-]	COV slip mod. 6 mm/ slip mod. own mean [%]
6 0,8d and 0,9d	1 (reference)	-
8 - 0,8d	0,82	42
8 - 0,9d	0,99	40
11 - 0,8d	0,73	47
11 - 0,9d	1,08	59

7.4.3. Influence of pre-drilling diameter on the stiffness

In figure 7.39 a box plot is shown with the screw diameter versus the slip modulus of pre-drilling 0,9d divided by the slip modulus of pre-drilling 0,8d. The ratios are calculated by dividing the mean slip modulus of a test piece with pre-drilling 0,9d with the mean slip modulus of a test piece with pre-drilling 0,8d. All other parameters such as the species, screw diameter and effective length are the same for every ratio (for example results from test 67 have been divided by results from test 61). It can be seen in figure 7.39 that a larger pre-drilling diameter has a larger influence with increasing screw diameter. It can also be observed that in general the stiffness decreases with increasing pre-drilling diameter. All values from figure 7.39 can be found in table 7.15.

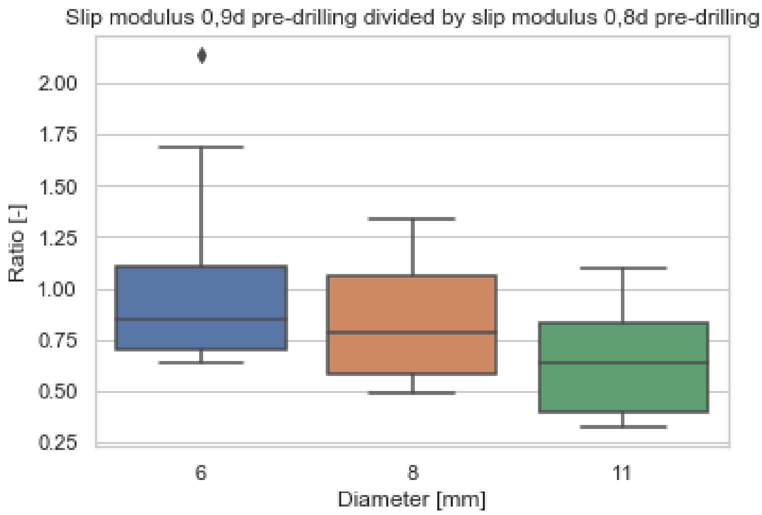

Figure 7.39: Slip modulus results from 0,9d pre-drilling divided by slip modulus results from 0,8d pre-drilling.

Table 7.15: Mean values from the ratio shown in figure 7.39.

Diameter	slip mod.0,9d/slip mod.0,8d mean value [-]	COV slip mod.0,9d/slip mod.0,8d [%]
6	1,01	44
8	0,83	35
11	0,64	41
All	0,82	44

7.4.4. Influence of effective length on the stiffness

During testing every screw diameter has been tested with two effective screw lengths, all other parameters were the same. In figure 7.40 ratios can be found were the mean slip modulus of the shortest screw length has been divided by the mean slip modulus of the longest screw length for a certain diameter. For example the mean slip modulus from test number 50 (Diameter: 8 mm; effective length: 40 mm; Species: Lati; pre-drilling diameter: 0,8d) was divided by the slip modulus of test number 62 (Diameter: 8 mm; effective length: 60 mm; Species: Lati; pre-drilling diameter: 0,8d). As could be expected is the stiffness of shortest screws lower. There is no clear difference between the ratios of the different screw diameters. Also the ratios for both pre-drilling diameters are very similar. Values from figure 7.40 can be found in table 7.16.

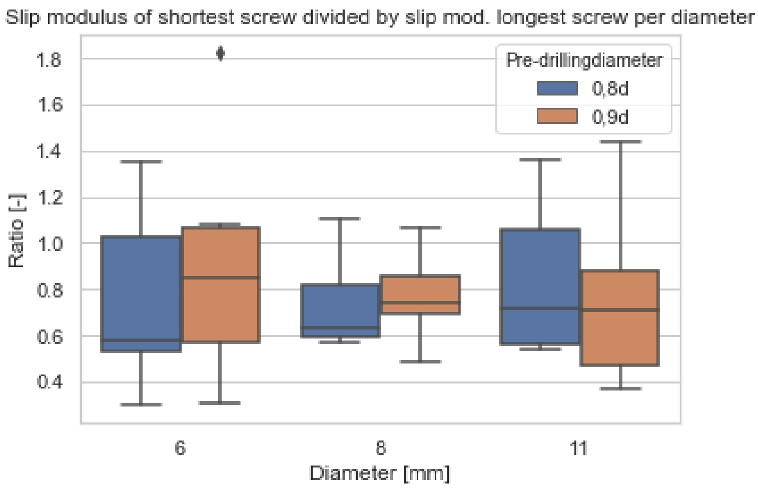

Figure 7.40: Slip modulus results from shortest screw length divided by slip modulus results from the longest screw length.

Table 7.16: Mean ratio values corresponding to figure 7.40.

Diameter	slip mod. short/slip mod. long mean value [-]	COV slip mod. short/slip mod. long [%]
6 - 0,8d	0,75	55
6 - 0,9d	0,91	59
8 - 0,8d	0,73	29
8 - 0,9d	0,77	25
11 - 0,8d	0,83	41
11 - 0,9d	0,76	52

7.4.5. Influence of moisture content on the stiffness

In figure 7.41 the difference between wet and dry testing results can be seen. The box plot shows the slip modulus versus the different species that were tested. Corresponding densities and moisture contents can be found in chapter 6.1 and 6.2.2 respectively. It can be observed in figure 7.41 that wet test pieces show a lower slip modulus compared to dry test pieces.

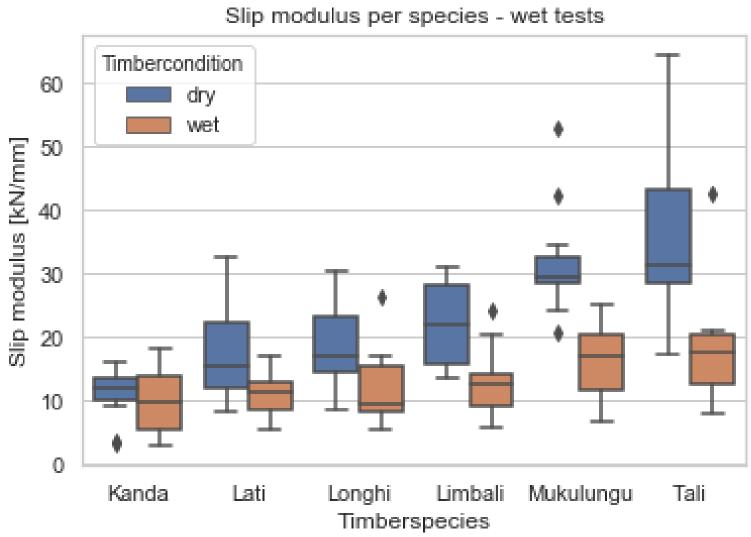

Figure 7.41: Slip modulus results from dry and wet testing.

In figure 7.42 ratios have been calculated where mean slip modulus results from wet testing have been divided by mean slip modulus results from wet testing. The mean differences are not very pronounced as can also be seen in table 7.17.

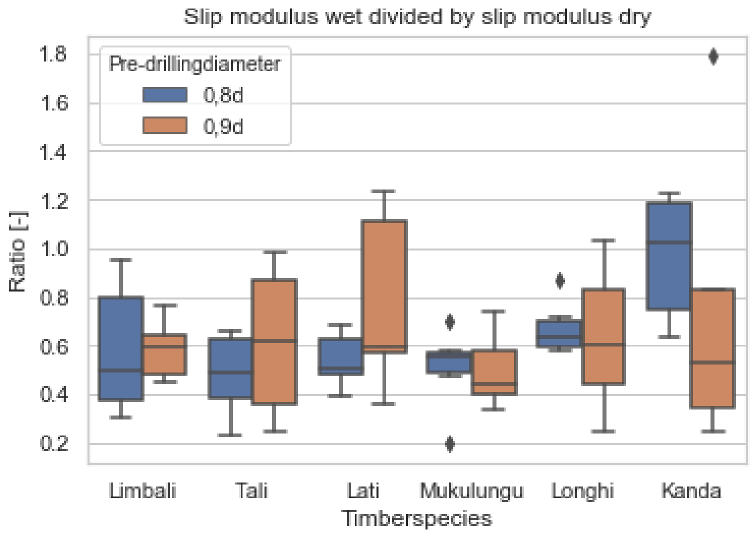

Figure 7.42: Slip modulus results from wet testing divided by slip modulus results from dry testing.

Table 7.17: Slip modulus results from wet testing divided by slip modulus results from dry testing, plotted in figure 7.42.

Species	slip mod. mean ratio wet/dry [-]	COV slip mod. mean ratio wet/dry [-]
Kanda 0,8d	0,97	27
Kanda 0,9d	0,75	83
Lati 0,8d	0,54	21
Lati 0,9d	0,77	49
Longhi 0,8d	0,67	17
Longhi 0,9d	0,63	47
Limbali 0,8d	0,58	48
Limbali 0,9d	0,59	22
Tali 0,8d	0,48	36
Tali 0,9d	0,62	51
Mukulungu 0,8d	0,51	33
Mukulungu 0,9d	0,50	33

7.5. Conclusion

Timber defects during testing and insertion moment

The test piece geometry was not according to EN 1382:2016, in general larger edge distances were required. Nevertheless did this not lead to any problems, no cracks or screw failure occurred during the insertion of the self-tapping screws nor was it any problem to insert the screws at all. This had all to do with the pre-drilling diameters of 0,8d and 0,9d what was used. Because of this very low insertion moments were measured as can be seen in chapter 7.3.

Also during and after withdrawal test no significant damage was observed. Even in extreme situations that were tested during pre-testing there was no evidence that a larger edge distance was needed.

Influence of parameters on the withdrawal strength

In the analysis it was found that with increasing density the withdrawal strength also increases, this is in line with literature. It was also found that the species does influence the withdrawal strength, as was found by calculating the withdrawal strength to density ratio per species. With increasing screw diameter the withdrawal strength decreases as was found in this analysis, and also in line with literature. Only in the case of pre-drilling 0,9d for the diameter 8 mm screw this was not the case when comparing it to the diameter 6 mm screw, this probably was a result of pre-drilling accuracy. Regarding the influence of pre-drilling it was found that on average the withdrawal strength is reduced by a factor of 0,68 when the pre-drilled hole is 0,9d instead of 0,8d. In literature it was found that the effective screw length does not influence the withdrawal strength. No clear influence of effective length has been found, except for screw diameter 6 mm and 8 mm when pre-drilled 0,9d. The diameter 6 mm and 8 mm screws are HSBH screws with a larger inner diameter and it might be that the withdrawal strength is not optimal for these types of screw when inserted in 0,9d pre-drilled holes. During testing wet and dry pieces were tested. It was found that the moisture uptake rate is very different for the various tropical hardwood species that were tested. It was also found that the withdrawal strength is negatively influenced by an increased moisture content.

Influence of parameters on the slip modulus

First of all it has to be mentioned that the scatter in data is larger when compared to the test data from withdrawal tests, this has to be taken into account. In the analysis it was found that with increasing density the slip modulus also increases. Also the timber species influences the slip modulus just like in the case of the withdrawal strength. No clear influence of screw diameter was found on the withdrawal strength. Just like for the withdrawal strength is the slip modulus influenced negatively when pre-drilling 0,9d has been used instead of 0,8d. This negative influence increases with increasing diameter. With increasing effective screw length also the slip modulus increases, this would be expected and was also found in the test results. Also a higher moisture content has a negative influence on the slip modulus, this was also as expected. A larger influence was observed in the case of timber species with the highest densities measured (Tali and Mukulungu), while for these species the lowest moisture content was measured in wet conditions compared to other species.

8 Empirical calculation model

In figure 8.1 the model from EN 1995-1-1:2011 (see chapter 2.3.1) is compared to the mean withdrawal capacity results from testing (dry, pre-drilling 0,8d). Figure 8.1 shows that the model from EN 1995-1-1:2011 underestimates the withdrawal capacity of tropical hardwood species.

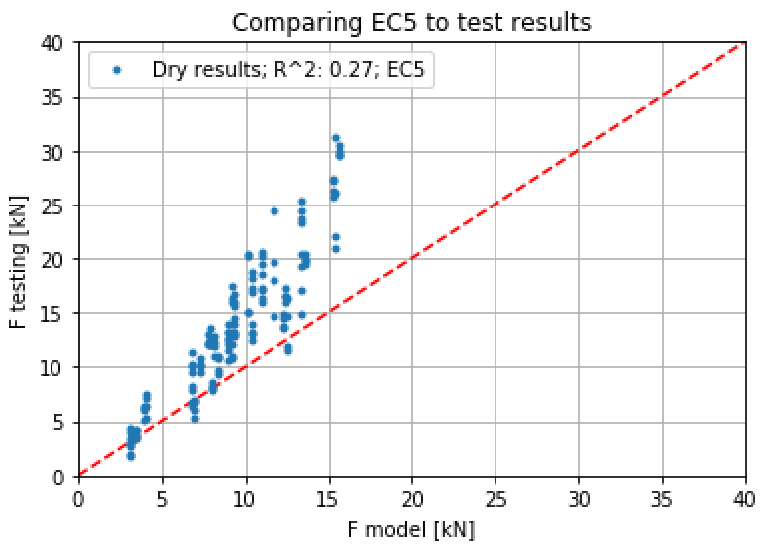

Figure 8.1: Comparing the test values (dry, pre-drilling 0,8d) with the method from EN 1995-1-1:2011 (see chapter 2.3.1).

In this chapter two types of calculation models will be proposed to better predict the withdrawal capacity of self-tapping screws perpendicular to the grain in tropical hardwood, these are the following:

- Model to calculate the withdrawal strength, determined per species;
- Model to calculate the withdrawal strength based on all test results;

8.1. Model definitions

In this sub-chapter the definitions of parameters used in the proposed models will be elaborated.

Withdrawal strength f_{ax}

The withdrawal strength will be calculated using the following formula:

$$f_{ax} = \frac{F_{ax}}{d * \pi * l_{eff}} \tag{8.1}$$

With:

- d is the outer thread diameter for screws in mm
- F_{ax} axial withdrawal load, in Newtons
- f_{ax} withdrawal strength, in N/mm^2
- l_{eff} effective depth of penetration in mm. For screws only the penetration depth of the profiled part

Diameter d

The diameters that have been used in this project are presented in table 8.1, figure 8.2 and figure 8.3. These are the dimensions as provided by Rothoblaas ([23] and [24]). The diameter used in the models proposed in this chapter is the nominal diameter (d1), meaning the models are also only valid for these diameters.

Table 8.1: Screws that were used in testing

Product name	Nominal diameter (d1) [mm]	Inner thread diameter (d2) [mm]	d1/d2	Screw length [mm]	l_{tip} [mm]
HBSH7160	6	4,5	0,75	160	8
HBSH9180	8	5,9	0,74	180	10
VGS11150	11	6,6	0,60	150	14

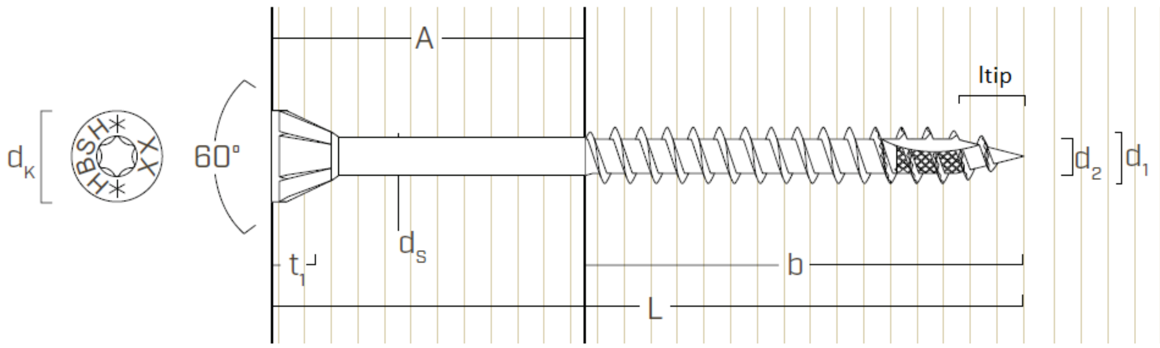

Figure 8.2: Geometry of the HBSH screws Rothoblaas [23].

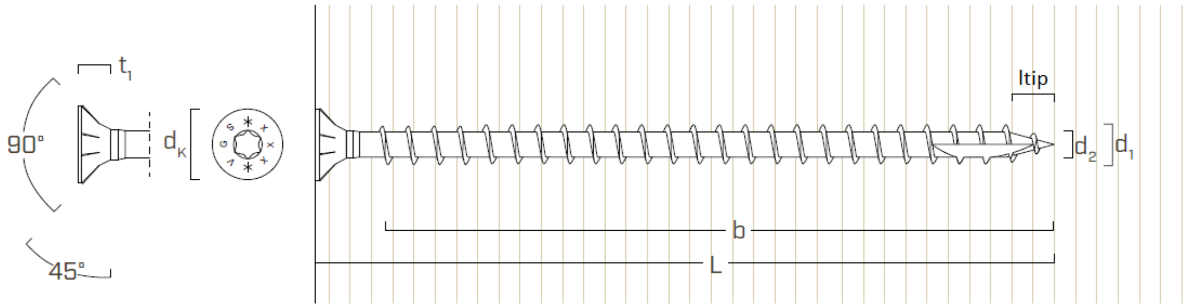

Figure 8.3: Geometry of the VGS screws Rothoblaas [24]

Effective length l_{eff}
The effective length used in the proposed models is the screw insertion depth (penetration length of the treaded part) minus the screw tip (l_{tip}). The screw tip length per screw are reported in table 8.1, figure 8.2 and figure 8.3.

Density ρ_{12}
The density values used for the model all have been corrected to 12 % moisture content. This has been done to create unity among this value. The moisture content of the used timber has been calculated in percent as followed (as has also been described in chapter 3.4):

$$\omega = \frac{m_1 - m_0}{m_0} * 100 \tag{8.2}$$

m_1 mass of the test slice before drying, in grams
m_0 mass of the oven dry test slice, in grams
ω moisture content, in percent

8.2. Calculation model 1: per species

8.2.1. Designing the calculation model

In this chapter a calculation model will be proposed based on the experimental results. During the analysis in chapter 7 it was found that the timber density influences the withdrawal strength, but also the timber species it self. Also it became clear that the difference in pre-drilling diameter has a significant effect on the withdrawal strength. Also the screw diameter has influence on the withdrawal strength, but there is no clear influence of effective screw length except in the case of diameter 6 mm and 8 mm for pre-drilling 0,9d.

In this sub chapter it has been chosen to propose withdrawal strength parameters (f_{ax}) per species and pre-drilling diameter. It has been chosen to do so because the timber species influences the withdrawal strength and therefore have to be separated. Also the results from pre-drilling have to be separated because the influence is very obvious and it is also difficult to express this as a parameter in a design formula. It has been chosen to not use the density and diameter as parameter to design a calculation method because this leads to results that are not logic, this is the result of a shortage of results per timber species. If this is the right way to go will be investigated by comparing the proposed formula with the test results, but first the calculation method itself will be proposed in chapter 8.2.2.

8.2.2. Calculation model

The withdrawal strength presented in chapter 7 were determined using formula 8.3. In engineering practice the withdrawal capacity in kN is used to calculate the axial withdrawal resistance of a screw. In chapter 7.2.1 mean withdrawal strength and characteristic withdrawal strength values were determined per species and for pre-drilling diameters 0,8d and 0,9d. The characteristic values from dry testing can be found in table 8.2. By using formula 8.4 the withdrawal capacity can again be determined.

$$f_{ax} = \frac{F_{ax}}{d * \pi * l_{eff}} \tag{8.3}$$

$$F_{ax} = f_{ax} * d * \pi * l_d \tag{8.4}$$

With:

d	is the outer thread diameter for screws in mm
F_{ax}	axial withdrawal load, in Newtons
f_{ax}	withdrawal strength, in N/mm^2
l_{eff}	effective depth of penetration in mm. For screws only the penetration depth of the profiled part

Table 8.2: Mean withdrawal strength and characteristic withdrawal strength per species divided for pre-drilling 0,8d and 0,9d (dry results).

Species	$f_{ax,mean,species}$ [MPa]	$f_{ax,k}$ (5^{th} percentile) [MPa]
Spruce 0,8d	5,51	4,55
Spruce 0,9d	4,28	3,53
Kanda 0,8d	7,49	6,71
Kanda 0,9d	4,74	3,33
Lati 0,8d	10,44	9,29
Lati 0,9d	7,57	5,57
Longhi 0,8d	11,34	9,96
Longhi 0,9d	7,81	5,54
Limbali 0,8d	11,83	10,37
Limbali 0,9d	7,85	5,20
Tali 0,8d	17,82	16,72
Tali 0,9d	10,53	8,55
Mukulungu 0,8d	15,73	13,89
Mukulungu 0,9d	10,37	7,39

During testing also wet conditioned timber specimens were tested. In a similar way formula 8.4 can be used in combination with the withdrawal strength values in table 8.3.

Table 8.3: Mean withdrawal strengths per species divided for pre-drilling 0,8d and 0,9d from wet testing.

Species	$f_{ax,mean,species}$ [MPa]	$f_{ax,k}$ (5^{th} percentile) [MPa]
Kanda 0,8d	6,12	5,81
Kanda 0,9d	3,59	2,48
Lati 0,8d	7,72	7,01
Lati 0,9d	5,19	4,00
Longhi 0,8d	8,96	8,62
Longhi 0,9d	5,81	4,38
Limbali 0,8d	10,74	9,19
Limbali 0,9d	5,59	4,77
Tali 0,8d	12,92	9,84
Tali 0,9d	7,13	4,99
Mukulungu 0,8d	10,31	9,53
Mukulungu 0,9d	6,44	5,35

8.2.3. Goodness of the fit to the calculation model

In this chapter the goodness of the fit of the proposed calculation models will be investigated by comparing the model with the test results. This is done per species in figure 8.4, 8.5, 8.6, 8.7, 8.8 and 8.9. For this comparison the mean values from table 8.2 (dry values) and table 8.3 (wet values) have been used in formula 8.4 to calculate the withdrawal capacity. Mean values will be used since this is a comparison with the test results, characteristic values could be used in design. In every plot a red dashed line has been plotted, the function is y=x.

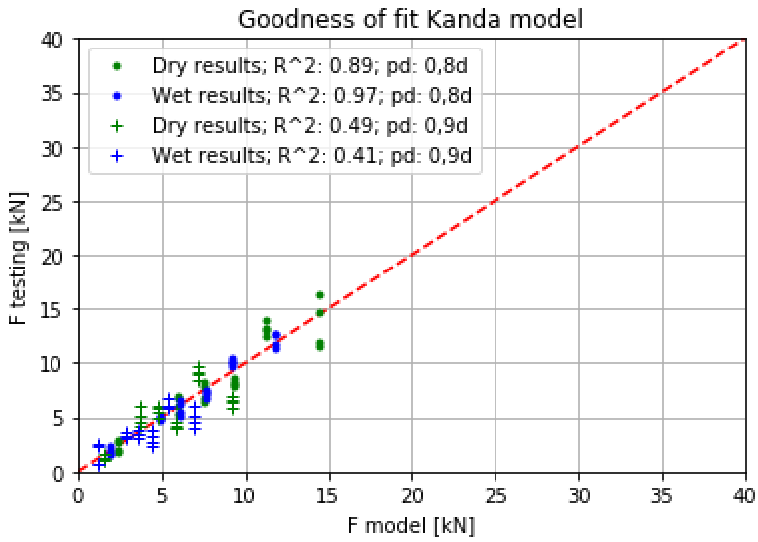

Figure 8.4: Comparison of the wet and dry test results with the proposed model for Kanda.

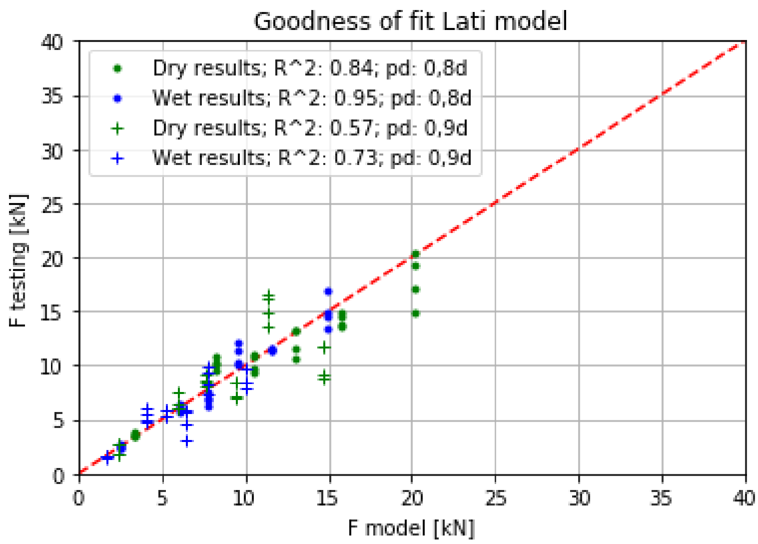

Figure 8.5: Comparison of the wet and dry test results with the proposed model for Lati.

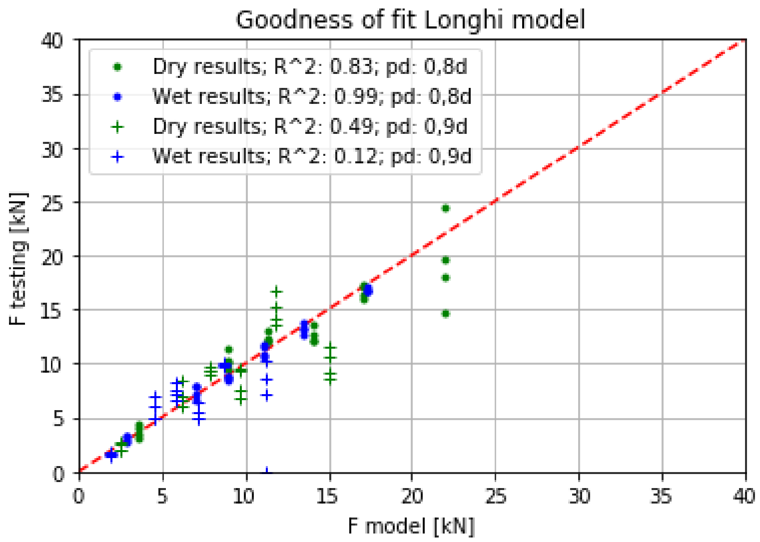

Figure 8.6: Comparison of the wet and dry test results with the proposed model for Longhi.

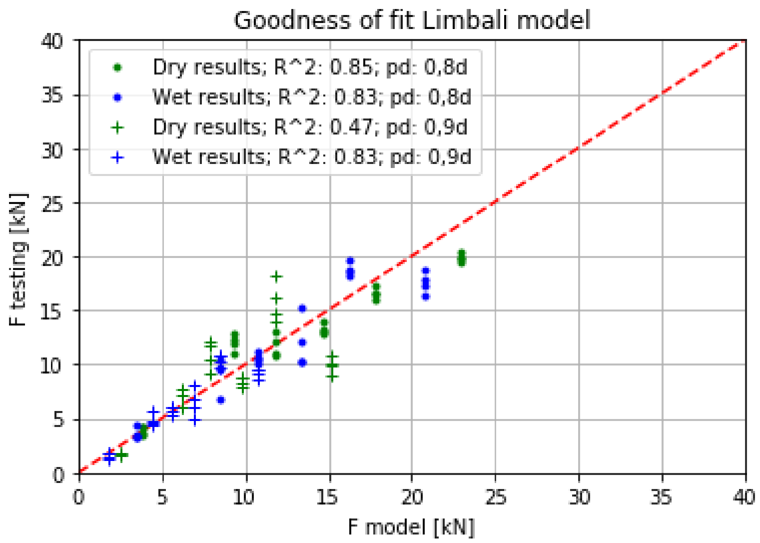

Figure 8.7: Comparison of the wet and dry test results with the proposed model for Limbali.

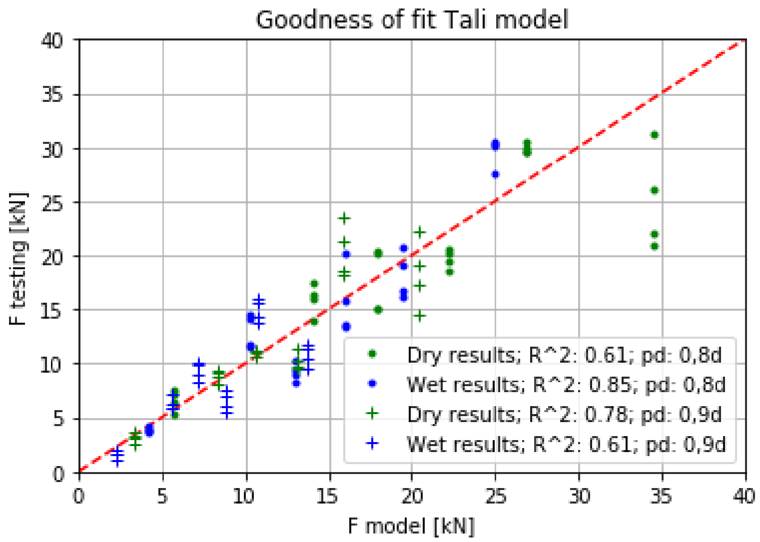

Figure 8.8: Comparison of the wet and dry test results with the proposed model for Tali.

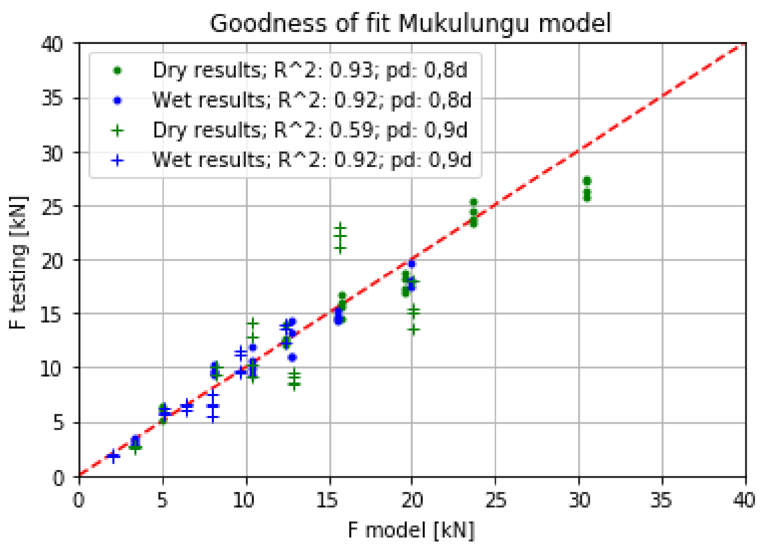

Figure 8.9: Comparison of the wet and dry test results with the proposed model for Mukulungu.

In most cases the proposed models are a good fit to the test data as can be seen in the legends of figure 8.4, 8.5, 8.6, 8.7, 8.8 and 8.9. Most models have a R^2 of 0,8 or higher. Results from dry testing 0,9d pre-drilling for Kanda, Lati, Longhi, Limbali and Mukulungu show a lower R^2 value of around 0,5. In chapter 7.2.1 it can be observed in figure 7.9 that for the pre-drilling 0,9d there is a larger variation in withdrawal strength compared to results for pre-drilling 0,8d. This in turn is possibly caused by the different influences pre-drilling 0,9d has on different screw diameters as was found in chapter 7.2.2. Also pre-drilling accuracy might be a cause of this as has also been explained in chapter 2.6.2. Finally in chapter 7.2.4 it was found that in the case of diameters 6 and 8 mm the effective length does have influence on the withdrawal strength when pre-drilled 0,9d, this has not been accounted for in the models.

Overall are the proposed methods a good fit to the tested data, and it has to be added that it is not very likely that pre-drilling 0,9d will be used in practice. Further in research done by Brandner, Ringhofer, and Reichinger [5] no influence of pre-drilling was found if the pre-drilling diameter was smaller or equal to 0,8 times the nominal screw diameter.

8.3. Calculation model 2: including all tropical hardwoods from this thesis

8.3.1. Designing the calculation model

In the analysis in chapter 7 it was found that the withdrawal strength is influenced by the timber species, screw diameter, pre-drilling diameter and timber density. No significant influence of the effective screw length was found except for screw diameters 6 mm and 8 mm with pre-drilling diameter 0,9d. In the previous sub-chapter 8.2 a model has been proposed based on the withdrawal strength per species and per pre-drilling diameter. Including parameters such as the density and screw diameter was difficult because of the lack of test data per species, this resulted in some cases in models that were not logic. In this sub-chapter a mean equation is proposed for all tropical hardwood species together (dry condition), including parameters for the density, effective screw length and screw diameter. These models have been designed with the help of the curve fit function from Python (scipy.optimize.curve_fit), this method has been used because it allows to use a self defined equation form that has to be fitted. The equation form to which the data will be fitted is as followed:

$$f_{ax,prop} = A * d^A * l_{eff}^B * \rho_{12}^C \tag{8.5}$$

With:

$f_{ax,prop}$	is the withdrawal strength in MPa
ρ_{12}	is the timber density with moisture content 12 %, in kg/m^3
l_{eff}	is the penetration length of the threaded part of the self-tapping screw, in mm
d	is the outer thread diameter of the self-tapping screw, in mm

The curve fit function will solve for factor A and for exponent B and C to find the best fit. As can be seen, the angle of the grain is not one of the parameters, tests have only been carried out perpendicular to the grain and the proposed models are therefore only valid for calculating the withdrawal strength of self-tapping screws perpendicular to the grain.

The model will be based on the dry test results with pre-drilled hole 0,8d. Correction factors for 'wet' results and pre-drilling 0,9d will be presented to modify the formula.

8.3.2. Calculation model

For pre-drilling 0,8d the following model is proposed:

$$f_{ax,prop,allmean} = (3,84 * 10^{-4} * d^{-0,39} * l_{eff}^{0,05} * \rho_{12,mean}^{1,64}) * k_{uc} * k_{Dp} \tag{8.6}$$

With:

$f_{ax,prop,mean}$	is the withdrawal strength in MPa
$\rho_{12,mean}$	is the timber density with moisture content 12 %, in kg/m^3
l_{eff}	is the penetration length of the threaded part of the self-tapping screw, in mm
d	is the outer thread diameter of the self-tapping screw, in mm
k_{uc}	correction factor for 'wet' results, if dry then k_{uc}= 1
k_{Dp}	correction factor for 0,9d pre-drilled results, if 0,8d then k_{Dp}=1

Correction factors to calculate the withdrawal strength in wet conditions can be found in table 8.4. These have been determined per species because the response to water and moisture uptake was very different per species. These factors have been determined by calculating the wet/dry witdrawal strength ratio in chapter 7.2.5. In table 8.4 also the correction factor for pre-drilling 0,9d is presented. This factor has been determined by calculating a mean ratio of all tests by dividing the withdrawal strength results of 0,9d pre-drilled test pieces by the withdrawal strength results of 0,8d pre-drilled test pieces (chapter 7.2.3). One value has been determined to correct for the pre-drilling diameter since all species have been pre-drilled with the same diameters and to keep the model as generic as possible.

Table 8.4: Correction factors for species in wet condition and for pre-drilling 0,9d.

Species	k_{uc}	k_{Dp} (correction for pre-drilling 0,9d)
Kanda	0,82	-
Lati	0,75	-
Longhi	0,80	-
Limbali	0,92	-
Tali	0,75	-
Mukulungu	0,66	-
All	-	0,68

8.3.3. Goodness of the fit to the calculation model

In this chapter the goodness of the fit of the proposed model will be investigated by comparing the model (formula 8.6) with the test results. Correction factors from table 8.4 have been used in this comparison. In every plot a red dashed line has been plotted, the function is y=x. As can be seen is the proposed model (formula 8.6) a good fit to the test results with some outliers, but overall acceptable r^2 values.

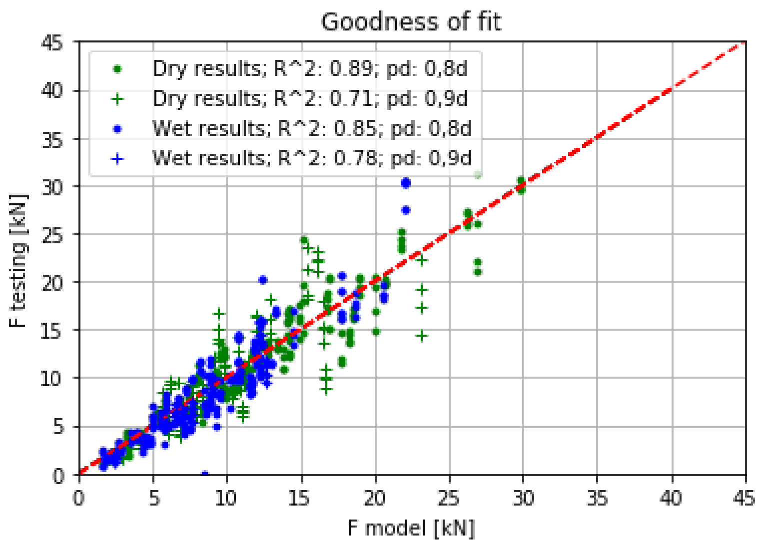

Figure 8.10: Comparison of the proposed model (formula 8.6) with test results.

8.4. Comparison proposed models with existing withdrawal strength results

In this sub-chapter the proposed models will be compared to an independent data set of the withdrawal strength of self-tapping screws in tropical hardwoods. The tests were carried out by Kieboom [15] for bachelor endwork. Kieboom [15] tested the withdrawal strength of self-tapping screws in tropical hardwood species perpendicular to the grain. Species that were used were Kanda and Mukulungu. Kieboom [15] did not report the moisture content of the test pieces so this is not included in the comparison. The self-tapping screws that were used were diameter 5 mm HTS screw, the diameter 9 mm VGS screw and the diameter 11 VGS screw from Rothoblaas.

Model 1 or formula 8.4 that has been proposed in chapter 8.2 is plotted in orange for Kanda and in green for Mukulungu in figure 8.11. The mean withdrawal parameter used in this comparison for Kanda was 7,49 MPa and for Mukulungu 15,73 MPa. These are parameters which relate to a dry timber condition and pre-drilling diameter 0,8d. Model 2 or formula 8.6 as proposed in chapter 8.3 is plotted in blue in figure 8.11. All models show a good fit to the data from Kieboom [15] with acceptable r^2 values. This gives confidence of the usability of the models.

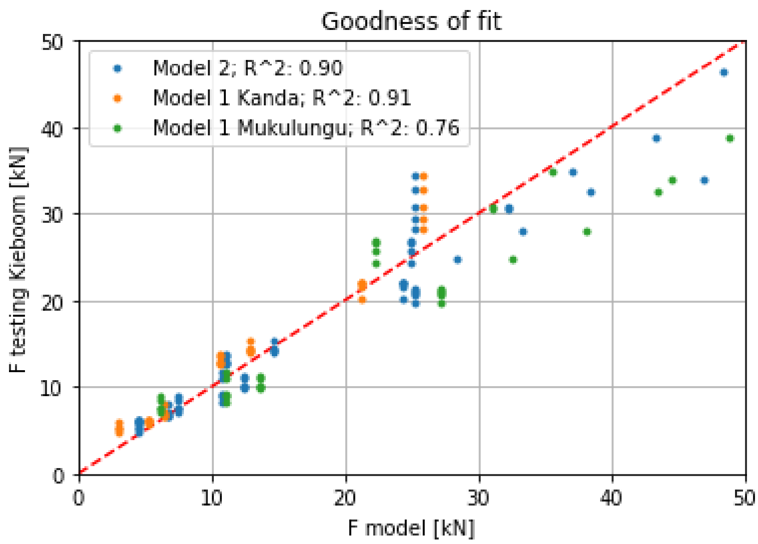

Figure 8.11: Comparison of the proposed models (formula 8.4 and 8.6) with test results from Kieboom [15].

8.5. Case study - Reinforced dowel connection

A small case study will be conducted to find out if the use of self-tapping screws inserted in tropical hardwood perpendicular to the grain is theoretically usable as reinforcement in timber dowel connections. Values in this case study will be taken from research done by Sandhaas [25] on the mechanical behaviour of timber joints with slotted-in steel plates. This research also includes results from testing with tropical hardwood.

In the problem analysis in chapter 1.1 it was mentioned that when dowel connections are loaded axially cracking could occur along the grain. This cracking leads to a decrease of effective dowels and therefore reduces the load bearing resistance of the connection. Research done by Schmid [28] concluded that by inserting self-tapping screws perpendicular to the grain cracking could be prevented and 100 % effective dowels could be achieved. This could be achieved as the following would be met:

$$F_{ax,screw} \geq 0,3 * F_V \tag{8.7}$$

With:

F_{ax}	is the withdrawal capacity of a self-tapping screw inserted in timber, in kN
F_V	is the load-carrying capacity per shear plane per fastener (dowel) in kN

Figure 8.12 was also shown earlier and gives a good overview of a reinforced dowel connection. The possible crack formation is also shown with the self-tapping screws inserted perpendicular to this crack. As can also be seen in figure 8.12 the connection is one steel plate with two timber parts on either side. The load on the connection is represented by N as can be seen in figure 8.12. This value will be divided by two because this represents the load on one dowel. Also notice that the effective length l_{eff} of the screw is half the height of the timber, divided by the crack. This is similar to other calculation methods for self-tapping screws used as reinforcement in timber as was described in chapter 2.4.

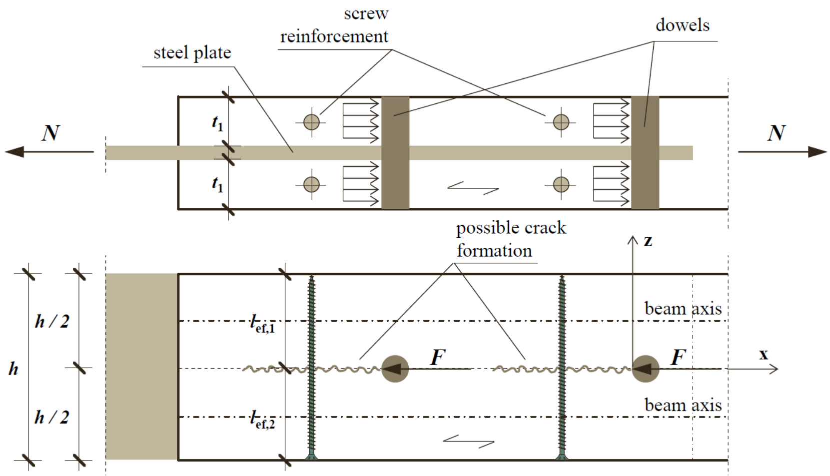

Figure 8.12: Top view and side view of a dowel type connection by Ringhofer [21].

It has been chosen to use the Azobe (Ekki) joint test results (maximum measured force) from research done by Sandhaas [25]. It is assumed that this maximum measured force is the load-carrying capacity of the dowel joint. Azobe has been chosen because this is also a high density tropical hardwood from Africa just like the timber used in this thesis. The self-tapping screw withdrawal resistance will be calculated with formula 8.6 $F_{ax,prop,0.8d,allmean}$ and formula 8.4 $F_{ax,prop,0.8d,Tali}$ as proposed in this thesis. The mean withdrawal strength value for Tali pre-drilling 0,8d (17,82 MPa) from table 8.2 is used in formula 8.4, because Tali has a density (mean of 972,88 kg/m^3 in this project) that is closest to the density of Azobe (see table 8.5).

The timber height (h in figure 8.12) for the diameter 12 mm dowels was 72 mm and for 24 diameter dowels was 144 mm. As said the effective length is around half the height of the timber so for the diameter 12 mm dowels effective length 35 mm was used in the calculations and for diameter 24 mm effective length 70 mm was used. The comparison can be found in table 8.5. In table 8.5 hss stands for high strength steel dowels and vhss stands for very high strength steel dowels.

In table 8.5 the values that are lower than 30 % are in bold text. As can be seen in table 8.5 in the cases of number 1, 2 and 4 the required 30 % of the load-carrying capacity per shear plane per dowel is reached. In the case of number 3 it could not be reached. The load that has to be taken up by the self-tapping screw is 45,9 kN which exceeds the characteristic tensile resistance of the 11 mm diameter screw (VGS11150 from Rothoblaas). The only screw that is able to take this tensile load is the 13 mm diameter screw, but still this is not enough. Also more effective length is required to get to the 30 % of the load-carrying capacity per shear plane per dowel for the withdrawal capacity of the self-tapping screw. Another option is to use threaded rods.

Table 8.5: Case study using formula 8.4 $F_{ax,prop,0.8d,Tali}$ and formula 8.6 $F_{ax,prop,0.8d,allmean}$ with maximum measured force on dowels $F_{V,max}$ from research done by Sandhaas [25].

no.	ρ_{12} [kg/m^3]	Dowel [mm]	Dowel type	$F_{V,max}$ [kN]	0,3*0,5* $F_{V,max}$ [kN]	Screw dia [mm]	$F_{ax,prop,0.8d,Tali}$ [kN]	$F_{ax,prop,0.8d,all}$ [kN]
1	1024	12	vhss	72	10,8	6	11,8	13,0
2	1029	12	hss	57	8,6	6	11,8	13,1
3	1064	24	vhss	306	45,9	11	**43,1**	**41,5**
4	1035	24	hss	181	27,2	8	31,3	32,7

What can be concluded from this case study is that it is possible to reach 30 % of the load-carrying capacity per shear plane per dowel as withdrawal capacity of self-tapping screws when used as reinforcement in dowel type connections. For large diameter dowels such as 24 mm diameter it is more difficult and especially in the case of very high strength steel dowels large diameter self-tapping screws are necessary and also more effective length is needed. Another solution could be to use multiple screws at one dowel for crack prevention, it might be that this would result in smaller diameter size self-tapping screws but this has to be verified in real life tests. It can also be observed that for the 11 diameter screw the characteristic tensile strength (38 kN) is reached, steel tensile failure could become a problem.

9 Conclusion

The objective of this thesis was to gain knowledge about the withdrawal strength of self-tapping screws in tropical hardwood species when loaded perpendicular to the grain. In the Introduction a main question and several sub-questions were formulated to help to achieve this objective. The main question was the following:

- **What is the withdrawal strength of self-tapping screws in tropical hardwood species perpendicular to the grain and is it possible to develop a verification model for engineering purposes?**

The sub-questions were meant to help narrowing down the subject because the main question has a very broad scope. In this conclusion the sub-questions will be answered, which all together answer the main question.

What are the most common failure mechanisms of withdrawal tests of screws perpendicular to the grain in topical hardwood?

- The aim in this thesis was to have screw withdrawal as dominant failure mode in oppose to screw steel tensile failure/rupture. This has been achieved in all of the main test series due to care full preparation by using several calculation methods and doing a pre-test series to find the limits. In the pre-test series it was found that if the insertion depth was changed from 90 mm to 70 mm screw steel tensile failure would probably not occur.
- Looking more closely at what is happening to the timber and the screw after testing. Generally two failure patters could be observed looking at the timber: screw slipping out of pre-drilled hole and screw pulling out the timber, this caused stretch marks of the screw in the pre-drilled hole or a completely pulverised pre-drilled hole respectively. A combination of the two was also observed. In very rare cases the screw was damaged after testing.

What is the influence of the self-tapping screw diameter on the withdrawal strength?

- With increasing screw diameter the withdrawal strength decreases as was found in this analysis. Only in the case of pre-drilling 0,9d for the diameter 8 mm screw this was not the case when comparing it to the diameter 6 mm screw, this probably was a result of pre-drilling accuracy.

What is the influence of the pre-driling diameter on the withdrawal strength?

- Two pre-drilling diameters were tested in the main test series during this project namely: 0,8d and 0,9d.
- It was found during testing that on average the withdrawal strength is reduced with a factor of 0,68 when pre-drilling 0,9d in stead of 0,8d.

What is the influence of the effective length of self-tapping screws on the withdrawal strength?

- No clear influence of the effective screw length could be observed, except for screw diameters 6 mm and 8 mm when pre-drilled 0,9d. These are special hardwood screws with an increased inner diameter, it is possible that the withdrawal strength is not optimal for these screw types when pre-drilled 0,9d.

What is the influence of the tropical hardwood density on the withdrawal strength?

- With increasing density the withdrawal strength also increases.
- When dividing the withdrawal strength with the density it can be observed that these ratios are different per species.

What is the influence of the moisture content in tropical hardwood on the withdrawal strength?

- With increasing moisture content the withdrawal strength decreases. The negative effect of a increased moisture content and moisture uptake rate are different per species. The measured Withdrawal strength decreased on average with a factor of between 0,65 and 0,92 depending on the species and moisture content.

Is it possible to validate the experimental findings using numerical analysis or an empirical formula?

- Yes, two models are proposed in this thesis:
- The first is based on withdrawal strength parameters per species and pre-drilling diameter. This method is a good fit to the test data but in engineering practice it is needed to determine this parameter per species. This is the following method to calculate the withdrawal capacity using the withdrawal strength:

$$F_{ax} = f_{ax} * d * \pi * l_d \tag{9.1}$$

  Values for f_{ax} can be found in table 8.2 in chapter 8.2.2.
- The second is based on all dry test data from testing on tropical hardwood with the nominal diameter, the effective screw length and the timber density as parameters. Also factors to account for the effects of a higher moisture content and pre-drilling are included, this is the following:

$$f_{ax,prop,allmean} = (3,84 * 10^{-4} * d^{-0,39} * l_{eff}^{0,05} * \rho_{12,mean}^{1,64}) * k_{uc} * k_{Dp} \tag{9.2}$$

  Factor k_{Dp} is 0,68 when pre-drilling 0,9d in stead of 0,8d. Factors for k_{uc} can be found in table 8.4 in chapter 8.3.

How do withdrawal test results compare to current engineering formula?

- The withdrawal test results from testing on dry tropical hardwood with pre-drilling diameter 0,8d were compared to the method provided by EN 1995-1-1:2011. It was found that this method underestimates the withdrawal strength of self-tapping screws perpendicular to the grain.

Is the withdrawal strength of tropical hardwood species applicable in engineering practice?

- It is possible to use the withdrawal strength of self-tapping screws in engineering practice. Pre-drilling is recommended since it can be very difficult to otherwise insert the screw. Further the tensile steel capacity of the screw can already be reached with only short insertion depths especially with very high density timber species, this has to be taken into account.

Could tropical hardwood meet the requirements to make sure 100 percent of the dowels are effective in reinforced dowel type connections?

- Splitting can be prevented in dowel type connections if the withdrawal strength of a screw inserted perpendicular to the grain is equal or larger than 30 % of the lateral load carrying capacity per shear plane of a dowel.
- A case study has been conducted regarding this topic using the proposed calculation models. It was found that in general it is possible to use self-tapping screws in tropical hardwood to prevent splitting, but the tensile steel capacity is already reached with short insertion depths.
- For large 24 mm dowels made from very high strength steel it is difficult to reach the required withdrawal strength even with large diameter screws, the tensile steel capacity is easily exceeded.

To finalize, some recommendations are given for further research:

- Expand testing with more diameters, more effective lengths, more species and also test several angles to the grain to get a better idea of the withdrawal strength of tropical hardwood;

- Better wet conditioning of the timber; The wet timber used in this project was conditioned in water for 20 days and then pre-drilled after which being put back in the water again. It might be better to do pre-drilling on the day of testing. It would even be better to simulate real engineering practice by inserting the screw in 'dry' timber and then condition the test pieces in water. This might give results very close to reality. Also longer conditioning might give more realistic results, timber in this thesis was at most more than a month underwater and some timber species did not reach constant mass underwater (this might have taken months to years in some cases).
- Research regarding the use of multiple screws for one dowel to prevent cracking. Methods are now only based on one screw. The reason for this is that is might be necessary as was found in the case-study in chapter 8.5.

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A

Results from testing

Some results are not available and therefore marked with n.a.

Test series	Plank code	Diameter [mm]	Insertion depth [mm]	Timber condition	Pre- drilling diameter [mm]	Timber species	F1 [kN]	F2 [kN]	F3 [kN]	F4 [kN]	Fave- rage [kN]	FCOV [%]	Density [kg/m3]	Moisture content [%]	Insertion moment1 [Nm]	Insertion moment2 [Nm]	Insertion moment3 [Nm]	Insertion moment4 [Nm]	Insertion moment av [Nm]	Insertion mo- ment COV [%]	slip modu- lus1 [kN/mm]	slip modu- lus2 [kN/mm]	slip modulus average [kN/mm]	slipCOV [%]
1	KA-3028	6	25	dry	0,8d	Kanda	2,7	3,0	2,1	1,7	2,4	24,5	696,8	8,8	1,0	0,8	0,9	1,4	1,0	25,0	4,4	1,9	3,1	56,8
2	LO-4018	6	25	dry	0,8d	Lati	3,6	3,5	3,4	3,8	3,6	4,1	775,0	9,5	1,5	2,5	3,4	2,2	2,4	32,9	9,9	15,2	12,5	30,3
3	CH-3001	6	25	dry	0,8d	Longhi	4,4	3,5	3,9	3,0	3,7	15,8	685,8	9,8	2,7	1,8	3,1	1,8	2,4	27,2	16,1	4,8	10,5	76,7
4	TA-1049	6	25	dry	0,8d	Tali	6,4	5,3	7,6	7,1	6,6	15,3	975,0	8,8	4,3	3,2	5,2	4,7	4,3	20,1	53,4	29,6	41,5	40,6
5	LM-1028	6	25	dry	0,8d	Limbali	4,2	3,5	4,2	3,7	3,9	9,0	800,5	9,9	3,3	2,9	2,2	1,8	2,6	26,6	18,2	14,5	16,3	16,0
6	MU-2015	6	25	dry	0,8d	Mukulungu	5,1	6,0	6,4	6,2	5,9	9,2	943,6	12,9	2,9	4,5	5,9	5,2	4,6	27,4	31,2	37,8	34,5	13,6
7	KA-6036	6	25	dry	0,9d	Kanda	1,2	1,7	1,1	1,0	1,3	22,4	594,6	9,1	0,3	0,5	0,3	0,9	0,5	58,2	4,5	2,8	3,6	33,4
8	LO-2045	6	25	dry	0,9d	Lati	2,7	2,7	1,8	1,8	2,2	22,7	796,1	9,7	3,0	3,0	2,5	2,2	2,7	14,0	10,3	6,1	8,2	36,3
9	CH-3002	6	25	dry	0,9d	Longhi	1,9	1,9	2,7	2,6	2,3	17,8	761,8	9,4	0,6	0,3	0,5	1,5	0,7	71,7	23,1	21,7	22,4	4,5
10	TA-1005	6	25	dry	0,9d	Tali	2,6	3,1	3,4	3,6	3,1	14,0	1031,7	9,0	2,7	2,5	4,0	3,1	3,1	21,1	39,9	24,7	32,3	33,4
11	LM-1034	6	25	dry	0,9d	Limbali	1,7	1,8	1,6	1,9	1,7	8,3	833,9	9,5	0,9	1,2	0,4	1,1	0,9	38,1	7,6	19,4	13,5	61,5
12	MU-1021	6	25	dry	0,9d	Mukulungu	2,6	2,6	2,7	2,7	2,7	3,0	938,1	13,0	1,1	0,9	2,1	2,2	1,6	42,6	29,6	29,1	29,3	1,4
13	KA-2007	6	50	dry	0,8d	Kanda	6,8	6,9	6,1	5,3	6,3	11,7	683,6	8,8	1,0	1,2	2,1	1,5	1,5	33,3	12,0	9,2	10,6	18,4
14	LO-4045	6	50	dry	0,8d	Lati	10,8	10,3	10,0	9,6	10,2	4,7	734,1	9,6	3,7	3,1	5,1	3,0	3,7	26,7	25,4	22,4	23,9	9,0
15	CH-3024	6	50	dry	0,8d	Longhi	10,2	11,4	9,5	10,1	10,3	7,6	673,9	9,7	4,0	3,1	2,8	2,3	3,0	23,7	15,1	19,6	17,4	18,3
16	TA-2007	6	50	dry	0,8d	Tali	17,5	16,4	16,0	14,0	15,9	9,0	977,5	8,8	6,1	5,3	5,6	3,1	5,0	26,6	35,3	26,1	30,7	21,4
17	LM-1014	6	50	dry	0,8d	Limbali	12,3	12,0	11,0	12,8	12,0	6,2	844,5	9,4	3,0	1,9	3,3	2,0	2,6	27,8	25,4	33,4	29,4	19,2
18	MU-2021	6	50	dry	0,8d	Mukulungu	12,2	13,9	12,6	12,4	12,8	6,0	966,1	12,9	5,0	3,0	3,7	4,0	3,9	20,4	30,6	28,5	29,5	5,1
19	KA-2002	6	50	dry	0,9d	Kanda	6,0	4,6	5,1	4,1	5,0	16,6	713,5	8,8	2,2	2,0	1,6	2,0	2,0	11,7	14,7	8,8	11,7	35,8
20	LO-2046	6	50	dry	0,9d	Lati	6,3	7,5	6,0	6,0	6,4	11,0	780,8	9,7	2,0	2,3	2,8	2,7	2,5	13,9	18,5	12,2	15,3	29,4
21	CH-2037	6	50	dry	0,9d	Longhi	7,0	8,3	6,0	6,5	7,0	14,2	680,9	9,5	2,6	2,9	2,3	1,3	2,3	30,3	13,0	11,6	12,3	8,2
22	TA-2026	6	50	dry	0,9d	Tali	8,7	9,1	9,4	8,1	8,8	6,5	949,0	9,3	2,4	2,8	1,7	2,5	2,4	20,2	32,2	27,5	29,9	11,2
23	LM-3001	6	50	dry	0,9d	Limbali	6,0	7,1	6,1	7,6	6,7	11,8	843,0	9,8	0,3	0,9	2,2	1,1	1,1	71,5	16,3	23,4	19,9	25,4
24	MU-2039	6	50	dry	0,9d	Mukulungu	10,1	10,0	10,0	9,3	9,9	4,1	953,1	12,3	3,6	1,4	2,7	2,4	2,5	37,3	31,8	26,0	28,9	14,3
25	KA-1063	6	25	wet	0,8d	Kanda	2,0	2,3	1,6	1,6	1,9	17,0	653,0	21,4	0,4	0,6	0,6	0,7	0,5	19,2	2,8	2,7	2,8	3,6
26	LO-4044	6	25	wet	0,8d	Lati	2,7	2,5	2,4	2,3	2,5	6,6	929,3	47,6	1,0	1,2	1,3	1,5	1,3	16,2	6,5	5,6	6,0	10,2
27	CH-3023	6	25	wet	0,8d	Longhi	2,8	3,3	3,3	2,7	3,0	9,6	859,0	46,7	1,5	1,6	1,9	1,7	1,7	10,9	7,6	4,8	6,2	31,4
28	TA-3031	6	25	wet	0,8d	Tali	4,2	3,8	3,6	3,7	3,9	6,8	945,5	16,4	1,7	1,5	1,5	1,2	1,5	14,3	9,8	9,2	9,5	4,4
29	LM-4025	6	25	wet	0,8d	Limbali	4,3	3,5	3,4	3,2	3,6	14,1	805,6	22,9	1,2	1,1	1,8	1,9	1,5	27,7	6,2	4,9	5,6	16,6
30	MU-2001	6	25	wet	0,8d	Mukulungu	3,5	3,3	3,0	3,0	3,2	7,9	954,5	27,0	1,1	1,0	1,4	1,0	1,2	13,5	6,8	6,7	6,7	0,5
31	KA-1068	6	25	wet	0,9d	Kanda	0,8	0,7	2,5	2,3	1,6	61,7	684,1	23,6	0,2	0,2	0,2	0,2	0,2	16,2	n.a.	n.a.	n.a.	n.a.
32	LO-4039	6	25	wet	0,9d	Lati	1,5	1,7	1,6	1,4	1,5	7,4	987,9	61,8	0,6	0,8	0,8	0,7	0,7	15,3	n.a.	n.a.	n.a.	n.a.
33	CH-3019	6	25	wet	0,9d	Longhi	1,7	1,7	1,6	1,4	1,6	10,2	823,3	45,2	0,6	0,7	0,9	0,6	0,7	15,1	5,4		5,4	
34	TA-1010	6	25	wet	0,9d	Tali	2,0	1,6	1,6	1,1	1,6	22,0	902,7	18,1	0,5	0,6	0,5	0,7	0,5	18,6	13,4	2,5	7,9	97,5
35	LM-4022	6	25	wet	0,9d	Limbali	1,4	1,2	1,8	1,7	1,5	19,5	802,1	19,8	0,7	0,7	0,8	0,6	0,7	11,7	n.a.	n.a.	n.a.	n.a.
36	MU-3048	6	25	wet	0,9d	Mukulungu	1,9	1,8	1,9	1,7	1,8	4,6	917,9	30,8	0,5	0,4	0,6	0,7	0,6	27,5	n.a.	n.a.	n.a.	n.a.
37	KA-1043	6	50	wet	0,8d	Kanda	5,0	5,0	4,8	5,1	5,0	2,3	671,1	20,4	1,1	1,1	1,0	1,4	1,2	15,4	9,6	16,4	13,0	37,5
38	LO-4023	6	50	wet	0,8d	Lati	5,6	6,1	6,3	6,1	6,0	5,0	925,8	53,3	2,4	2,6	3,1	2,5	2,6	12,3	12,0	10,9	11,5	6,7
39	CH-3026	6	50	wet	0,8d	Longhi	7,8	7,9	7,1	6,6	7,3	8,4	838,3	45,0	2,7	2,8	2,5	2,3	2,6	8,4	10,7	9,3	10,0	9,6
40	TA-3026	6	50	wet	0,8d	Tali	14,1	14,4	11,7	11,5	12,9	11,7	995,5	17,1	3,5	3,4	4,3	3,4	3,6	11,3	22,4	18,3	20,4	14,3
41	LM-2009	6	50	wet	0,8d	Limbali	9,6	9,8	10,4	6,8	9,1	17,2	873,6	22,6	3,5	3,0	3,6	2,8	3,2	12,4	19,8	8,9	14,3	53,9
42	MU-2002	6	50	wet	0,8d	Mukulungu	9,6	9,4	10,3	9,8	9,8	4,1	978,3	25,1	3,4	2,8	3,5	3,1	3,2	9,5	22,0	19,4	20,7	8,9
43	KA-1050	6	50	wet	0,9d	Kanda	3,3	3,0	3,6	3,2	3,3	7,5	755,0	24,5	0,9	0,6	0,9	1,1	0,9	21,9	10,7	8,8	9,8	13,6
44	LO-2036	6	50	wet	0,9d	Lati	6,0	5,6	4,8	4,9	5,3	11,0	934,9	48,1	1,9	1,3	1,5	1,9	1,6	16,1	8,9	8,6	8,8	2,6
45	CH-3021	6	50	wet	0,9d	Longhi	6,0	7,0	5,0	4,9	5,7	17,1	839,2	38,2	1,9	2,2	1,8	1,9	2,0	8,3	7,6	7,5	7,5	0,2
46	TA-2009	6	50	wet	0,9d	Tali	7,1	5,9	6,3	5,9	6,3	9,2	921,9	16,3	2,1	1,5	1,6	1,7	1,7	13,6	14,3	11,8	13,1	13,6
47	LM-4203	6	50	wet	0,9d	Limbali	4,6	5,7	4,8	4,4	4,9	11,2	914,3	21,8	1,8	1,4	1,3	1,2	1,4	18,4	10,6	7,2	8,9	26,9
48	MU-1025	6	50	wet	0,9d	Mukulungu	6,3	5,7	5,9	5,8	5,9	4,7	991,0	26,2	1,3	1,5	2,3	1,3	1,6	28,3	13,0	12,4	12,7	3,4

Figure A.1: Results test numbers 1 to 48.

Test series	Plank code	Diameter [mm]	Insertion depth [mm]	Timber condition	Pre- drilling diameter [mm]	Timber species	F1 [kN]	F2 [kN]	F3 [kN]	F4 [kN]	Fave-rage [kN]	FCOV [%]	Density [kg/m3]	Moisture content [%]	Insertion moment1 [Nm]	Insertion moment2 [Nm]	Insertion moment3 [Nm]	Insertion moment4 [Nm]	Insertion moment av [Nm]	Insertion mo-ment COV [%]	slip modu-lus1 [kN/mm]	slip modu-lus2 [kN/mm]	slip modulus average [kN/mm]	slipCOV [%]
49	KA-5010	8	50	dry	0,8d	Kanda	7,8	8,2	6,7	6,4	7,3	11,3	590,5	9,5	2,1	2,0	1,0	1,6	1,7	30,0	9,9	8,6	9,2	9,8
50	LO-2047	8	50	dry	0,8d	Lati	9,3	9,7	11,0	10,8	10,2	8,2	766,3	10,1	3,9	2,6	3,7	3,9	3,5	16,8	22,7	20,5	21,6	7,0
51	CH-2003	8	50	dry	0,8d	Longhi	12,9	12,1	12,4	12,2	12,4	3,0	705,1	10,1	5,1	3,6	4,4	3,3	4,1	20,4	16,8	15,2	16,0	7,3
52	TA-2008	8	50	dry	0,8d	Tali	20,4	15,1	20,3	15,0	17,7	17,2	978,9	9,1	6,2	5,9	5,8	3,9	5,4	19,6	40,4	20,4	30,4	46,5
53	LM-1018	8	50	dry	0,8d	Limbali	10,8	11,0	12,1	13,1	11,8	8,9	867,7	9,4	2,0	2,3	3,8	3,3	2,8	28,9	27,0	28,9	28,0	4,8
54	MU-3009	8	50	dry	0,8d	Mukulungu	16,6	16,0	14,5	15,6	15,7	5,7	896,6	13,7	5,7	5,7	5,2	5,1	5,4	6,3	26,2	21,8	24,0	13,2
55	KA-1051	8	50	dry	0,9d	Kanda	4,9	5,8	5,6	6,0	5,6	8,6	641,0	8,8	2,1	2,4	0,9	1,3	1,7	42,2	12,0	8,4	10,2	24,8
56	LO-4019	8	50	dry	0,9d	Lati	8,1	9,3	8,6	8,5	8,6	5,5	807,2	9,2	1,5	2,0	2,0	1,4	1,7	19,6	10,6	10,5	10,6	0,8
57	CH-2040	8	50	dry	0,9d	Longhi	9,3	9,3	8,9	9,7	9,3	3,3	673,3	9,7	4,0	2,2	3,5	3,3	3,2	23,7	15,0	15,0	15,0	0,3
58	TA-1044	8	50	dry	0,9d	Tali	10,6	11,2	11,1	11,2	11,0	2,8	889,0	8,8	2,3	1,9	3,7	3,8	2,9	32,5	18,1	16,5	17,3	6,3
59	LM-4045	8	50	dry	0,9d	Limbali	11,8	12,2	9,1	10,4	10,9	12,6	851,0	9,1	2,6	2,8	2,9	2,5	2,7	7,1	14,7	13,8	14,3	4,3
60	MU-3015	8	50	dry	0,9d	Mukulungu	10,3	9,2	12,8	14,2	11,6	19,4	957,2	13,4	1,8	1,4	4,0	3,1	2,6	46,3	37,3	26,7	32,0	23,4
61	KA-1052	8	70	dry	0,8d	Kanda	13,2	13,9	13,1	12,5	13,1	4,3	635,6	8,9	1,3	0,9	1,9	1,3	1,3	29,9	17,8	14,1	15,9	16,5
62	LO-2049	8	70	dry	0,8d	Lati	14,9	14,4	13,6	13,8	14,2	4,3	790,9	9,2	4,0	2,8	4,5	3,3	3,7	20,5	27,7	21,3	24,5	18,5
63	CH-2017	8	70	dry	0,8d	Longhi	16,0	16,3	17,1	17,2	16,7	3,5	684,3	10,2	2,6	3,3	3,4	3,7	3,3	14,9	24,9	25,8	25,3	2,6
64	TA-3016	8	70	dry	0,8d	Tali	29,6	29,6	29,9	30,5	29,9	1,4	1064,1	9,1	4,6	5,4	6,0	4,5	5,1	13,7	53,2	43,1	48,2	14,9
65	LM-1044	8	70	dry	0,8d	Limbali	16,4	16,0	17,2	16,5	16,5	3,0	796,0	9,1	2,2	2,4	2,9	2,4	2,5	12,5	27,0	23,6	25,3	9,6
66	MU-3014	8	70	dry	0,8d	Mukulungu	23,2	23,7	25,3	24,4	24,2	3,7	899,7	13,7	7,5	5,9	5,1	6,3	6,2	16,1	46,7	38,0	42,4	14,5
67	KA-5014	8	70	dry	0,9d	Kanda	9,8	9,0	9,2	8,4	9,1	6,4	588,4	9,1	0,9	1,1	1,2	1,1	1,1	11,4	14,9	12,4	13,7	12,9
68	LO-4040	8	70	dry	0,9d	Lati	16,5	16,2	14,9	13,6	15,3	8,9	772,5	9,3	3,5	3,3	1,6	2,6	2,8	30,4	20,2	10,5	15,4	44,4
69	CH-2018	8	70	dry	0,9d	Longhi	14,1	16,7	13,6	15,2	14,9	9,4	669,2	9,8	1,9	3,0	3,4	3,1	2,9	23,4	16,6	16,9	16,7	1,5
70	TA-3017	8	70	dry	0,9d	Tali	23,5	21,3	18,5	18,3	20,4	12,3	901,2	9,0	3,3	3,0	3,0	2,6	3,0	10,0	28,3	19,4	23,9	26,6
71	LM-4046	8	70	dry	0,9d	Limbali	14,0	14,7	16,2	18,2	15,8	11,8	810,2	9,5	2,4	2,0	2,9	1,9	2,3	19,0	30,4	28,1	29,2	5,6
72	MU-3024	8	70	dry	0,9d	Mukulungu	22,2	21,1	22,3	23,0	22,2	3,5	943,8	12,8	4,3	3,9	4,8	4,7	4,4	9,7	29,8	30,4	30,1	1,3
73	KA-1061	8	50	wet	0,8d	Kanda	6,7	6,3	5,4	5,1	5,9	12,6	672,3	25,8	2,0	2,1	1,9	1,5	1,9	13,4	6,5	5,4	5,9	13,1
74	LO-4038	8	50	wet	0,8d	Lati	6,9	7,5	6,2	6,7	6,8	7,5	994,6	54,7	2,9	3,1	2,3	3,6	3,0	18,8	7,5	9,5	8,5	16,5
75	CH-2011	8	50	wet	0,8d	Longhi	8,6	8,8	8,8	8,4	8,6	2,1	822,1	47,6	4,1	4,2	4,5	4,2	4,2	4,5	12,0	10,7	11,4	8,1
76	TA-1028	8	50	wet	0,8d	Tali	9,3	10,2	8,2	8,9	9,2	8,8	983,9	21,6	2,3	3,1	3,0	3,6	3,0	17,7	12,5	10,1	11,3	14,5
77	LM-2015	8	50	wet	0,8d	Limbali	11,1	10,7	10,5	10,0	10,6	4,3	904,8	23,3	4,7	4,2	3,9	4,1	4,2	8,0	13,7	14,5	14,1	3,9
78	MU-3039	8	50	wet	0,8d	Mukulungu	10,7	11,9	9,3	9,9	10,5	10,6	997,6	27,9	4,0	3,9	5,0	4,5	4,3	11,8	14,8	11,3	13,1	19,1
79	KA-1054	8	50	wet	0,9d	Kanda	3,4	3,9	3,5	3,1	3,5	8,9	675,1	23,6	1,2	1,0	1,2	1,0	1,1	12,1	7,8	28,9	18,3	81,7
80	LO-4033	8	50	wet	0,9d	Lati	5,8	5,9	5,3	5,2	5,6	6,1	1007,1	60,1	2,4	2,2	2,8	2,3	2,4	10,7	17,2	8,9	13,0	45,3
81	CH-3008	8	50	wet	0,9d	Longhi	7,5	8,2	6,5	7,1	7,3	9,4	884,2	41,1	2,7	2,5	2,6	2,2	2,5	7,6	9,0	8,8	8,9	1,8
82	TA-2019	8	50	wet	0,9d	Tali	9,0	10,0	8,2	10,1	9,3	9,8	1025,9	14,0	1,7	1,6	1,5	1,1	1,5	17,1	15,1	16,8	17,0	1,6
83	LM-4016	8	50	wet	0,9d	Limbali	5,7	6,0	5,3	6,0	5,7	5,6	820,5	25,7	1,6	1,7	2,2	2,1	1,9	17,2	9,0	9,4	9,2	3,4
84	MU-2040	8	50	wet	0,9d	Mukulungu	6,3	6,5	6,5	6,0	6,3	3,8	945,1	27,2	1,7	1,8	2,1	1,8	1,8	10,3	11,1	10,3	10,7	5,0
85	KA-4062	8	70	wet	0,8d	Kanda	10,1	9,8	10,1	10,4	10,1	2,6	698,2	26,1	2,2	1,9	2,1	2,0	2,0	6,6	11,6	10,7	11,1	6,0
86	LO-4022	8	70	wet	0,8d	Lati	11,3	11,6	11,5	11,4	11,5	1,3	1014,8	58,4	4,5	4,2	5,6	5,1	4,8	12,8	17,7	14,8	16,3	12,6
87	CH-2013	8	70	wet	0,8d	Longhi	13,8	13,3	13,1	12,7	13,2	3,3	895,4	55,1	5,7	5,2	6,6	5,9	5,8	10,0	18,1	15,5	16,8	10,9
88	TA-1025	8	70	wet	0,8d	Tali	19,1	20,7	16,1	16,7	18,1	11,8	990,4	22,2	4,8	5,0	4,0	4,0	4,5	12,0	20,8	20,1	20,5	2,4
89	LM-2014	8	70	wet	0,8d	Limbali	19,7	18,5	18,2	18,6	18,8	3,4	949,6	21,2	5,7	5,4	5,5	5,6	5,6	2,7	24,3	23,9	24,1	1,2
90	MU-2022	8	70	wet	0,8d	Mukulungu	14,3	14,5	14,7	15,3	14,7	2,9	1014,1	30,6	5,0	5,1	6,0	5,6	5,4	8,4	24,5	23,6	24,1	2,8
91	KA-1060	8	70	wet	0,9d	Kanda	5,9	6,8	5,9	6,0	6,2	7,1	693,5	26,5	1,6	1,3	2,2	1,3	1,6	26,3	7,3	7,2	7,3	1,1
92	LO-2035	8	70	wet	0,9d	Lati	9,4	9,9	8,2	7,3	8,7	13,4	1022,3	59,1	2,8	2,4	2,2	2,6	2,5	10,5	10,0	8,2	9,1	13,6
93	CH-3009	8	70	wet	0,9d	Longhi	9,7	9,8	9,9	10,0	9,9	1,5	839,3	49,5	3,5	3,1	3,7	2,9	3,3	10,7	15,6	14,6	15,1	4,8
94	TA-1039	8	70	wet	0,9d	Tali	15,6	15,9	13,8	14,4	14,9	6,7	966,7	16,5	3,7	3,7	3,7	2,6	3,4	16,5	22,3	20,0	21,2	7,5
95	LM-1013	8	70	wet	0,9d	Limbali	10,3	10,8	9,8	10,8	10,4	4,6	839,7	26,4	2,2	1,9	2,8	2,4	2,3	16,3	13,6	14,6	14,1	4,9
96	MU-1040	8	70	wet	0,9d	Mukulungu	9,5	11,2	9,7	11,5	10,5	9,6	988,2	28,4	3,2	3,5	3,7	3,9	3,6	8,9	16,5	18,5	17,5	7,7

Figure A.2: Results test numbers 49 to 96.

Test series	Plank code	Diameter [mm]	Insertion depth [mm]	Timber condition	Pre- drilling diameter [mm]	Timber species	F1 [kN]	F2 [kN]	F3 [kN]	F4 [kN]	Fave- rage [kN]	FCOV [%]	Density [kg/m3]	Moisture content [%]	Insertion moment1 [Nm]	Insertion moment2 [Nm]	Insertion moment3 [Nm]	Insertion moment4 [Nm]	Insertion moment av [Nm]	Insertion mo- ment COV [%]	slip modu- lus1 [kN/mm]	slip modu- lus2 [kN/mm]	slip modulus average [kN/mm]	slipCOV [%]
97	KA-2006	11	50	dry	0,8d	Kanda	8,7	8,1	7,8	8,2	8,2	4,5	670,0	8,7	2,5	2,4	2,5	2,3	2,4	3,4	11,5	15,6	13,5	21,5
98	LO-4017	11	50	dry	0,8d	Lati	13,2	13,2	10,6	11,5	12,1	10,5	769,4	9,5	5,1	5,1	5,7	4,5	5,1	9,5	17,3	19,7	18,5	8,9
99	CH-2035	11	50	dry	0,8d	Longhi	12,6	12,1	13,7	12,0	12,6	6,0	656,2	9,5	7,3	5,2	7,7	4,2	6,1	27,3	26,5	26,4	26,4	0,4
100	TA-2022	11	50	dry	0,8d	Tali	20,5	20,2	19,4	18,5	19,7	4,4	995,2	9,1	8,1	10,0	7,4	10,1	8,9	15,3	35,4	34,1	34,8	2,7
101	LM-1012	11	50	dry	0,8d	Limbali	13,0	12,9	13,9	13,2	13,3	3,3	810,3	9,6	3,5	3,9	2,8	2,8	3,2	16,7	28,6	33,4	31,0	10,9
102	MU-1038	11	50	dry	0,8d	Mukulungu	17,3	18,7	17,0	18,1	17,8	4,5	943,8	12,8	10,2	9,1	7,7	10,8	9,5	14,5	26,4	32,6	29,5	15,1
103	KA-2025	11	50	dry	0,9d	Kanda	4,5	4,0	4,0	4,1	4,1	6,5	681,0	9,2	0,6	1,2	0,3	1,2	0,8	54,5	15,2	9,5	12,3	32,5
104	LO-4036	11	50	dry	0,9d	Lati	7,1	8,5	7,0	8,5	7,8	10,9	779,6	9,6	2,7	2,9	4,4	4,5	3,6	26,1	13,7	16,9	15,3	14,9
105	CH-2027	11	50	dry	0,9d	Longhi	9,4	9,5	7,4	6,7	8,3	16,8	673,4	9,9	2,4	3,3	3,2	2,6	2,9	14,8	9,5	7,5	8,5	16,5
106	TA-1045	11	50	dry	0,9d	Tali	10,3	11,4	9,7	9,6	10,3	7,9	912,9	8,9	3,3	3,9	5,2	3,5	4,0	20,9	22,5	17,0	19,8	19,7
107	LM-1015	11	50	dry	0,9d	Limbali	8,9	8,2	8,8	7,9	8,5	5,4	871,7	9,3	1,6	2,7	2,4	1,8	2,1	24,9	16,4	11,8	14,1	23,0
108	MU-2023	11	50	dry	0,9d	Mukulungu	8,6	8,4	9,1	9,6	8,9	6,1	897,8	13,1	3,5	6,7	4,4	3,4	4,5	33,9	18,6	23,0	20,8	15,0
109	KA-2003	11	70	dry	0,8d	Kanda	16,4	14,7	11,5	12,0	13,6	17,0	719,1	9,0	3,1	2,6	2,7	2,4	2,7	11,1	11,6	12,6	12,1	6,0
110	LO-4020	11	70	dry	0,8d	Lati	20,4	19,3	17,0	14,9	17,9	13,8	776,7	9,6	6,7	7,3	9,1	5,8	7,2	18,9	39,8	25,2	32,5	31,6
111	CH-2002	11	70	dry	0,8d	Longhi	24,4	19,7	14,7	17,9	19,2	21,1	657,8	10,1	11,2	8,5	9,9	7,9	9,4	15,9	32,2	28,4	30,3	8,8
112	TA-2011	11	70	dry	0,8d	Tali	31,3	26,0	21,0	22,1	25,1	18,6	928,0	8,8	8,8	8,8	6,8	7,7	8,0	12,0	90,4	38,7	64,5	56,6
113	LM-1019	11	70	dry	0,8d	Limbali	20,3	19,9	19,7	19,5	19,9	1,7	793,0	9,1	3,6	6,0	5,2	5,8	5,1	21,4	27,8	17,9	22,8	30,7
114	MU-1022	11	70	dry	0,8d	Mukulungu	27,3	26,3	25,8	27,1	26,6	2,6	933,0	12,9	10,9	9,1	11,2	11,8	10,8	10,8	80,7	25,1	52,9	74,3
115	KA-2027	11	70	dry	0,9d	Kanda	6,3	5,9	6,5	6,9	6,4	6,5	679,6	9,1	0,6	0,9	0,9	0,3	0,7	42,6	13,1	13,6	13,3	2,8
116	LO-4013	11	70	dry	0,9d	Lati	11,7	11,7	9,2	8,8	10,3	15,2	697,7	9,8	1,8	3,3	1,5	2,7	2,4	35,5	11,4	9,9	10,6	9,8
117	CH-2029	11	70	dry	0,9d	Longhi	11,6	8,7	10,6	9,2	10,0	13,4	680,1	10,0	2,1	3,0	5,0	4,3	3,6	35,4	11,1	31,2	21,1	67,4
118	TA-2027	11	70	dry	0,9d	Tali	22,3	19,2	17,3	14,5	18,3	17,8	1072,2	9,6	4,8	3,7	4,0	2,1	3,7	30,8	22,6	85,3	53,9	82,3
119	LM-2011	11	70	dry	0,9d	Limbali	10,8	10,0	9,8	8,9	9,9	7,9	880,0	10,1	1,8	2,0	3,9	2,2	2,5	38,0	26,7	15,6	21,1	37,2
120	MU-2041	11	70	dry	0,9d	Mukulungu	18,0	15,0	15,4	13,5	15,5	12,1	893,3	13,2	5,3	4,4	3,9	4,0	4,4	14,1	29,1	25,8	27,4	8,5
121	KA-2004	11	50	wet	0,8d	Kanda	6,8	7,6	7,3	7,2	7,2	4,5	760,4	23,4	2,8	2,9	3,7	3,5	3,2	14,1	17,1	14,2	15,7	13,1
122	LO-4043	11	50	wet	0,8d	Lati	12,0	11,4	10,1	10,3	11,0	8,3	989,9	58,8	6,8	6,5	7,2	6,7	6,8	4,7	13,8	11,7	12,7	11,9
123	CH-3025	11	50	wet	0,8d	Longhi	11,5	11,8	10,7	10,7	11,2	5,0	873,4	53,0	3,8	4,0	7,0	6,9	5,4	32,8	16,7	15,1	15,9	7,0
124	TA-1048	11	50	wet	0,8d	Tali	20,3	15,8	13,5	13,4	15,7	20,5	965,2	19,4	13,7	9,5	8,4	8,1	9,9	26,2	23,2	14,8	19,0	31,1
125	LM-1030	11	50	wet	0,8d	Limbali	15,2	12,2	10,2	10,3	12,0	19,5	871,8	25,3	9,5	6,6	6,8	7,4	7,6	17,6	10,0	8,7	9,4	10,3
126	MU-2044	11	50	wet	0,8d	Mukulungu	14,4	13,2	10,9	11,0	12,4	13,7	934,0	27,8	7,5	6,3	6,7	6,6	6,8	7,9	17,9	16,1	17,0	7,2
127	KA-6041	11	50	wet	0,9d	Kanda	3,9	3,3	2,7	2,3	3,0	23,3	655,1	32,1	1,9	1,6	0,7	0,9	1,3	43,7	4,0	2,2	3,1	42,0
128	LO-4016	11	50	wet	0,9d	Lati	5,7	4,5	5,8	3,1	4,8	26,3	932,6	53,5	2,4	2,4	2,6	2,1	2,4	8,6	8,1	2,8	5,5	68,6
129	CH-2024	11	50	wet	0,9d	Longhi	4,8	6,3	4,9	5,5	5,4	12,8	833,8	46,8	2,7	2,9	3,1	3,1	2,9	7,0	9,4	8,0	8,7	11,7
130	TA-1047	11	50	wet	0,9d	Tali	6,9	6,1	7,5	5,4	6,5	14,0	933,6	24,3	5,9	1,7	3,4	3,6	3,6	46,9	17,7	14,2	15,9	15,4
131	LM-4050	11	50	wet	0,9d	Limbali	6,1	6,7	8,1	4,9	6,5	20,8	942,7	26,9	3,7	3,1	2,5	2,4	2,9	20,4	14,3	7,2	10,8	46,4
132	MU-1010	11	50	wet	0,9d	Mukulungu	7,4	6,6	6,5	5,4	6,5	12,8	996,6	33,1	3,5	3,0	3,8	3,1	3,3	11,5	9,9	6,6	8,3	27,9
133	KA-6020	11	70	wet	0,8d	Kanda	12,6	12,7	11,7	11,3	12,1	5,6	727,5	33,3	4,2	4,3	4,6	4,1	4,3	5,5	14,1	14,9	14,5	4,0
134	LO-4037	11	70	wet	0,8d	Lati	16,9	14,8	14,5	13,4	14,9	9,9	1033,1	62,4	6,8	7,5	6,5	8,6	7,3	12,6	18,9	15,1	17,0	15,8
135	CH-3007	11	70	wet	0,8d	Longhi	16,6	16,7	17,1	16,7	16,8	1,3	864,5	49,7	9,6	9,0	9,3	8,7	9,2	4,2	26,5	26,1	26,3	1,1
136	TA-1046	11	70	wet	0,8d	Tali	30,3	30,5	30,2	27,6	29,6	4,7	1012,1	15,8	12,8	14,8	9,0	15,0	12,9	21,7	39,9	45,2	42,6	8,9
137	LM-3002	11	70	wet	0,8d	Limbali	18,7	17,8	17,3	16,3	17,5	5,8	899,1	35,2	10,0	9,8	8,7	9,1	9,4	6,3	22,1	18,7	20,4	11,6
138	MU-1030	11	70	wet	0,8d	Mukulungu	19,6	18,0	17,5	18,1	18,3	4,9	971,1	31,3	7,8	9,9	11,0	8,3	9,2	15,8	29,1	21,2	25,1	22,2
139	KA-1026	11	70	wet	0,9d	Kanda	4,6	6,0	4,1	5,2	5,0	16,9	714,5	45,1	2,0	2,0	2,3	1,5	1,9	17,5	4,8	4,4	4,6	7,1
140	LO-4041	11	70	wet	0,9d	Lati	9,8	8,3	8,4	7,8	8,6	9,7	1011,4	62,3	5,4	5,3	5,0	4,8	5,1	5,6	14,2	9,4	11,8	28,6
141	CH-2025	11	70	wet	0,9d	Longhi	10,2		8,7	7,2	8,7	17,4	882,6	59,3	3,5	4,3	3,7	4,7	4,0	13,0	9,9	6,7	8,3	26,9
142	TA-1043	11	70	wet	0,9d	Tali	11,3	10,4	11,7	9,5	10,7	9,1	960,3	25,6	5,1	3,4	3,9	3,3	3,9	21,0	20,6	15,2	17,9	21,3
143	LM-1026	11	70	wet	0,9d	Limbali	9,6	9,2	8,5	9,5	9,2	5,1	843,7	33,7	2,9	3,5	3,9	3,2	3,4	11,9	14,6	10,6	12,6	22,7
144	MU-2030	11	70	wet	0,9d	Mukulungu	14,0	12,4	13,5	14,0	13,5	5,6	1021,6	30,0	5,0	4,6	5,4	5,0	5,0	6,9	20,9	19,6	20,3	4,6

Figure A.3: Results test numbers 97 to 144.

Test series	Plank code	Diameter [mm]	Insertion depth [mm]	Timber condition	Pre- drilling diameter [mm]	Timber species	F1 [kN]	F2 [kN]	F3 [kN]	F4 [kN]	Fave-rage [kN]	FCOV [%]	Density [kg/m3]	Moisture content [%]	Insertion moment1 [Nm]	Insertion moment2 [Nm]	Insertion moment3 [Nm]	Insertion moment4 [Nm]	Insertion moment av [Nm]	Insertion mo-ment COV [%]	slip modu-lus1 [kN/mm]	slip modu-lus2 [kN/mm]	slip modulus average [kN/mm]	slipCOV [%]
145	SPA-1101	6	25	dry	0,8d	Spruce	2,8	2,6	2,0	2,2	2,4	16,2	499,1	12,6	0,8	1,6	1,9	2,2	1,6	36,5	3,2	5,4	4,3	36,6
146	SPA-0502	6	25	dry	0,9d	Spruce	1,4	1,4	1,1	1,1	1,2	12,9	493,6	12,2	1,2	0,7	0,7	0,8	0,9	29,2	n.a.	n.a.	n.a.	n.a.
147	SPA-8003	6	50	dry	0,8d	Spruce	3,8	3,9	3,6	3,6	3,7	4,0	416,7	12,3	1,3	1,7	1,0	0,7	1,2	35,3	6,4	5,8	6,1	7,3
148	SPA-1104	6	50	dry	0,9d	Spruce	3,4	3,3	2,9	3,7	3,3	9,6	483,5	12,5	1,3	1,7	1,7	1,2	1,5	18,6	7,7	12,9	10,3	35,4
149	SPA-0501	8	50	dry	0,8d	Spruce	6,5	6,9	5,0	5,3	5,9	15,1	484,9	12,1	1,6	2,0	2,3	2,0	2,0	16,4	4,9	4,1	4,5	12,4
150	SPA-1102	8	50	dry	0,9d	Spruce	5,3	4,3	3,4	4,0	4,3	18,1	493,4	12,5	1,2	1,4	2,3	2,1	1,7	31,4	5,5	5,3	5,4	2,5
151	SPA-8004	8	70	dry	0,8d	Spruce	6,5	6,8	6,9	6,9	6,8	3,3	420,3	12,2	1,5	1,4	1,7	1,5	1,5	7,6	7,4	8,4	7,9	8,9
152	SPA-0504	8	70	dry	0,9d	Spruce	8,3	7,3	6,4	7,3	7,3	10,4	499,3	12,0	2,1	1,9	2,1	1,9	2,0	7,1	6,7	7,6	7,1	8,5
153	SPA-1103	11	50	dry	0,8d	Spruce	6,7	5,9	6,4	6,5	6,4	5,0	487,5	12,5	4,1	2,8	4,0	2,6	3,4	23,4	23,9	7,6	15,8	73,0
154	SPA-8001	11	50	dry	0,9d	Spruce	4,4	3,6	4,2	4,8	4,2	12,1	412,6	11,8	1,6	0,7	2,5	2,3	1,8	45,6	5,4	6,4	5,9	12,1
155	SPA-8002	11	70	dry	0,8d	Spruce	8,8		11,5	11,0	10,4	14,0	402,7	12,2	3,6	5,2	3,7	4,0	4,1	17,6	34,3	16,7	25,5	48,8
156	SPA-0503	11	70	dry	0,9d	Spruce	11,5	10,2	9,1	8,9	9,9	12,0	489,8	12,1	5,5	3,7	4,3	3,5	4,3	21,3	10,0	6,7	8,4	28,0

Figure A.4: Results test numbers 145 to 156.