Modeling of nailed timber connection

Displacement path dependency in sheathing-to-framing connections

Authors: Winston Mmari
Supervisor LNU: Thomas K. Bader
Examinar, LNU: Björn Johannesson

Course Code: 4BY35E

Semester: Spring 2017, 15 credits

Linnaeus University, Faculty of Technology
Department of Building Technology
Abstract

Connections in wood have been investigated and advanced ever since the ground-breaking work of Johansen in the early nineteenth century. Nevertheless, not much investigation has been undertaken on the existence of load-displacement path dependency in a sheathing-to-framing connection. Herein, a sheathing-to-framing connection is investigated in relation to displacement path dependency. This work uses 3D Finite Element beam-on-foundation models of an Oriented Strand Board (OSB/2) sheathing nailed to a C24 wood framing, to study possible strategies to numerically simulate the displacement path dependency. The models are used to study if non-linear elastic or elastic-plastic embedment properties of an annular-ringed shank nail in the wood-based materials bring about the path dependency using Connector elements in combination with different material models in the FE software Abaqus. Numerical results are compared with corresponding experimental test results of the connection together with the Eurocode 5 approach. The outcome of the numerical study both; confirms the existence of displacement path dependency and shows that this property in the connection can be described by plasticity properties in nail, sheathing material and the wood framing.

Keywords: Displacement path, Sheathing-to-framing, Beam-on-foundation, Embedment properties, Connector Elements.
Acknowledgement

This master thesis finalizes my one year long master program in Structural Engineering at Linnaeus University, Sweden. The study topic was proposed by Associate Professor Thomas K Bader following experimental tests performed at the Linnaeus University faculty of technology laboratory.

I firstly thank the almighty God for the blessings I continue to have every day and the good health throughout my studies.

I would like to express my deepest appreciation to Professor Thomas K Bader, for supervising this work. His calm, close and friendly support, and endless encouragement have played key role in the completion of this work. His ideas and contribution have been profoundly valuable.

I wish to extend immense gratitude to the faculty and staff at the department of Building Technology and Linnaeus University at large for their support in many ways during the entire period of my studies. The same feeling of appreciation goes to my fellow classmates, colleagues and friends, without them I would not have reached this point.

I extend my sincere thanks to the Swedish Institute SI., for financing my studies and a wonderful life experience in Sweden. Without them, all this would not be possible. I am very grateful. I also thank the whole organization of the University of Dar-es-Salaam, Tanzania, for their contribution towards the completion of my studies.

Finally, but not least I am very grateful to my wonderful parents and most beloved sisters who have been beside me all the way through. Their love, encouragement and moral support keep me going day after day.

Winston Mmari

Växjö 24th of May 2017
Table of contents

ABSTRACT ................................................................................................................................. III

ACKNOWLEDGEMENT ................................................................................................................ V

1. INTRODUCTION ....................................................................................................................... 1

1.1 BACKGROUND AND PROBLEM DESCRIPTION .................................................................. 2
1.2 AIM AND PURPOSE .............................................................................................................. 3
1.3 HYPOTHESIS AND LIMITATIONS .................................................................................... 4
1.3.1 HYPOTHESIS .................................................................................................................. 4
1.3.2 LIMITATIONS .................................................................................................................. 4
1.4 RELIABILITY, VALIDITY AND OBJECTIVITY .................................................................... 4

2. LITERATURE REVIEW ............................................................................................................. 5

2.1 LITERATURE RESEARCH ON NAILED TIMBER CONNECTIONS ..................................... 5

3. THEORY .................................................................................................................................. 9

3.1 WOOD AS A MATERIAL ........................................................................................................ 9
3.1.1 Natural characteristics ..................................................................................................... 9
3.1.2 Physical properties .......................................................................................................... 10
3.1.3 Mechanical properties .................................................................................................... 10
3.1.4 Orthotropic elastic behavior of wood ......................................................................... 11
3.1.5 Elasto-plastic behavior of wood .................................................................................. 11
3.1.6 Engineered wood products ......................................................................................... 11

3.2 LATERAL LOADING (WIND LOADING) IN BUILDINGS ...................................................... 12
3.2.1 Shear walls .................................................................................................................. 12
3.2.2 Elastic analysis of shear walls .................................................................................... 12
3.2.3 Plastic analysis of shear walls ..................................................................................... 13

3.3 NAILED CONNECTIONS ...................................................................................................... 13
3.3.1 Capacity of a connection ............................................................................................... 14
3.3.2 Failure modes in timber-to-timber joints and timber-to-panel joints ....................... 15
3.3.3 Tension capacity of single dowels (Rope effect) ......................................................... 17

3.4 LOAD/SLIP PROPERTIES (PHYSICAL BEHAVIOR OF CONNECTIONS) ....................... 18
3.4.1 Loading, unloading and reloading behavior ................................................................. 18

3.5 FEM MODELLING OF CONNECTIONS ............................................................................... 19
3.5.1 Single spring models .................................................................................................... 21
3.5.2 Spring pair models (non-oriented and oriented) ......................................................... 22
3.5.3 Influence of different sheathing-to-framing joint characteristics ......................... 23

4. METHODS .............................................................................................................................. 25

4.1 MATERIALS ....................................................................................................................... 25
4.1.1 Framing materials ......................................................................................................... 25
4.1.2 Sheathing material ....................................................................................................... 25
4.1.3 Embedment tests on the timber and OSB sheathing ................................................. 26
4.1.4 Fastener ........................................................................................................................ 27
4.1.5 Tests on the fastener ...................................................................................................... 28
4.1.6 Nail withdrawal test ...................................................................................................... 29

4.2 DESCRIPTION OF THE LABORATORY TESTS ................................................................ 29

4.3 NUMERICAL MODELING OF CONNECTION ..................................................................... 31
4.3.1 Beam on foundation modeling .................................................................................... 31
4.3.2 Connector element in Abaqus ..................................................................................... 32

5. IMPLEMENTATION ................................................................................................................. 35

5.1 MATERIAL PROPERTIES .................................................................................................... 35
5.1.1 The nail elastic-plastic properties ............................................................................. 35
5.1.2 Embedment properties ............................................................................................... 37
1. Introduction

The art and science in timber construction has increasingly been revolutionized in recent years despite being used for ages with limitations that were perceived as not feasible until these modern times. One important piece in this advancement of timber engineering is the growing knowledge on timber connection, which brings effect from the overall capacity and structural behavior to the extent of allowing increased use of timber in modern structures subjected to rather complicated loading conditions.

The use of timber has always been subjected to challenges related to moisture effect, material properties itself in relation to its anisotropic behavior among others. Yet, the contemporary methods of timber production as well as the sophisticated practices in structural analysis and design, has enabled the use of timber at a higher capacity with growing efficiency day after day.

With improved use of timber, there comes challenges of achieving adequate stability against horizontal loads in tall timber buildings. Apart from using diagonal bracing or the use of framed systems, shear walls are widely employed to solve this stability problem. These walls may be arranged in a variety of systems, yet all consist of wood-based sheets nailed or screwed onto a timber frame (sheathing-to-framing connection) and rely on the distribution of the lateral loads to a series of nail connections in a rather complex manner that is of interest in this study.

Nailed connections fall under dowel-type mechanical connections, whose performance consequently depend on the properties of the dowel itself and the timber or timber based material. The anisotropic property of timber then makes it valuable to study and quantify the performance of dowelled connections subjected to varying loading directions in relation to the grain angle of wood.

The use of advanced material test setups together with the use of computer-aided Finite Element Methods (FEM) has been important in the thorough investigation and simulation of the behavior of a full structure and its subparts/elements like the connections. Whereby the modeling of displacement path dependency of nailed timber connections is investigated and discussed in the subsequent sections of this work.
1.1 Background and problem description

The limitations of the relatively small size of timber elements produced in industries, to the size of large structures, together with the varying shapes, orientations and configurations of different structural elements, brings about the requirement of timber connections at different points of a structure for it to function as a system. Joints in timber can not only be a strong contributor to the overall economy in a building system but also affect the structural behavior of the elements by either providing moment stiff connections or hinges [1] and ductility in the connection with recent studies.

Timber joints are commonly classified as either; traditional timber joints, glued joints or dowelled joints. Traditional joints were largely used when steel dowels and improved wood adhesives were still unavailable. These were time consuming and had great limitations on load transfer capacity, therefore, they are uneconomic. Glued joints are frequently used in timber engineering when producing large elements and Engineered Wood Products (EWP), but they are seldom used for joining members since they require close control of moisture and temperature during production [1].

Dowel-type connections have been used since traditional times where dowels of hardwood were used in the connections. Then the use of steel dowels has revolutionized this type of connection making it the most common connection type today. Dowelled joints work through shear force transfer of the fastener placed at an angle to the loading direction or in some cases at full or partial axial force transfer contribution. Dowel-type fasteners include; nails, screws, dowels and bolts.

Through experimental investigations, dowelled fasteners have been evaluated and quantified for single-dowel connections. The behavior of the local timber material and steel dowels up to the global behavior of the single dowel connection as a whole have been studied [2]. Models have also been proposed for the analysis of single-dowel fasteners in finite element software, see e.g. [3]. However, little had been said about the displacement path dependency of the connections, whereby single-dowel connection tests, embedment tests of wood and wood products were mostly limited to loading parallel and perpendicular to the grain see e.g. [4].

Contemporary methods in timber engineering have not only improved timber as a material with the use of EWPs but also the need and possibility of designing highly ductile connections in timber, whereby use of self-tapping screws has become common and efficient in application [5]. Therefore, large deformations are usually encountered and it is necessary to investigate single-dowel connections under such large deformations.

Recent studies have experimentally examined the behavior of specific sheathing-to-framing nail connections with respect to its possible dependency on the displacement path taken. Results of which have revealed
a very ductile behavior of the connection type with displacements up to 50 mm. Weakening of the overall behavior of the connection was observed as the displacement direction changed. Work done through various displacement paths were investigated and a strong displacement path dependence was observed [6].

The current method of dowelled connection design, the European Yield Model (EYM), is based on the limit state approach. Whereby, an ideal plastic material behavior of the steel dowels and for timber under embedment stresses is assumed. This has shortcomings of providing limit loads and no deformations, yet also it lacks information on semi-rigid connectors which are very essential in the analysis of structures under serviceability and ultimate limit states.

Over time, several researchers have studied and developed finite element method (FEM) models of dowel-type connections, these studies involved the investigation of the embedment characteristics of timber materials. The effects of reinforcements on dowel connections have been simulated as well using FEM simulations of connections with elasto-plastic and brittle material models for wood [3,7,8]. These simulations allow gaining insight into the formation of plastic deformations in steel dowels (in this case nails) and the distribution of stress in timber members (framing and sheathing). Nevertheless, in most cases, they are based on small strain theory, limiting the maximum strains in the component materials of the dowelled connection [2].

Other researchers have developed models using the approach of beam-on-foundation to predict the load-displacement behavior of dowelled connections [9], yet their potential for application have not been fully taken advantage of [2]. Thus, this work is intended to develop suitable numerical models for dowelled connections, incorporating the effects of displacement path dependency and large deformations in timber, using the principles of beam-on-foundation.

1.2 Aim and purpose

The aim of this master thesis is to develop a numerical model and apply it in the simulation of the displacement path dependency for single dowel-type nail connections.

Therefore, the output of this study has the purpose of providing knowledge for the engineering design. This in turn will influence the design of more advanced experimental test setups for a better understanding of connections.
1.3 Hypothesis and limitations

1.3.1 Hypothesis

This study suggests that the load-displacement properties (i.e., the displacement path dependency) of a sheathing-to-framing nailed connection can be associated to, and explained by only the plasticity in the nail and non-linear elastic embedment behavior of the wood-based materials.

1.3.2 Limitations

This master thesis is limited to the following scope and assumptions;
- Displacement path dependence in single dowelled nail connection as applicable in the assembly of sheathing-to-framing connections in the construction of shear walls;
- Plastic distribution of forces in the shear walls, (i.e., without risk of brittle failure);
- Effects of moisture content is not considered (i.e., all timber elements are at suitable temperature and relative humidity);
- Effects of knots and other timber imperfections are not considered;
- Focus is on short-term elasto-plastic behavior, no fatigue, creep or long-term behavior will be studied.

1.4 Reliability, validity and objectivity

The results of this master thesis were compared to a comprehensive database developed by relevant experimental test series from corresponding researches as described in Laboratory test results at LNU [6].

The results in this study were compared to the current European design standard for timber structures [10].

The modeling relies on a previously proposed and validated approach for single-fastener connections [2].

The simulations were carried out using ABAQUS/CAE.
2. Literature Review

This section addresses the work performed by other researchers in relation to the subject of this master thesis. Relevant studies associated with the performance and modeling of nailed sheathing-to-framing connections will be summarized and their outcomes described briefly.

2.1 Literature research on nailed timber connections

As it was presented earlier in section 1.1, the design of nailed connections and dowelled connections in general has been studied by several scientists, and also several design codes have been formulated. However, the behavior of a nailed connection is more complex than it may be assumed and it has a great influence on the behavior of the structure as a whole. Among the applicable scholarly studies that support this are as follows.

In a study presented by Judd, et al. [3], the importance of applying displacement-based (performance-based) design on timber structures was first pointed out. Whereby the structure is designed to meet a target displacement instead of a force requirement. This is important in limiting structural damages under conditions such as reverse-cyclic loading. Therefore, an understanding of monotonic response and energy dissipation is key.

This work also addresses the behavior of a single nailed connection, whereby the force-displacement relationship for a sheathing-to-framing connection subjected to reverse-cyclic loading is described. Judd P. et al. [3] also pointed out the inelastic behavior, and strength and stiffness reduction with increased displacement after yielding has passed.

The study went on to describe the various models for sheathing-to-framing connections by discussing the single spring models, oriented (coupled) and non-oriented (uncoupled) spring pair models. Comparison of these models was performed in a general-purpose FE software Abaqus and a specific purpose program CASHEW on a full-scale shear wall together with data from experimental measurements. It was concluded in the study that the oriented spring pair models more closely depict the response of the structure for both monotonic and cyclic loading conditions and the use of this approach can be applied to both general purpose and specialized programs [3].

Another exciting study was carried out by Vessby, et al. [7]. This study analyses the sheathing-to-framing models whereby single spring (SS) models and spring pair (SP) models (both oriented and non-oriented) were discussed. For the oriented (coupled) SP models the characteristics of the
coupling was checked, whereby coupled SP models with rectangular, elliptic and hyper-elastic outer bounds were analyzed.

The study was based on monotonic loading. Still, all models considered were elastic meaning that the loading, unloading and reloading of the connection will follow the same path which is unrealistic in practice. Emphasis was put on the fact that the uncoupled SP models behave differently and lead to overestimation of the connection capacity at directions in between the two main orientations of the spring pairs. To a lesser extent, the coupled SP model with hyper-elastic outer bound gave similar results [7].

Path dependency was also addressed with regard to the SP models and results indicated the existence of path dependence from force-displacement response analysis of these SP models.

In addition to this, the study in [7] modelled and analyzed a whole wall using these different SP models and the results corresponded to the behavior of the individual SP models showing that they influence the behavior of the full structure.

Nevertheless, it was concluded that the coupled SP models are preferred but require calibrations for the paths other than those of the orthogonal spring pairs. Concerns were raised over the SP model coupled with rectangular outer bound as they overestimate the capacity at mixed mode loading but SP models with an elliptic outer bound provided the best results compared to the experimental test data [7].

Modelling of sheathing-to-framing connections is again deliberated by Vessby J., et al. [11]. Aimed at creating a thorough understanding of how the choice of different sheathing-to-framing connection models affect the behavior and capacity of the shear wall as a whole. Single spring and spring pair models are again discussed in relation to sheathing-to-framing joints. In addition to the effects of the models are assessed in two cases of non-linear elastic and plastic model.

This study also addresses the loading, unloading and reloading behavior of the connection in relation to non-linear elastic and plastic models. The non-linear elastic models have unloading and reloading paths similar to the original loading path whereas for plastic models the unloading-reloading paths are parallel to the initial elastic portion of the loading path. Emphasis is put on the fact that a significant difference is observed among these two models when unloading and reloading occurs in the non-linear range of the load-displacement curve. This difference can be minimal if unloading-reloading does not occur.

Nevertheless, framing connections were studied and the combination of all these properties were modelled into a single segment shear wall and
compared to experimental test results to describe the influence of the connection models to the wall. It was concluded that different models impart different behavior and a good correlation of the results is achieved if a suitable model is chosen adequate enough to the actual case [11].

Furthermore, interesting results are observed if the loading is applied diagonally leading to a change of direction of the displacement path, together with unloading for the connections at the edges of the shear wall. This not only depicts the displacement path dependency but also makes the difference between the elastic and plastic models more obvious [11].

Another relevant study is discussed in [12]. Here investigation of the displacement dependency in an OSB sheathing-to-framing mechanical connection was studied. The dependency of the loading effect on the loading direction at different loading stages and for different directions was investigated. In addition, this study aimed at quantifying directional dependency experimentally and evaluating the source of this dependency in a sheathing-to-framing connection.

Firstly, the embedment properties of an 11 mm thick OSB/2 board and a 70 x 225 mm C24 graded structural timber were determined experimentally, then the connection of these materials with a 2.5 mm diameter, 60 mm long annular-ringed shank nail (AISI 316/A4) was tested. The tests were performed in a uniaxial setup and only the tangential and longitudinal directions with respect to the fiber direction were investigated.

Results from the study suggested that the embedment behavior of the OSB/2 sheathing in its length direction and cross direction are close to each other. This can allow the simplification of modelling the sheathing as an isotropic element. No significant difference was also observed in the connection test from the two perpendicular directions, yet it is important to note that further tests in a biaxial setup and at directions in between the two main perpendicular directions are needed for the analysis of path dependency [12].

Another interesting study is presented in Girhammar, et al. [13], the study focused on the finite element modeling of shear walls with the aim of presenting a new shear connector element basing on continuum plasticity theory.

This work [13], presented the different analytical non-linear elastic and plastic methods of analyzing shear walls, then the incremental load-displacement relationship of the sheathing-to-framing connections is discussed based on elastic-plastic stiffness tensor including the elastic stiffness tensor. The plasticity theory applied is presented including the plastic modulus, the yielding criterion, plastic potential equations and the hardening rule. These connector models are applied in the load-displacement
analysis of shear wall and the results were then compared to corresponding experimental data. A good correlation was found and concluded [13].

Considering the outputs and suggestions from these studies, it is obvious that the behavior of a nail connection is complex in relation to the models used to simulate it numerically. Moreover, it is evident that the behavior of the sheathing-to-framing connection influences the overall behavior of the shear wall and there exists a displacement-path dependency in the connection that is subject to the fundamental material properties (elasticity, plasticity and anisotropy) of the wood, sheathing material and the nail. These facts certainly call for more research and this is the motivation of this master thesis.
3. Theory

This section follows into the principles that govern the behavior and performance of nailed timber connections and numerical modelling techniques of such connections. First, a brief introduction of wood properties is presented before the theories related to sheathing-to-framing nailed connections are discussed.

3.1 Wood as a material

Wood species are generally classified as either, softwood species containing species like pine and spruce or hardwood species as for example beech. In the production of sawn timber for the purposes of construction, softwoods are dominant [1].

To attain the required properties of wood for construction purposes, the forestation techniques and age of the forests play a great role and alteration of these methods can lead to a great variation of the timber properties and defects.

The wood structure is composed of a series of connected strands of organic molecules. These molecules are built up of three main elements; 50 % carbon, 6 % hydrogen and 44 % oxygen in the form of hemicellulose, cellulose and lignin. Tubular-shaped wood cells of approximately 2 to 4 mm in length and 0.1 mm in diameter and their orientation give rise to the orthotropic behavior of wood [1].

This study will focus on softwood as applicable to most sheathing-to-framing connections of shear walls. Yet, the methods can be applied to other wood species with their respective material properties.

3.1.1 Natural characteristics

Wood is characterized by different defects in its structure as it is seen from an engineering point of view; these are knots, spiral grain angle, juvenile wood formed during the early ages of a tree and reaction wood formed due to exposure of the tree to environmental conditions that alter its equilibrium position. These are the properties of timber that in engineering we ought to minimize as much as possible to attain most desired engineering (mechanical) properties in the wood with as low as possible variations [1,14].

Herein, this study is limited to clear wood with the absence of any such defects.
3.1.2 Physical properties

Wood is hygroscopic in nature, allowing it to gain or lose water into the surrounding depending on the relative moisture content difference between the wood cells and the surrounding environment. The physical properties and mechanical properties of wood are then greatly affected by the moisture content in the wood.

Moisture change in wood leads to shrinkage and swellings that alter the shape of the wood which can lead into distorted modes like: twists, cupping, bowing and spring. Hence, moisture content is a crucial physical property of wood. In addition to this, depending on different wood species, the density of wood is an important property that determines the mechanical properties of wood [1].

This study will be limited to wood with a constant moisture content and a specific density, while variations of the properties together with their corresponding effects are out of the scope of this master thesis.

3.1.3 Mechanical properties

For engineering purposes, it is the mechanical properties of wood that interest us most. These properties are mainly the strength and stiffness of wood at different loading conditions; of tension, compression, shear, bending and at different directions of loading with respect to the grain direction of the wood [1].

These properties are affected by the wood structure, the natural and physical properties as discussed previously. In addition to the previously mentioned properties, the loading time of the timber elements affects the strength of timber in aspects of strength and deformation due to fatigue and creep. Moreover, the cross-section size (or volume) of the specimen also alters mechanical properties of wood, most commonly described by the weakest link theory of the Weibull distribution that states, “A chain subjected to tension is never stronger than its weakest link” [14].

These influencing factors are taken care of in the design using the Eurocode 5 by respectively altering the modification factors, $k_{\text{mod}}$ and $k_{h}$ values for moisture content, initial defects and size effects respectively [1,10].

Herein, mechanical properties of wood related to short-term loading durations only are dealt with, whereby, effects of creep and fatigue are not considered.
3.1.4 Orthotropic elastic behavior of wood

As mentioned earlier, due to the fiber-like structure and orientation of the wood, it is characterized as an orthotropic material. This means the mechanical behavior of the wood in the three perpendicular directions of the wood, namely, radial, tangential and longitudinal directions are different. This orthotropic property has been described by different theories like the generalized Hook’s law, whereby the constitutive relation of timber is described. For further information on this the reader is referred to for example [15].

3.1.5 Elasto-plastic behavior of wood

When wood is loaded in compression, it initially displaces elastically [3]. When loading in progressed the wood fibers crush and some strain softening is observed, this non-linear permanent behavior of the wood may be described by plasticity theories [16]. In addition to this, local material densification of the wood fibers at large deformations leads to plastic behavior of the wood [17]. Oudjena, et al., [17], suggests that the modeling of wood requires appropriate constitutive laws when dealing with its three orthotropic directions.

3.1.6 Engineered wood products

Engineered Wood Products (EWPs) are the wood products designed specifically to overcome the shortcomings of wood such as; the relatively small size of regular sawn timber in relation to the engineering requirements of size and shapes, the size effect of timber, the defects in wood, the orthotropic behavior and most importantly to improve the strength and stiffness of wood, and minimizing the mechanical properties variation in wood specimens.

Figure 3.1 compares structural sawn timber of strength class C30 and glulam of strength class GL32, it describes how the use of EWPs reduces the variation between samples, therefore, a narrower curve for the glulam is achieved and the desired strength is increased with a higher probability of samples crossing above the desired characteristic strength [1,18].

These EWPs are produced in strategic combinations of sawn timber of wood based particles using a variety of adhesives leading to products like; Glue Laminated Timber (Glulam), Cross Laminated Timber (CLT), Laminated Veneer Lumber (LVL), Plywood, Oriented Strand Boards (OSB) among others.

For the sheathing-to-framing connection studied herein, OSB sheathing (OSB/2) was used as the sheathing material. This was strategically chosen to
be comparable with the corresponding tests series conducted with this material.

![Diagram of strength variation for Glulam beams and structural timber](image)

*Figure 3.1: Strength variation for Glulam beams and structural timber [18].*

3.2 Lateral loading (wind loading) in buildings

3.2.1 Shear walls

Lateral loads acting on timber buildings either from strong winds or earthquakes are transferred through the roof and within floor diaphragms into the shear walls, which then transfer the loads to the ground.

Currently, most common construction of shear walls in timber buildings is by nailing or screwing the sheathing to the framing system. In a shear wall as an independent member, two kinds of connections can be considered, those joining the framing members in place and the connection between the sheathing and the framing [11].

The performance and capacity of a shear wall is influenced by different mechanical properties. These are, the buckling strength of the framing members and the sheathing, the compressive strength of the bottom rail perpendicular to the grain, the strength of the hold down bolt, and more importantly the overall behavior of the wall is dominated by the properties of the sheathing-to-framing connections [3,11].

3.2.2 Elastic analysis of shear walls

Elastic analysis of shear walls consists of among the simplest and most commonly used models for analysis of shear walls by engineers. These models determine the strength using the elastic approach whereby the shear capacity of the shear wall is governed by the most loaded fastener [11]. In
these models, the framing and sheathing members are assumed rigid, with the framing members connected by frictionless hinges. The bottom rail is also assumed to interact fully with the foundation. The shear wall capacity can then be determined using methods described for example in Källsner [19] and in Källsner and Girhammar [20].

### 3.2.3 Plastic analysis of shear walls

This analysis approach of shear walls can be performed from the whole wall scale to the single fastener consideration. This three-dimensional consideration is done if the needed deformation capacity is secured; this means the fastener elastic behavior and ductility must be well considered and verified. Plastic analysis provides more realistic load paths in the sheathing-to-framing connection with the advantage of when the loads are approaching ultimate values, the load transfer in single fasteners change in both direction and magnitude [11]. Behaviors like these of the sheathing-to-framing connection are among the motivations of this work.

Källsner and Girhammar [20] have proposed methods that include the dead load of the building but also the effects of lateral loads. Alternatives suggested by Ni and Karacabeyli [21], consider the anchorage of the leading stud in addition to the dead load of the building.

### 3.3 Nailed connections

Nailed connections fall under mechanical dowel-type connections and to the scope of this study, sheathing-to-framing nail connections are laterally loaded in shear. The interaction between the sheathing and the frame surfaces is therefore termed a shear plane. Dowelled connections can either have a single shear plane, double shear plane or multiple shear planes, which are a combination of several shear planes. Single shear planes will be studied in this study as related to sheathing-to-framing connections.

Fasteners in dowel-type connections may either be nails, bolts, dowels or screws of different sizes and properties. A nail is usually smaller than 8 mm in diameter and they may have smooth or rugged shanks of circular or grooved shapes. In Eurocode 5 (EC5) [10] these are termed as smooth and other than smooth nails, respectively. Where other than smooth nails can, for instance, be annular shanked, round jagged or twisted nails [1]. Furthermore, nails are usually not predrilled into wood material with a diameter less than 8 mm [10].

Herein, annular-ring shanked nails were used as fasteners.
3.3.1 Capacity of a connection

When a dowel-type connection is loaded in shear, it is pressed against the surrounding timber, which creates a pressure on the dowel as well as the wood. Depending on the size, material properties of the dowel and timber, it may or may not bend as the fastener acts as a beam subjected to distributed load. The capacity of the connection, therefore, depends on the material properties of the timber and dowel, hereafter described as the embedding strength of the timber, \( f_h \), and yield moment of the dowel, \( M_y \), respectively [10].

In addition to material properties of the dowel, the surface texture and anchorage capacity may also influence the capacity of the connection by enabling a tensile action in the dowel, \( F_{ax} \) [10].

3.3.1.1 Embedding strength

The embedding strength of wood material is the amount of pressure the wood around a dowel can withstand when the dowel is loaded in shear at a particular direction to the grain. This is determined by dividing the force by the projected area of the dowel, \( A = dt \), with a test setup described in for example in [22], whereby \( d \) is the dowel diameter and \( t \) the thickness of timber [1].

The embedment strength depends on: the density of the timber, fastener diameter where the hole can exceed the fastener diameter by 2 mm without affecting the embedding strength [23], the loading angle relative to the grain orientation, friction between dowel and timber, moisture content in timber, if the hole is pre-drilled or not and the presence of reinforcements in tension perpendicular to grain [10]. Empirical expressions for characteristic embedment strength of nails, \( f_{h,0,k} \) determination parallel to the grain as per EC5 are (cf. Eq. (8.15) and Eq. (8.16) in EC5 [10]),

\[
\begin{align*}
  f_{h,0,k} &= 0.082 \rho_k d^{-0.3}, \text{ without pre-drilling, } (d < 8 \text{ mm}), \quad (1) \\
  f_{h,0,k} &= 0.082(1 - 0.01d)\rho_k, \quad \text{with pre-drilling}, \quad (2)
\end{align*}
\]

whereby, \( \rho_k \) is the characteristic density in kg/m\(^3\), \( f_{h,0,k} \) and \( d \) are as described before.

Embedment strengths at other directions (angles), \( \alpha \), against the grain are then determined using the Hankinson’s formula, (cf. Eq. (8.31) and Eq. (8.33) in EC5 [10]),

\[
\begin{align*}
  f_{h,\alpha,k} &= \frac{f_{h,0,k}}{k_{90} \sin^2 \alpha + \cos^2 \alpha} \left[ \frac{\text{N}}{\text{mm}^2} \right], \quad (3)
\end{align*}
\]

with,

\[
k_{90} = 1.35 + 0.015d. \quad (4)
\]
For other materials than softwood like particleboards, plywood and fiberboards, more elaboration is found in EC5, section 8.3 and 8.5. Nevertheless, for the scope of this study, the characteristic embedment strength for OSB sheathing materials is determined as (cf. Eq. (8.22) in EC5 [10]),

\[ f_{h,k} = 65 d^{-0.7} t^{0.1} \]  \hspace{1cm} (5)

where, \( t \) is the panel thickness and \( d \), the fastener diameter.

It is yet important to note that the embedment strength obtained using these methods as per EC5 is for an un-deformed nail at each instance or direction, whereas, when a sheathing-to-framing connection is loaded, unloaded then reloaded, subjected to reverse loading or loaded in different paths successfully the nail is usually already deformed in the subsequent stages of loading after the first loading step.

3.3.1.2 Yield Moment

Yield moment can be described as the moment needed to produce a plastic hinge in a dowel. The yield moment depends on the size of the fastener (diameter, \( d \)) and the ultimate steel strength of the dowel, \( f_u \) (cf. Eq. (8.14) in EC5 [10]),

\[ M_{y,Rk} = \frac{f_u}{600} 180 d^{2.6} \text{ [Nmm]} \]  \hspace{1cm} (6)
\[ M_{y,Rk} = \frac{f_u}{600} 270 d^{2.6} \text{ [Nmm]} \]  \hspace{1cm} (7)
\[ M_{y,Rk} = 0.3 d^{2.6} \text{ [Nmm]} \]  \hspace{1cm} (8)

whereby, Eqs. (6) - (8) are for round nails, square and grooved nails, and for all fasteners respectively.

3.3.2 Failure modes in timber-to-timber joints and timber-to-panel joints

A sheathing-to-framing connection can be referred to as a timber-to-panel joint. Whereby, as a connection is loaded in shear it can fail in several ways depending on the combination of the embedding strength, the size of the timber member and dowel diameter [1]. According to Johansen theory, these failure modes are associated with shear failure and formation of plastic hinges in the dowels. The possible failure modes are summarized in Figure 3.2.

Sheathing-to-framing connections are simply single shear plane joints and the small sizes of the nails allow the occurrence of failure modes, \( d \) or \( e \) and \( f \) (see Figure 3.2).
The respective empirical formulas for determination of the connection capacities, \( F_{v,Rk} \) for the respective failure modes \( a \) through \( k \) in Figure 3.2, are reading as, (cf. Eq. (8.6(a)) - (8.6(k)) in EC5 [10]),

\[
f_{h,1,k} t_1 d, \tag{9a}
\]

\[
f_{h,2,k} t_2 d, \tag{9b}
\]

\[
\frac{f_{h,1,k} t_1 d}{1+\beta} \left[ \sqrt{\beta + 2\beta^2 \left[ 1 + \frac{t_2}{t_1} + \frac{t_2^2}{t_1^2} \right] + \beta^3 \left( \frac{t_2}{t_1} \right)^2} - \beta \left( 1 - \frac{t_2}{t_1} \right) \right], \tag{9c}
\]

\[
1.05 \frac{f_{h,1,k} t_1 d}{2+\beta} \left[ \sqrt{2\beta(1 + \beta) + \frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} d t_1^2}} - \beta \right] + \frac{F_{ax,Rk}}{4}, \tag{9d}
\]

\[
1.05 \frac{f_{h,2,k} t_2 d}{1+2\beta} \left[ \sqrt{2\beta^2(1 + \beta) + \frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} d t_2^2}} - \beta \right] + \frac{F_{ax,Rk}}{4}, \tag{9e}
\]

\[
1.15 \sqrt{\frac{2\beta}{1+\beta}} \sqrt{2M_{y,Rk} f_{h,1,k} d} + \frac{F_{ax,Rk}}{4}, \tag{9f}
\]

\[
f_{h,1,k} t_1 d, \tag{9g}
\]

\[
0.5f_{h,2,k} t_2 d, \tag{9h}
\]

\[
1.05 \frac{f_{h,1,k} t_1 d}{2+\beta} \left[ \sqrt{2\beta(1 + \beta) + \frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} d t_1^2}} - \beta \right] + \frac{F_{ax,Rk}}{4}, \tag{9j}
\]

\[
1.15 \sqrt{\frac{2\beta}{1+\beta}} \sqrt{2M_{y,Rk} f_{h,1,k} d} + \frac{F_{ax,Rk}}{4}, \tag{9k}
\]

with:

\[
\beta = \frac{f_{h,2,k}}{f_{h,1,k}} \tag{10}
\]
\( t_i \), is the timber or board thickness or penetration depth \((i = 1 \text{ or } 2)\), \( f_{h,i,k} \) is the characteristic embedment strength in wood member \( i \), \( d \) is the fastener diameter, \( M_{y,Rk} \) the characteristic yield moment of fastener and \( F_{ax,Rk} \) is the characteristic withdrawal capacity of the fastener. The latter, namely the axial bearing capacity is only added when the failure mode includes pronounced bending of the steel fastener.

However, nail pulling through, withdrawal or tearing through the sheathing panels is a leading failure mode on reverse-cyclic loading of wood shear walls and diaphragms [24]. A consequence of which the connection displacement path will not subsequently follow the prescribed path, like circular path when the sheathing tears. Whereby, the nail movement is restricted to a relatively narrow path [3].

3.3.3 Tension capacity of single dowels (Rope effect)

As described earlier, the shear failure modes of the connections involve bending of the nail. The case of which some of the load is taken up in tension by the nail depending on the surface and end anchorage of the nail. The surface of the nail can either be twisted, annular ringed or threaded to increase tension capacity [1] compared to a smooth nail.

Kuipers and Van Der Put (1982) showed that the tension capacity in the dowel can substantially increase the connection capacity by as much as 2.6 times the shear capacity. However, the design of connection capacity using the Eurocode 5, allows the addition of one-fourth of the tension capacity to the shear capacity with the rope effect limited to a maximum contribution of 15 %, 25 % and 50 % for round, square or grooved and other nails respectively, of the connection shear capacity [10].

For sheathing-to-framing connections, the tension capacity of the nail is subject to its surface roughness giving, \( f_{ax} \), the axial withdrawal capacity and the anchorage of the nail head giving, \( f_{head} \), the head pull-through strength. These values can be obtained by performing tests as per SS-EN 1382, SS-EN 1383 and SS-EN 14358 or SS-EN 14592. For other than smooth nails, empirical formulas exist to evaluate characteristic values of \( f_{ax,k} \) and \( f_{head,k} \) as in the Austrian national appendix to EC5 [25],

\[
\begin{align*}
f_{ax,k} &= 50 \cdot 10^{-6} \rho_k^2, \\
f_{head,k} &= 100 \cdot 10^{-6} \rho_k^2.
\end{align*}
\]

Then the withdrawal capacity \( F_{ax,Rk} \) of the nail can be given by,

\[
F_{ax,Rk} = \min \left\{ \begin{array}{l}
f_{ax,k} d_{pen} \\
\frac{f_{ax,k} d_t + f_{head,k} d_h^2}{d_t + d_h}
\end{array} \right\}
\]

\[
F_{ax,Rk} = \min \left\{ \begin{array}{l}
f_{ax,k} d_{pen} \\
f_{head,k} d_h^2
\end{array} \right\}
\]
for smooth nails, and other than smooth nails, respectively, whereby, $t_{pen}$ is the penetration depth (or depth of threaded part for annular-ringed shank nails) and $d_h$ is the nail head diameter.

3.4 Load/slip properties (physical behavior of connections)

Timber being a highly orthotropic material, it is evident that the load-displacement properties of a connection depend on the direction of the loading [6].

The load-displacement relationship of a sheathing-to-framing nailed connection may be established from experimental tests of individual connection setups. From such experiments, the load-displacement relation for monotonic loading is then established by a mathematical expression. This monotonic load-displacement relationship provides a response envelope for the cases of reverse cyclic loading conditions, whereas hysteresis behavior of the connection is idealized using predefined sets of load paths describing unloading, load reversal and reloading [3].

Whereas, the load-displacement relation for monotonic loading of a connection can be achieved by modeling the fastener (i.e. nail) as an elastoplastic element embedded into a non-linear layered medium (i.e. the wood frame and sheathing material). To model this, the properties of the sheathing, framing and fastener are needed [3,26].

3.4.1 Loading, unloading and reloading behavior

When a sheathing-to-framing connection is loaded in shear, the force transmitted from the sheathing through the nail deforms the nail by displacing the nail head relative to the nail shank. At the early stages of loading, the load-deformation relationship is linear, whereby the wood fibers, sheathing materials and the nail all behave elastically. Increasing the load then crushes the wood fibers and the nail yields. If the load is reversed the connection will show a low strength and stiffness as the nail is pushed through the gap formed in the initial displacement, this will continue until it gets in contact with the wood fibers again [3].

Dolan and Madsen (1992), suggest that the angle of the applied load with respect to the wood fibers has a negligible effect on the load-slip behavior of the nail connection, only the connection capacity will differ [27].

The load-displacement behavior of a sheathing-to-framing connection at various conditions of load application i.e. loading, unloading and reloading, can be modelled depending on the material property assumed. Principally, non-linear elastic or plastic models can be used [11].

In the non-linear elastic model, the unloading and reloading paths (curves) follow the same initial loading curve of the connection. However, for the
plastic model, the unloading and reloading curves are determined by the initial stiffness of the elastic part of the load-displacement curve [11] see Figure 3.3 below.

![Figure 3.3: Unloading-reloading behaviors for non-linear elastic (el) and Plastic (pl) connection models.](image)

### 3.5 FEM modelling of connections

Experimental tests are irreplaceable, yet computer-based modelling and simulations provide a relatively less expensive analysis procedures and are less time-consuming. Therefore, finite element method (FEM) becomes very useful due to its flexibility of use with respects to varied geometries and materials. Moreover, an increased understanding of the force distribution between interacting elements in a FEM model is achieved [3].

An increased interest regarding the current analysis programs is the lack of a rigorous analytical model for the simulation of all the behaviors of a sheathing-to-framing connection. For example, the use of single non-linear spring models fails to demonstrate reverse cyclic loading. A limitation that is significant when the determination of energy dissipation is of interest. Moreover, single spring models may be unstable, especially near ultimate loading of the connection [3,28].

Furthermore, the use of two orthogonal non-linear spring models (non-oriented spring pair model) tends to exaggerate the connection strength and stiffness. Several researchers have tried to counteract this issue, for example, Folz and Filiatrault (2001) proposed a method using the structural analysis software CASHEW [20]. With CASHEW, the spacing of the sheathing-to-framing connections is adjusted and scaled internally until the energy absorbed by the wall using this model concurs with the energy absorbed when the single spring model is adopted [28]. Yet, this approach has not
found its feasibility in a general-purpose finite element program eliminating
the need for scaling or adjustment of the sheathing-to-framing connection;
such rigorous analytical models have been proposed for example by Johnn
P. Judd, et al., [3].

In addition, considerations of the energy dissipated during fastener (nail)
withdrawal have not been effectively incorporated into the overall
performance of the connection.

The FEM simulation of load-displacement behavior of a sheathing-to-
framing connection using spring element models are generally presented in
terms of forces versus displacement (cf. Eqs. (15) – (16)),

\[
F = Ku.
\]  \(\text{(15)}\)

\[
\begin{bmatrix}
F_x \\
F_y \\
F_z \\
M_x \\
M_y \\
M_z
\end{bmatrix} =
\begin{bmatrix}
K_{xx} & K_{xy} & K_{xz} & \lambda_{xx} & \lambda_{xy} & \lambda_{xz} \\
K_{yx} & K_{yy} & K_{yz} & \lambda_{yx} & \lambda_{yy} & \lambda_{yz} \\
K_{zx} & K_{zy} & K_{zz} & \lambda_{zx} & \lambda_{zy} & \lambda_{zz} \\
\lambda_{xx} & \lambda_{xy} & \lambda_{xz} & C_{xx} & C_{xy} & C_{xz} \\
\lambda_{yx} & \lambda_{yy} & \lambda_{yz} & C_{yx} & C_{yy} & C_{yz} \\
\lambda_{zx} & \lambda_{zy} & \lambda_{zz} & C_{zx} & C_{zy} & C_{zz}
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y \\
u_z \\
\theta_x \\
\theta_y \\
\theta_z
\end{bmatrix}
\]  \(\text{(16)}\)

where, \(F_i, u_i\) are the forces and relative displacements along the coordinate
direction \(i\) and \(M_i, \theta_i\) are the moments and relative rotations about the \(i^{th}\)
axis. \(K_{ij}\) and \(C_{ij}\) are the translational and rotational stiffnesses for the
forces/moments about axis-\(i\) for a displacement/rotation about axis-\(j\)
respectively and \(\lambda_{ij}\) represents coupling between the translational and
rotational degrees of freedom.

Nevertheless, in this simulation, the rotational stiffnesses are assumed to be
zero, whereby, the nodes are free to rotate without any resistance.
Furthermore, the forces along the \(z\)-axis, \(F_z\) are taken to be the axial forces
in the connection (i.e. the nail withdrawal and head pull-through forces)
which are taken into consideration separately Eq. (18).

This leaves Eqs. (15) – (16) with only \(F_x\) and \(F_y\) (cf. Eq. (17)), which are the
forces parallel and perpendicular to the fiber direction of the framing
member.

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} =
\begin{bmatrix}
K_{xx} & K_{xy} \\
K_{yx} & K_{yy}
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y
\end{bmatrix}
\]  \(\text{(17)}\)

\[
F_z = K_{zz} u_z.
\]  \(\text{(18)}\)
3.5.1 Single spring models

This is when the sheathing-to-framing connection is modelled by a single (two-node) non-linear spring with two degrees of freedom at each node. This type of model is useful when the connection is subjected to monotonic loading. The displacement path is basically unidirectional in such loading conditions, hence the total displacement of the connection will in this case be estimated as the resultant displacement of the two degrees of freedom with a resultant stiffness \( K_r \). This means that in the single spring model the orthotropic properties of wood are not considered [3,7,8,29], see Figure 3.4.

For single spring models, Eq. (17) will then change into Eq. (19);

\[ F_r = K_r \Delta_r, \]  
\[ (19) \]

with,

\[ K_{xx} = K_{yy} = K_r, \]  
\[ (20) \]

\[ \Delta_r = \sqrt{u_x^2 + u_y^2}, \]  
\[ (21) \]

\[ K_{xy} = K_{yx} = 0. \]  
\[ (22) \]

This model describes the element stiffness matrix as a shear element, whereby the spring stiffness is the same in both directions of the two degrees of freedom and the nodal forces are therefore proportional to the nodal displacements.

As noted earlier, this model has shortcomings in two-fold; firstly, loads on the connection can be highly non-linear and the displacement path can be bi-directional under cyclic loading. Therefore, the displacement of the connection is path dependent and not equal to the resultant deformation of the two degrees of freedom. Moreover, the use of resultant displacement in single spring models fails to describe a positive or negative displacement for the case of hysteresis models [3].

![Figure 3.4: Element representation of a single spring model [3].](image)

Winston Mmari
Secondly, the element stiffness matrix of rank one in this model does not provide stiffness values to the directions perpendicular to the spring direction creating numerical instability. To fix this issue stiffness values must be added to these perpendicular directions and in doing so we create a different model that is not purely single spring model [3,8].

3.5.2 Spring pair models (non-oriented and oriented)

A better modeling approach is with the use of spring pair models. Here the sheathing-to-framing connection is represented by two non-linear springs that are orthogonal to each other. In this case, the difference in stiffness properties of the two orthogonal directions in the timber will be taken into account. Spring pair models are further divided into non-oriented spring pair models (uncoupled models) and oriented spring pair models (coupled models) [3,7].

3.5.2.1 Non-oriented spring pair models (uncoupled spring models)

Non-oriented spring pair models take into account the two orthogonal directions of the model say $x$ and $y$ directions. In this model, the connection stiffnesses, $K_x$ and $K_y$, and the connection forces, $P_x$ and $P_y$, are functions of the displacements in the $x$ and $y$ directions respectively. This leads to the situation that the change in displacement, in say the $x$ direction, $(\Delta u_x)$ has no effect in the element forces in the $y$ direction, $P_y$ and vice versa which is not the real case [3,7,8] see Figure 3.5.

![Figure 3.5: Element representation of an uncoupled spring pair model [3].](image)

In this case the element stiffness matrix in the tangential direction will only have diagonal components [7].

This has the effect of overestimating the connection stiffness and forces under non-linear loading, as a result, the strength of the whole shear wall is exaggerated as well. To overcome this researcher like Folz and Filiatrault (2000) [28], have proposed an alternative approach. It is however convenient and simple to use the oriented spring models in the analysis of sheathing-to-framing connections of shear walls.
For non-oriented spring pair models, Eq. (17) will then change into Eq. (23);

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = \begin{bmatrix}
K_{xx} & 0 \\
0 & K_{yy}
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y
\end{bmatrix},
\]

(23)

with,

\[K_{xx} \neq K_{yy},\]

(24)

\[K_{xy} = K_{yx} = 0.\]

(25)

3.5.2.2 Oriented spring pair models (coupled spring models)

As in the uncoupled spring pair model, this approach models the connection with two non-linear orthogonal springs. Whereby, in contrary to the uncoupled spring models the connection stiffnesses, \(K_x\) and \(K_y\), and the connection forces, \(P_x\) and \(P_y\), are functions of the displacements in both; the \(x\) and \(y\) directions altogether. The element stiffness in the tangential direction matrix in this case will be a full matrix which can be a symmetric matrix, but generally it is an un-symmetric matrix.

For oriented spring pair models, Eq. (17) will then change into Eq. (26);

\[
\begin{bmatrix}
F_x \\
F_y
\end{bmatrix} = \begin{bmatrix}
K_{xx} & K_{xy} \\
K_{yx} & K_{yy}
\end{bmatrix}
\begin{bmatrix}
u_x \\
u_y
\end{bmatrix},
\]

(26)

with,

\[K_{xx} \neq K_{yy},\]

(27)

\[K_{xy} \neq K_{yx} \neq 0.\]

(28)

3.5.3 Influence of different sheathing-to-framing joint characteristics

Researchers have also studied the influence of using the single spring and spring pair models on the behavior of the connection. Vessby J., (2011) [10], has shown that using the spring pair models resulted in a higher connection stiffness and capacity than the single spring model. The significance of which is dependent on the actual displacement path of the fastener and the level of non-linearity of the load-displacement curve [3].

Nevertheless, an interesting feature of these two models is that for small displacements, no difference in the load-displacement curve is observed. An explanation of this behavior is that the load-displacement curves for the connection when using the spring pair model coincides with the curve of the single spring model within the elastic range (i.e. at small displacements) [3].
4. Methods

4.1 Materials

For a timber sheathing-to-framing connection, the materials involved are the wood framing material, the wood-based sheathing material and the fastener.

4.1.1 Framing materials

The reference framing material in this study is softwood, Norway spruce timber of grade C24 of dimensions 70 x 225 mm. This structural timber class has the following properties [30], see Table 4.1.

Table 4.1: Mechanical properties of the reference framing material, C24.

<table>
<thead>
<tr>
<th>Property</th>
<th>( f_{c,0,k} )</th>
<th>( f_{c,90,k} )</th>
<th>( f_{t,0,k} )</th>
<th>( f_{t,90,k} )</th>
<th>( E_{0,mean} )</th>
<th>( E_{90,mean} )</th>
<th>( \rho_{mean} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Mpa]</td>
<td>21</td>
<td>2.5</td>
<td>14</td>
<td>0.4</td>
<td>11000</td>
<td>370</td>
<td>420</td>
</tr>
</tbody>
</table>

\( f_{c,0,k} \) is the characteristic compressive strength parallel to grain, \( f_{c,90,k} \) the characteristic compressive strength perpendicular to grain. \( f_{t,0,k} \) the characteristic tensile strength parallel to grain, \( f_{t,90,k} \) the characteristic tensile strength perpendicular to grain, \( E_{0,mean} \) the elastic modulus parallel to grain, \( E_{90,mean} \) the elastic modulus perpendicular to grain and \( \rho_{mean} \) is the density.

4.1.2 Sheathing material

The reference sheathing material is an 11 mm thick Oriented Strand Board (OSB/2). The properties of which are as described in [31], see Table 4.2.

Table 4.2: Mechanical properties of the reference framing material

<table>
<thead>
<tr>
<th>Property</th>
<th>( f_{c,ll} )</th>
<th>( f_{c,\perp} )</th>
<th>( f_{t,ll} )</th>
<th>( f_{t,\perp} )</th>
<th>( E_{c,ll},E_{t,ll} )</th>
<th>( E_{c,\perp},E_{t,\perp} )</th>
<th>( \rho_{k} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>[Mpa]</td>
<td>15.4</td>
<td>12.7</td>
<td>9.4</td>
<td>7.0</td>
<td>3800</td>
<td>3800</td>
<td>550</td>
</tr>
</tbody>
</table>

\( f_{c,ll} \) is the compressive strength parallel to the strands in the outer layer, \( f_{c,\perp} \) the compressive strength perpendicular to the strands in the outer layer, \( f_{t,ll} \) the tensile strength parallel to the strands in the outer layer, \( f_{t,\perp} \) the tensile strength perpendicular to the strands in the outer layer and \( E_{c,ll},E_{t,ll} \), \( E_{c,\perp},E_{t,\perp} \) are the mean compressive and tensile stiffness parallel and perpendicular to the outer layer strands, respectively.
4.1.3 Embedment tests on the timber and OSB sheathing

In the sheathing-to-framing connection, the most interesting property of the wood framing and the sheathing is their embedment strengths. In addition to the empirical formulas in the EC5, test setups as described in for example SS-EN 383 [22] are to be performed on both materials.

A uniaxial test setup is arranged, and a nail is driven through the timber and the OSB. The nail is then pushed under controlled displacement conditions until failure. The load attained is then divided by the projected area of the dowel, $A = dt$, whereby $d$ is the dowel diameter and $t$ the thickness of timber [10], which yields the so called nominal embedment stresses.

Herein, the embedment properties of the grade C24 Norway spruce and the 11 mm OSB/2 sheathing will be adopted from a relevant literature by Vessby, et al., [12]. Four test series were performed on the reference materials, two in the longitudinal and cross directions of the OSB/2 sheathing and two on the longitudinal and tangential direction of the timber with respect to grain directions [12].

A 2.5 mm annular-ringed shank nail was driven into specimens of C24 timber and OSB/2 both of 11 mm thickness. The nail was then pulled in a uniaxial testing machine MTS 810, see Figure 4.1, at a controlled displacement rate of 3 mm/min.

![Figure 4.1: Embedment test setups a) the OSB/2 sheathing and b) C24 wood specimens. (Vessby., et al., 2014) [12].](image)
The non-linear embedment behavior

The embedment of the fastener in wood and OSB is described by a non-linear curve. These curves were obtained from tests described in section 4.1.3 and they are to be used in the properties of the connector elements in Abaqus. Different methods exist, but herein the approach proposed by Foschi as described in [32] will be used.

Foschi used an exponential function to describe the experimentally obtained non-linear load-slip curves of a nailed connection. This exponential function Eq. (29) provides the backbone of a bilinear relationship. The coefficient $k_0$ describes the initial gradient, $k_f$ the final gradient, with the initial gradient emerging from the origin while the final gradient intersects the vertical axis at a point denoted by $P_0$. The embedment depth (i.e. the nail displacement) is denoted by, $w$, see for example Figure 4.2,

$$ P = (P_0 + k_f w)(1 - e^{-\frac{k_0 w}{P_0}}). $$

(29)

Using this equation, appropriate bilinear relationships of the embedment behavior of the wood and OSB sheathing are formulated and used as input properties of the connector elements.

![Figure 4.2: The Bilinear curve of the exponential function fitted to nail-embedment test data.](Hong. J., et al., 2010) [32].

4.1.4 Fastener

When assembling the sheathing to the frame, nails of small diameters are often used. The reference fastener in this sheathing-to-framing connection is an annular-ringed shank nail with a diameter of 2.5 mm and a length of 60 mm.
4.1.5 Tests on the fastener

It is also desirable to determine and verify the mechanical properties of the nail. The mechanical property of interest is the ultimate steel strength, $f_u$, of the nail which will be used to determine its yield moment, $M_{y,Rk}$. The empirical formulas for yield moment determination have been described earlier in section 3.3.1.2.

The nail wire of known size is put in a tensile testing condition until failure, see Figure 4.3. The load and displacement are recorded during the test until failure is reached and the ultimate load determined [12]. The stress-strain relationship obtained will be assigned to the fastener beam element in Abaqus.
4.1.6 Nail withdrawal test

The most common failure of a sheathing-to-framing connection is the nail withdrawal [3]. This makes it important to know the nail withdrawal capacity. This withdrawal capacity is needed in the determination of the rope effect of the fastener.

A sheathing-to-framing connection under loading may only fail in two ways: the nail head pull through the sheathing or the nail shank withdrawal from the framing [33]. Corresponding properties will be taken from literature.

Studies have been performed by, for example, Izzi., et al., [34] on CLT specimens and by APA – The Engineered Wood Association, [33] on plywood and OSB panels using the procedures described in ASTM D1761.

4.2 Description of the Laboratory tests

In this section, the laboratory setup and procedures for the experimental investigation of the displacement path dependency in an OSB sheathing-to-framing mechanical connection is described.

The experimental investigation was performed in a biaxial setup (see Figure 4.4), whereby various displacement paths were prescribed.

![Figure 4.4: The biaxial test setup. (Laboratory results report at LNU,2016) [6].](image)

The sheathing (OSB/2) was connected to the vertical actuator of the testing machine by bolts and a steel plate, whereas the frame was mounted to the horizontally movable sledge by a steel device. A minimum of 3 up to 6
repetitions were performed to nine different test series (series A to J). Each test series described a different displacement path (i.e. 9 different displacement paths), see Figure 4.5.

Test series A through C describe the connection tests performed with an initial vertical displacement with a subsequent horizontal displacement, test series D, E and F describe connections subjected to horizontal displacement and a subsequent vertical displacement. Whereas, series G, H and J described tests performed at a straight displacement path at angles 30°, 45° and 60° respectively, to the grain direction of the framing timber member [6].

The loading for all test series was performed under displacement control at a loading rate of 2 mm/min. The machine displacements together with the vertical and horizontal reaction forces were being recorded at a frequency of 4 Hz.

![Figure 4.5: Displacement paths for test series A – J [6].](image)

In addition, the out-of-plane displacements were monitored and measured with a specifically mounted Linear Variable Differential Transformer (LVDT), attached to the timber framing.

Moreover, for some selected specimen, full-field optical surface deformation measurements were performed on the OSB sheathing and the wood framing using digital image correlation (DIC) to further increase the reliability of the data obtained.
4.3 Numerical modeling of connection

Currently, there are many commercial FE programs in the market suited for different purposes; some are for specific purposes while there also general-purpose FE programs as well. A specific purpose FE program is usually developed to solve a particular problem in most cases aimed to quicken the workflow. Whereas, general purpose can be used in a range of problems varying between different fields, as it is in the case of Abaqus® [35].

For the simulations and analyses performed in this study, Abaqus® will be used. Abaqus® is among the well-known commercial FE programs that suit well this study with its strong functionality and power. Not to mention its ability to incorporate well a variety material properties and simulate different loading conditions including static and dynamic loads in relation to mechanics of materials [35].

Matlab scripts were written and run to create input files for the models to be analyzed in Abaqus. Corresponding Matlab scripts were also used to define the material properties of the connector elements that will simulate the embedment behavior of the nail in wood and OSB together with the axial behavior of the nail head and the nail shank.

4.3.1 Beam on foundation modeling

The nailed sheathing-to-framing connection will be modelled as a beam-on-foundation. The steel dowel is simulated by a deformable beam element in Abaqus. Then along the length of this chain of the beam elements, it is supported by coupled spring pair elements that characterize the embedment of the nail into the framing and sheathing materials in 3D-space [2]. These coupled springs are modelled by connector elements in Abaqus, simulating the embedment properties of the nail into the wood and OSB materials respectively.

The foundation properties are defined from nail embedment tests, whereby a foundation modulus and yield point are calculated [32]. Herein, the connection will be modeled using connector elements that simulate embedment behavior in 3D space. This simplifies the model as in Figure 4.6.
Figure 4.6: Illustration of a beam on a foundation model of a sheathing-to-framing connection in 3D-space using connector elements.

4.3.2 Connector element in Abaqus

Abaqus has suitable connector elements for simulation of several types of actuals connections, with the ability of modeling two-dimensional, axisymmetric (CONN2D2) and three-dimensional (CONN3D2) elements for analysis, functionality to define specific connector attributes. It has comprehensive kinematic and kinetic output and can be used to monitor kinematics in local coordinate systems [35].

Abaqus connector elements are used to describe oriented (coupled) spring pair models. The fastener is modeled as an elasto-plastic deformable linear beam elements (B31) embedded in non-linear elastic or elastic-plastic foundation (the connectors).

Abaqus contains a vast number of connector elements and a large number of connector behaviors to be assigned to the connector elements. Since this study focuses on the displacement path dependency of a nailed timber connection, the beam element is embedded in a 3D foundation. To simulate this, a series of suitable connector elements were chosen namely, CONN3D2 were chosen each connecting two nodes; one on the nail and the other on either the sheathing or wood respectively depending on the location of the connector.

A single connector element connects only two points (node $a$ and $b$ in Figure 4.8) or a single point and the ground. To simulate the embedment behavior of the nail throughout the entire penetration depth into the wood and OSB, a series of connector elements were used.
The connector element connection type *Cartesian-Euler* were selected in the analysis. These, therefore, provided six available components of relative motion, three translational components in the connector’s local X, Y, Z-directions and three rotational components about the same axes. See Figure 4.7 below.

**Figure 4.7: Connector connection type (Abaqus CAE [35]).**

The components of relative motion of interest are of the cartesian connection type. The cartesian connection does not impose any kinematic constraints but defines three local directions \((u_1^a, u_2^a\text{ and } u_3^a)\) at the first node (node \(a\)), herein named node, \(a\). The change of position of node, \(b\) is measured along these local coordinates.

Position of node \(b\) relative to node \(a\) is determined by,

\[
x = u_1^a(x_b - x_a),
\]
\[
y = u_2^a(x_b - x_a),
\]
\[
z = u_3^a(x_b - x_a),
\]

the available components of relative motion are determined as

\[
u_1 = x - x_0,
\]
\[
u_2 = y - y_0,
\]
\[
u_3 = z - z_0,
\]

where \(x_0, y_0,\) and \(z_0\) are the initial coordinates of node \(b\) relative to local coordinate system at node \(a\). \(u_1, u_2,\) and \(u_3\) are the relative motions along the local directional coordinates of node \(a\) [35].
5. Implementation

This section describes how methods were applied in the modeling of the connection. The procedures for the creation of the model in Abaqus together with the determination of the relevant material properties of the nail fastener, OSB sheathing and wood will be discussed. The implementation of these properties in the connector elements is also described.

5.1 Material properties

To accurately model the connection, adequate and consistent material data must be assigned to the three elements of the sheathing-to-framing connection. In this section, analysis the material property data obtained from the tests as described in section 4.1 is discussed in conjunction with their application in Abaqus.

5.1.1 The nail elastic-plastic properties

The 2.5 mm diameter wire used to manufacture the steel nail was tested and the results describe a ductile behavior with an initial linear elasticity and afterwards the nail starts yielding at around 3.36 kN corresponding to a stress of about 685 MPa, see Figure 5.1. Abaqus allows the description of the elasticity and plasticity of metals in several ways as well as a combination of different material properties, but of interest to this context are isotropic elastic and plastic mechanical properties.

![Figure 5.1: Experimentally determined load-displacement curve for the steel wire used to manufacture the nail [12].](image-url)
The nail has a modulus of elasticity of approximately 210000 MPa and a poisson’s ratio of 0.3. Plasticity of the nail was also defined since the connection is subjected to large displacements beyond its elastic limit. Taking these into account, Abaqus defines the plasticity using true stresses and logarithmic strains. These operations were performed on the test data, leading to a plot of true stress vs logarithmic stain Figure 5.2, using the following assumptions

\[
\varepsilon_T = -v \varepsilon_l, \tag{36}
\]
\[
\Delta d = d \varepsilon_T, \tag{37}
\]
\[
d_{\text{real}} = d - \Delta d, \tag{38}
\]
\[
A_{\text{real}} = \pi d_{\text{real}}^2 / 4, \tag{39}
\]
\[
\sigma_{\text{true}} = F / A_{\text{real}}, \tag{40}
\]
\[
\varepsilon_{\text{ln}} = \ln \left( \frac{l_0 + \Delta l}{l_0} \right), \tag{41}
\]

whereby, \( \varepsilon_T \) is the transversal strain, \( \varepsilon_l \) is the longitudinal strain, \( v \) the poisson’s ratio, \( d \) the nail diameter, \( A \) the cross-sectional area of the nail, \( F \) the applied load and \( l_0 \) is the initial length of the extensometer, \( \Delta l \) is the displacement measured by the extensometer.

![Figure 5.2: A plot of true-stress against logarithmic-strains for the steel nail wire](image)

Information from Figure 5.2 then provides the yield stress of 680 MPa and plastic strain properties for the nail plasticity definition in Abaqus. To confirm the results a simple simulation of nail tensile test was performed in leading to results in Figure 5.3 (b) that to a close extent correspond to the
Experimental test results Figure 5.1. Figure 5.3 (a) shows the 2.5 mm diameter nail wire modeled with an assumed cylindrical shape.

![Figure 5.3: Abaqus simulation of nail tensile test](image)

5.1.2 Embedment properties

The nail fastener simulated by a deformable beam is embedded into a foundation, i.e. the wood framing and sheathing by means of the connector elements in Abaqus. Suitable embedment data of the nail into the wood and OSB sheathing materials is assigned to the respective connector elements.

Experimental results obtained from tests described in section 4.1 were analyzed in Matlab to give the necessary data for the model. The beam on foundation model analysis was performed in two respects: first with only non-linear elastic properties in wood and OSB sheathing materials and secondly with plasticity properties in the embedding materials.

These embedment properties were extracted from the test results using regression analysis and plotted using the Foschi approach described in section 4.1.3.1. The corresponding coefficients required in the exponential function (cf. Eq. 29) for both wood and OSB sheathing are summarized in Table 5.1 below for longitudinal and perpendicular directions to the grain respectively.
Table 5.1: Coefficients for the Foschi exponential equation for wood and OSB sheathing.

<table>
<thead>
<tr>
<th></th>
<th>$k_{0,\parallel}$</th>
<th>$k_{f,\parallel}$</th>
<th>$P_{0,\parallel}$</th>
<th>$k_{0,\perp}$</th>
<th>$k_{f,\perp}$</th>
<th>$P_{0,\perp}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>71.156</td>
<td>0.1128</td>
<td>45.08</td>
<td>59.356</td>
<td>4.2</td>
<td>26.913</td>
</tr>
<tr>
<td>OSB/2</td>
<td>89.73</td>
<td>2.011</td>
<td>52.084</td>
<td>135.033</td>
<td>5.347</td>
<td>33.987</td>
</tr>
</tbody>
</table>

Whereby, the coefficients $k_0$, $k_f$ and $P_0$ reserve the same meaning as before whereas the subscripts $\parallel$ and $\perp$ represents the longitudinal direction (parallel to grain) and perpendicular to grain direction respectively. $P_0$ is in [N/mm$^2$] and stiffnesses $k_0$ and $k_f$ are in [N/mm$^2$/mm].

It as also important to note that for the OSB sheathing, parallel to grain means the length direction and perpendicular to grain is the cross direction.

5.1.2.1 The non-linear elastic embedment properties in wood and OSB

As it was discussed earlier, the models were analyzed in the first place considering only non-linear elastic behavior in the wood framing and OSB sheathing. Using the coefficients in Table 5.1, a bilinear relationship of the embedment force against embedment length was established.

For the C24 wood framing, Figure 5.4 shows the experimentally obtained load displacement curves (blue curve) and the load-displacement embedment curves derived by regression analysis using bilinear relationship (red curve), for the direction parallel to grain. Figure 5.5 describes the experimental and analytical load-displacement embedment properties in the direction perpendicular to grain.
Figure 5.4: Nail embedment behavior for the wood framing parallel to grain direction.

Figure 5.5: Nail embedment behavior for the wood framing perpendicular to grain direction.
Similar curves were developed for the OSB/2 sheathing using for parts of linear approximation to describe its softening behavior and the results are summarized in Figures 5.6 and Figure 5.7, for the direction parallel to its length side and direction perpendicular to its length side respectively.

Figure 5.6: Nail embedment behavior for the OSB/2 sheathing parallel to its length direction.

Figure 5.7: Nail embedment behavior for the OSB/2 sheathing perpendicular to its length direction.
The resulting data was implemented into Abaqus as the embedment behavior of the nail into the wood and OSB for each connector element, considering only non-linear elastic behavior. This will be discussed further in section 5.2.

5.1.2.2 The elastic-plastic embedment behavior in wood and OSB

The beam on foundation model is then analyzed when elastic-plastic embedment properties of the wood framing and the OSB sheathing is considered.

Following the non-linear load-displacement relationship described in section 5.1.2.1 for both wood and OSB. Plasticity models were generated from the obtained data. For the connector property definition, only isotropic plasticity is possible in Abaqus, in this sense the hardening behavior does not depend on the load direction. Therefore, a necessary simplification was adopted with an elastic-plastic model with an initial linear elastic region and then followed by kinematic plastic hardening.

Plasticity formulation in the connector elements in Abaqus

Abaqus allows plasticity formulation in connector elements similar to the classical metal plasticity theories [35]. Whereby, in connector elements the stress corresponds to the force, $f$ and the equivalent plastic strain corresponds to the equivalent plastic relative motion, $\bar{u}^{pl}$. The yield function is then described as,

$$\varphi(f, \bar{u}^{pl}) = P(f) - F^0 \leq 0,$$  \hspace{1cm} (42)

where, $f$ is the collection of forces and moments that contribute to the yield function, $P(f)$ is the connector potential that defines the magnitude of the connector tractions similar to defining equivalent state of stress in von Misses plasticity (cf. Section 5.3.3) and $F^0$ is the yield force [35].

Therefore, the connector relative motion is elastic when $\varphi < 0$ and when $\varphi \geq 0$ plastic flow occurs.

In this regard, the non-linear load-displacement curves were split into two parts: the initial elastic part and plastic part. The former involves the definition of the initial elastic stiffness in both directions parallel and perpendicular to grain together with the yield load, $F^0$, which are the loads in Table 5.2. Whereas the latter defines the plastic hardening curves.

To define the hardening rule, equivalent plastic relative motion, $\bar{u}^{pl}$, was determined from the corresponding experimental data as,

$$\bar{u}^{pl} = u^{exp} - u^{el},$$  \hspace{1cm} (43)
where, $u^{exp}$ is the displacement from the experimental embedment monotonic test and $u^{el}$, is the corresponding elastic displacement. The hardening curve in this case was defined in tabular form into Abaqus by specifying the size of the yield surface, $F^0$, as a tabular function of the equivalent plastic relative flow, $\bar{u}^{pl}$.

The initial stiffnesses for the wood framing and OSB sheathing are summarized in Table 5.2. Whereas the kinematic hardening curves shown in Figure 5.8 and Figure 5.9 for wood and OSB sheathing respectively.

![Figure 5.8: Plastic kinematic hardening curve for the nail embedment behavior in wood.](image1)

![Figure 5.9: Plastic kinematic hardening curve for the nail embedment behavior in OSB.](image2)
Table 5.2: Stiffnesses of wood and OSB for the initial linear-elastic region of embedment behavior together with the load at the start of yielding.

<table>
<thead>
<tr>
<th></th>
<th>$D_\parallel$ [MPa/mm]</th>
<th>$D_\perp$ [MPa/mm]</th>
<th>Yield Stress [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wood</td>
<td>177.89</td>
<td>148.39</td>
<td>677.48</td>
</tr>
<tr>
<td>OSB/2</td>
<td>337.6</td>
<td>315</td>
<td>1024.4</td>
</tr>
</tbody>
</table>

Whereby, $D_\parallel$ and $D_\perp$ represents elastic stiffnesses in the longitudinal direction (parallel to grain) and perpendicular to grain direction respectively.

The results from Figure 5.8 and Figure 5.9 are then adjusted to the mesh size of the beam element which becomes the property assigned to each connector element in the sheathing and framing members in their respective locations.

The properties described in Figure 5.8 and Figure 5.9 were generated using Matlab scripts, herein attached in Appendix 3 and Appendix 4 respectively.

5.1.3 Axial properties of the connection

Despite that the sheathing-to-framing nailed connection is a shear connection, axial forces usually arise as soon as the fastener (nail) starts to yield. These have a major influence on the capacity of the connection.

Nevertheless, the connection under study is subjected to large deformations, making the axial stiffness of the connection to be of important concern.

The axial stiffness for this matter is brought about by the annular-ringed Shank of the nail (nail withdrawal resistance) and the resistance of the nail head to pull through, Figure 5.10 shows the specific nail used in this study.

![Figure 5.10: The annular-ringed shank nail under study.](image)
5.1.3.1 Axial withdrawal property of the nail

The nail shank withdrawal properties adopted in this study are the result of a corresponding study by Izzi [34]. The test setup is described in Figure 5.11. a), and the results are shown in Figure 5.11. b).

Correspondingly, a similar load-withdrawal relationship was approximated by a polynomial function using regression analysis. Figure 5.12 shows the results that were used as input properties for the nail withdrawal behavior. Adjustments were done for the difference in nail diameter from the test in [34] of 4.0 mm to 2.5 mm with respect to this study.
Figure 5.12: Load-displacement curve used as input data for nail shaft withdrawal property.

5.2 Assignment of properties to the connector elements in Abaqus

5.2.1 The connector orientation in the model

The chosen cartesian connection type allows three components of relative motion which make the fastener to be embedded in 3D space, Figure 5.13. A specific orientation of each connector section was selected to allow the assignment of connector properties to their respective directions with respect to the grain direction. The material property assignment to the local components of relative motion, \( u_1 \), \( u_2 \), and \( u_3 \) corresponding to the global \( x \), \( y \), and \( z \) directions in Abaqus, are summarized in Table 5.3.
Figure 5.13: Local orientations assigned to each connector element.

Table 5.3: Connector material property assignment to the components of relative motion.

<table>
<thead>
<tr>
<th>Component of relative motion</th>
<th>Material property</th>
</tr>
</thead>
<tbody>
<tr>
<td>$u_1$</td>
<td>Nail shank withdrawal properties and Nail head pull-through properties.</td>
</tr>
<tr>
<td>$u_2$</td>
<td>Embedment properties parallel to grain</td>
</tr>
<tr>
<td>$u_3$</td>
<td>Embedment properties perpendicular to the grain.</td>
</tr>
</tbody>
</table>

5.2.2 Connector wire features in the model

Each connector element is connected between two points using connector wire features. Three sets of connector wire features were defined in the model: the first set (Set-1) defines the connector elements for embedment into the OSB/2 sheathing, the second set (Set-2) defines the connector elements for embedment into the wood framing and the third wire set (Set-3) defines the connector for head pull-through property.

5.2.3 Connector section assignment

Each connector wire feature described above must be assigned a connector section behavior at the respective component of relative motion. Three connector section behaviors were created, namely: ConnSect-1, ConnSect-2 and ConnSect-3, to model the embedment behavior in OSB sheathing, the embedment behavior in wood and the head pull-through behavior respectively.
5.2.3.1 ConnSect-1

Connector section, ConnSect-1 was created to model the non-linear elastic embedment properties and the elastic-plastic embedment properties of the nail into the OSB sheathing. Material properties were defined in the component of relative motion $u_2$ and $u_3$ for the parallel (length) and perpendicular (cross) directions to grain respectively. This connector section property was then assigned to wire feature Set-1.

For the non-linear elastic model, tabular data for the non-linear elastic embedment behavior were defined and coupled to position. Coupled nonlinear elasticity was attained by using a trigonometric function (cf. Eq. 44) similar to Hankinson’s equation, knowing the embedment properties parallel and perpendicular to fiber directions (cf. Section 5.1.2.1).

$$F_\alpha = \frac{F_0 F_{90}}{F_0 \sin^2 \alpha + F_{90} \cos^2 \alpha}, \quad (44)$$

$$\alpha = \tan^{-1} \left( \frac{F_{90}}{F_0} \right), \quad (45)$$

where, $F_\alpha$ is the embedment force at a direction $\alpha$ to the fibers, $F_0$ and $F_{90}$ are the embedment forces parallel and perpendicular to fiber directions respectively.

The material properties for the OSB sheathing in 3D space is graphically described in Figure 5.14 and Figure 5.15 for its length and cross directions respectively.

The properties described in Figure 5.14 and Figure 5.15 were generated using Matlab scripts, herein attached in Appendix 2.
Figure 5.14: 3D presentation of the embedment behavior of the nail into the OSB sheathing along the length direction, coupled to position.

Figure 5.15: 3D presentation of the embedment behavior of the nail into the OSB sheathing along the cross direction, coupled to position.
For the case of the plastic-elastic model, the kinematic hardening curve was defined as discussed in section 5.1.2.2. The plasticity properties for the two perpendicular directions of grain were coupled with an elliptical outer bound Eq. (46) for a general elliptical form and Eq. (47), for the function applied in this model. In Abaqus, this was achieved by defining connector potentials in the connector functions for coupled behavior [35],

\[
P(u) = \left( \sum_{i=1}^{N_p} s_i P_i^\alpha(u) \right)^{\frac{1}{\beta}},
\]

\[
P(u) = \left( P_2^2(u) + P_3^2(u) \right)^{\frac{1}{2}},
\]

where \( u \) is the connector intrinsic components of relative motion, \( P_i \) is the \( i^{th} \) contribution to the potential, \( N_p \) is the number of contributions (in this case it is 2, being \( u_2 \) and \( u_3 \)), \( s_i \) is the overall sign of the contribution, \( \alpha_i \) and \( \beta \) are positive numbers that define the elliptical function.

Similar procedures were performed for the elastic-plastic embedment behavior of the nail into the wood framing.

5.2.3.2 ConnSect-2

Similarly, connector section ConnSect-2 was created for the embedment behavior in the wood framing. Material properties were defined in the component of relative motion \( u_2 \) and \( u_3 \) for the parallel and perpendicular directions to grain respectively, in addition material properties for the axial nail shank withdrawal were defined in the \( u_2 \) component of relative motion. This connector section property was then assigned to wire feature Set-2.

For the non-linear elastic model, tabular data for the non-linear elastic embedment behavior were defined and coupled to position. The material properties of the wood in 3D space is graphically described in Figure 5.16 and Figure 5.17 for the length and cross directions respectively.

The properties described in Figure 5.16 and Figure 5.17 were generated using Matlab scripts, herein attached in Appendix 1.
Figure 5.16: 3D presentation of the embedment behavior of the nail into the wood framing, parallel to grain, coupled to position.

Figure 5.17: 3D presentation of the embedment behavior of the nail into the wood framing, perpendicular to grain, coupled to position.
5.2.3.3 ConnSect-3

Connector section, ConnSect-3 was created to model the nail head pull-through properties. Material properties were defined in the component of relative motion $u_1$. This connector section property was then assigned to wire feature Set-3.
6. Results and Analysis

This chapter presents the findings of this study. Included are the plots of data stemming from the numerical analysis, diagrams and calculations of the performed tasks. Comparison of the results from the simulations against the corresponding experimental results from the laboratory tests performed at the Linnaeus University laboratory is also made.

6.1 Connection capacity according to Eurocode 5

As it was discussed in section 3.3.1 through section 3.3.3, EC5 [10] predicts the connection capacity depending on its geometry, the yield moment of the nail and the embedment strength of the wood and OSB with respect to this study. Figure 6.1 shows the comparison of the capacity of the nailed sheathing to framing connection under study loaded parallel to the grain direction. The plot clearly shows that the connection capacity is underestimated by the approach in EC5 and it describes how the axial withdrawal capacity of the nail has a significant effect on the development of strength after yielding start to occur.

Figure 6.1: Comparison of the numerical results against the connection capacity design by EC5.
For the calculations of the connection capacity and slip moduli ($K_{ser}$ and $K_u$), EC5 requires the use of characteristic values of the material properties such as, density, $\rho_k$. But, herein the mean values of the corresponding material properties are used in the calculation. This is adopted as a suitable assumption to attain a more representative connection capacity. The mean densities, $\rho_m$, for the C24 wood framing and OSB/2 sheathing used in these calculations are as in Table 6.1.

Table 6.1: Mean densities for the OSB/2 and C24 wood framing.

<table>
<thead>
<tr>
<th></th>
<th>C24 wood framing [kg/m$^3$]</th>
<th>OSB/2 [kg/m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean density, $\rho_m$</td>
<td>420</td>
<td>600</td>
</tr>
</tbody>
</table>

The failure mode of the connection was found to be failure mode d (cf. Eq. 8.69(d) in EC5 [10]) and the corresponding calculations are attached in Appendix 5.

The connection capacity calculated according to EC5 was found to be 581.638 MPa without the withdrawal capacity and 807 MPa with the inclusion of the axial capacity (cf. Figure 6.1).

Eurocode 5 [10] also provides a model for predicting the instantaneous slip modulus, $K_{ser}$, for timber to timber joint together with the ultimate modulus, $K_u$, that is derived from the $K_{ser}$ value. For the nailed sheathing-to-framing connection under study, the corresponding values for $K_{ser}$ and $K_u$, were determined to be 780.335 [N/mm] and 520.223 [N/mm] respectively. Respective curves describing the instantaneous moduli $K_{ser}$ and $K_u$, are shown in Figure 6.1.
6.2 Displacement paths analysis

In this sub-section, the sheathing-to-framing nailed connection under study was loaded along various displacement paths (cf. Figure 4.5). The development of the resultant loads together with the forces parallel and perpendicular to the grain of the wood framing were investigated along the entire paths and the behavior at the points of change in path direction. Furthermore, the behavior of the magnitude and direction of the resultant forces at the intersection points of these paths were studied for both the elastic and plastic models in comparison with the experimental results.

6.2.1 Results from experimental test series

A summary of the experimental test results is described here. Figure 6.3 describes the development of the resultant force (total force) of the connection along displacement paths: A, B and C, Figure 6.2. The total force and total displacement were determined as,

\[ F = \sqrt{F_x^2 + F_y^2}, \]
\[ u = u_x + u_y, \]

where, \( F_x \) and \( u_x \) are the force and displacement in the direction parallel to the grains of the wood framing, \( F_y \) and \( u_y \) are the force and displacement perpendicular to the grain direction respectively.

The bold lines in Figure 6.3 represent the total force, whereas the dotted lines show the profiles of the forces parallel and perpendicular to the wood grain for the respective paths.

Figure 6.2: Description of the displacement paths, A, B and C.
The connection was loaded perpendicular to grain direction first then parallel to the grain. It is then observed that the total force in the initial path direction is entirely dependent on the $F_y$ (Part-1 in Fig. 6.3 for path B), then as the path changes a sharp fall in $F_y$ (Part-2 in Fig. 6.3 for path B) is observed as the $F_x$ start rising. This sharp fall of the $F_y$ also creates a sharp fall of the total force at the points of change in displacement paths of the connection. Nevertheless, the total force then rises once more as the forces parallel to grain, $F_x$, keeps on growing. This develops up to a point where the total force is entirely dependent on the forces parallel to grain (Part-3 in Fig. 6.3 for path A).

Similar behavior was observed for the results obtained when the connection was loaded along paths, D, E and F, Figure 6.4 and Figure 6.5. Whereby, the connection was loaded parallel to grain direction then perpendicular to grain for the respective paths.
Figure 6.4: Description of the displacement paths, D, E and F.

Figure 6.5: Development of the total force, and forces parallel and perpendicular to grain for the displacement paths, D, E and F.

Path dependency was studied for the total force vector at intersection points of the displacement paths. Figure 6.6 shows the force vectors for the paths at different intersection points.
The results from Figure 6.6 further suggests path dependency in relation to the total forces. It is observed that the force component (either \( F_x \) or \( F_y \)) parallel to the displacement path at the point of intersection is higher in the case of a non-uniform displacement path.

This is evident especially for total force vector for example at intersections X, Y and Z (cf. Fig. 6.6) whereby, equal displacements have been achieved both parallel and perpendicular to grain for the intersecting displacement paths. However, the total force vector is more inclined with the current path direction of each displacement path at the intersection.

6.2.2 Results from the beam on non-linear elastic foundation model

For the beam on a non-linear elastic foundation model, the connection was loaded along the paths along similar path-A through path-F. The development of total force, the forces parallel to grain, \( F_x \) and the forces perpendicular to grain, \( F_y \) was also investigated. Furthermore, the direction of the total force at the intersection of the paths was studied.
6.2.2.1 Development of the total forces along the paths

In a comparable procedure described for the experimental results and through Eq. (48) – (49). Figure 6.7 shows the development of the total forces (bold line curves) and the forces parallel to wood grain, \( F_x \) (dotted lines) and perpendicular to grain, \( F_y \) (dashed lines) for path-A, path-B and path-C (cf. Fig. 6.2). Figure 6.8 shows related results for path-D, path-E and path-F respectively (cf. Fig. 6.4).

![Graph showing force development](image)

*Figure 6.7: Development of the total force, and forces parallel and perpendicular to grain for the displacement paths, A, B (non-linear elastic model).*

For this non-linear elastic model, the behavior at the points of displacement path change did not match the results observed from the experimental tests. The expected sharp falls in component forces when the displacement path is changed are not observed.

This observation on the beam on elastic foundation model is further described in Figure 6.9, showing the change in \( F_y \) along paths, A and B, and Figure 6.10 showing the change of \( F_x \) along paths, D, E and F. It is observed that as the path direction changes, these component forces start decreasing at a slower rate than it is seen in the experimental results (Fig. 6.3 and Fig. 6.5).
Figure 6.8: Development of the total force, and forces parallel and perpendicular to grain for the displacement paths, D, E and F (non-linear elastic model).

Figure 6.9: The change in $F_y$ along path-A and path-B in the non-linear elastic model.
6.2.2.2 Total force vector at intersection points

The plots in Figure 6.11 shows the total force vectors at the intersection points of paths, A, B, D, E and F. It is observed that the force vectors are the same at the intersections points regardless of the path taken by the load. This goes against the behavior observed in experimental results as described in (Fig. 6.6).

Figure 6.10: The change in $F_x$ along path-D, path-E and path-F in the non-linear elastic model.

Figure 6.11: Total force vectors at intersection points of the displacement paths A, B, D, E and F, for the beam on non-linear elastic model.
6.2.3 Results from the beam on elastic-plastic foundation model

As for the beam on a non-linear elastic model, the connection modeled as a beam on an elastic-plastic foundation was loaded along the paths along the path-A through path-F and path-H. The development of total force, the forces parallel to grain, \( F_x \) and the forces perpendicular to grain, \( F_y \) was also investigated. Furthermore, the direction of the total force at the intersection of the paths was studied.

6.2.3.1 Development of the total forces along the paths

Similar approach as for the experimental data and using Eq. (48) – (49), Figure 6.12 shows the development of the total forces (bold line curves) and the forces parallel to wood grain, \( F_x \) (dotted lines) and perpendicular to grain, \( F_y \) (dashed lines) for path-A, path-B and path-C (cf. Fig. 6.2). Figure 6.13 shows related results for path-D, path-E and path-F respectively (cf. Fig. 6.4).

![Figure 6.12: Development of the total force, and forces parallel and perpendicular to grain for the displacement paths, A, B and C (elastic-plastic model).](image)

Figure 6.12 and Figure 6.13 to a better extent characterize the behaviors similar to the experimental results regarding the change in the component forces when the displacement path is changed. This is observed for example by the relatively similar fall in the forces parallel to grain, \( F_x \) when the path
changes in Figure 6.13, similarly the rapid rise in forces perpendicular to grain, $F_y$. In addition, after the displacement direction changes the total forces depends more on the force component in the new path direction.

These observation on the beam on elastic-plastic foundation model can be seen in Figure 6.14, showing the change in $F_y$ along paths, A, B and C, and Figure 6.15 showing the change of $F_x$ along paths, D, E and F. It is observed that as the path direction changes, these component forces start decreasing in an analogous manner as it is seen in the experimental results (Fig. 6.3 and Fig. 6.5).
Figure 6.14: The change in $F_y$ along path A, path B and path C in the elastic-plastic model.

Figure 6.15: The change in $F_x$ along path D, path E and path F in the elastic-plastic model.
Another interesting observation is the progressive decrease of the absolute level of the forces parallel to grain, $F_x$, along displacement paths A, B and C. As the displacement direction changes from perpendicular to parallel to the grain the forces $F_x$ starts rising, yet through the same displaced length parallel to grain the value of $F_x$ is highest in displacement path A and progressively falls in paths B and C. Figure 6.16 and Figure 6.17 show this observation from the experimental results and numerical results respectively.

Figure 6.16: Development of $F_x$ along path-A, path-B and path-C in the elastic-plastic model (experimental test results).
6.2.3.2 Total force vector at intersection points

The plots in Figure 6.18 show the total force vectors at the intersection points of paths, A, B, C, D, E, F and H. In comparison to the results from the experimental tests (cf. Fig. 6.6), it is observed that the total force vectors describe a path dependency at the intersection points of the displacement paths.

The force component (either $F_x$ or $F_y$) parallel to the displacement path at the point of intersection is higher.

Similarity is seen on the orientation of the total force on a displacement path after the direction has changed, whereby, the total force starts depending more and more on the component in the current displacement direction whereby the total force orientation keeps on tilting towards the current displacement direction.
6.3 Development of axial forces in the connection

From experiments on dowel type connections, Blaß et al., [36] concluded that failure occurs at low values of fastener bending and that the plasticity capacity of the dowel is not attained at that point. In result, a calculation model was proposed by Blaß et al., [36] which is currently prescribed in EC5 [10]. Nevertheless, for nailed connection, the fastener cross-section is relatively small and yielding occurs at very early stages of shear displacement of the connection. The implication of this is that the axial forces in the connection also develop at these initial stages, and therefore play an important role in the nailed connection capacity.

Figure 6.19 shows the deformations states of the connection as it is loaded parallel to the grain. After about a displacement of only 0.8 mm and a stress level of 685 MPa, the fastener starts to yield and at the same time the axial forces in the connection start to develop which play a significant role in the growth of the connection capacity see Figure 6.20.
Figure 6.19: Deformed states of the connection when loaded parallel to the grain.

Figure 6.20: Development of axial forces in the connection when loaded parallel to the grain.
7. Discussion

The aim of this master thesis was generally to investigate the influence of the embedding material properties of wood and OSB in the displacement path dependency of a sheathing-to-framing connection.

Its implementation using Abaqus is found to be reasonably acceptable considering the strength of the software in simulating a wide range physical processes with adequate accuracy. Therefore, the models have provided an effective way to represent the real nailed sheathing-to-framing connection in the context of this project.

3D modeling of such a connection using connector elements in Abaqus to simulation embedment behavior of wood and the sheathing has proven to be an efficient approach in comparison to 3D solid elements. This accounts for the excessive cost of computational time and machine power requirements in the latter than the former.

It goes without notice that the limitation of enough studies on the head pull-through behavior of the nail through the OSB/2 sheathing has to some extent affected the findings of this study. This is because the axial stiffness of the connection has been observed to have considerable influence in the overall capacity as seen in Figure 6.1 and Figure 6.20. An advancement of this knowledge could have benefited this study significantly.

It is important to remark the overestimation in the magnitude of the overall connection capacity in comparison to the experimental results. This gives an impression that the material properties used in the input could be higher than the requisite. More extensive database on the embedment properties into wood and OSB and alternative approximations of the non-linear load slip curves will address this issue positively.

In addition to this, it is important to state that the experiments were performed in a bi-axial test setup and it is suggested that minor errors that occur experimentally when loading at different paths could have influenced in some slight discrepancy with the numerical results.

Nevertheless, the current approach used in this study: including material property input data from corresponding tests and the configuration of the model, appears to conform well with the displacement path dependency behavior observed in the experimental test results of the connection as discussed in Chapter 6 of this work.
8. Conclusion

The overall aim of this work was to numerically investigate the displacement path dependency in a nailed sheathing-to-framing connection. It was hypothesized that this behavior is validated by only plasticity properties in the nail fastener in combination with the non-linear elastic embedment properties of the sheathing and wood framing.

It can be concluded that the results of this study refute the hypothesis formulated and that the displacement path dependency behavior can most certainly not be described by the non-linear elastic properties of the OSB/2 sheathing and wood framing in combination with only the elastic-plastic properties of the nail fastener. Therefore, the results, lead to a conclusion that the displacement path dependency of the sheathing-to-framing connection can be attributed to the elastic-plastic properties in both: the nail fastener and the embedding materials.

This gives an interesting implication that even at displacements as low as 5 mm, the plastic material properties of wood and the OSB sheathing has a significant effect on the behavior of the connection.

The results of this study have then demonstrated that the displacement path behavior observed in the experimental test results was not just incidental, but they can be numerically simulated and also attributed to some specific fundamental material properties of the connection components.

In addition, the numerical models in this study have observed that the approach to predicting connection capacity in Eurocode 5, not only underestimates the influence of the axial stiffness of the connection but also the overall connection capacity.
9. Further Studies

The various possibilities for future work to compliment this study and the general knowledge of connections are as follows.

Since the nail fastener is usually already deformed when the path direction changes, the knowledge of displacement path dependency would be advanced with a study on the embedment properties of the already deformed fastener into the wood framing.

A thorough understanding of the head pull-through behavior will have a great significance in the knowledge of nailed connections.

Another interesting study would be an experimental and numerical investigation of the influence and implications of out of plane movement of the sheathing in the overall connection behavior, capacity and failure.
References


Appendixes

Appendix 1: Matlab function for the definition of non-linear elastic embedment behavior of wood

Appendix 2: Matlab function for the definition of non-linear elastic embedment behavior of the OSB sheathing

Appendix 3: Matlab function for the definition of plastic hardening embedment behavior of wood

Appendix 4: Matlab function for the definition of plastic hardening embedment behavior of the OSB sheathing

Appendix 5: Connection capacity calculations according to Eurocode 5
APPENDIX 1: Matlab function for the definition of non-linear elastic embedment behavior of wood

```matlab
function [Fx_alpha,Fy_alpha,ux_crush,uy_crush] = connectorproperties_edited_new(doweldiameter,delta_l,woodtype)
u_crush1=[-20:1:20];

if woodtype==1
    % embedment behaviour nail in WOOD
    % nail diameter d=2.5 mm
    Fin_0=45.08;    % fh_in0
    Fin_90=26.913;  % fh_in90
    kf_0=0.1128;
    kf_90=4.1998;
    k0_0=71.156;
    k0_90=59.356;
elseif woodtype==2
    % embedment behaviour nail in OSB
    % nail diameter d=2.5 mm
    Fin_0=52.084;
    Fin_90=33.987;
    kf_0=2.011;
    kf_90=5.347;
    k0_0=126;
    k0_90=135.033;
end
%
%% 2dimensional definition of the slip behavior
alpha1=0;
for i=1:length(u_crush1)
    Fin_alpha(i)=(Fin_0*Fin_90)/(Fin_0*(sind(alpha1))^2+Fin_90*(cosd(alpha1))^2);
    kf_alpha(i)=(kf_0*kf_90)/(kf_0*(sind(alpha1))^2+kf_90*(cosd(alpha1))^2);
    k0_alpha(i)=(k0_0*k0_90)/(k0_0*(sind(alpha1))^2+k0_90*(cosd(alpha1))^2);
    F_alpha1(i)=(Fin_alpha(i)+kf_alpha(i)*u_crush1(i))*(1-exp((-k0_alpha(i)*u_crush1(i))/Fin_alpha(i)));
    Fx_alpha1(i)=F_alpha1(i)*cosd(alpha1);     % force component parallel to the grain
    Fy_alpha1(i)=F_alpha1(i)*sind(alpha1);     % force component perpendicular to the grain
    ux_crush1(i)=u_crush1(i)*cosd(alpha1);     % displacement component parallel to the grain
    uy_crush1(i)=u_crush1(i)*sind(alpha1);     % displacement component perpendicular to the grain
end
%
%% 3dimensional definition of the slip behavior
```

clear Fin_alpha kf_alpha k0_alpha F_alpha Fx_alpha Fy_alpha
ux_crush uy_crush u_crush

ux_all=[(-20:1:-12),(-11:0.1:11),(12:1:20)];
uy_all=[(-20:1:-12),(-11:0.1:11),(12:1:20)];

alpha=0;
for i=1:length(ux_all)
    for j=1:length(uy_all)
        u_crush(i,j)=sqrt(ux_all(i)^2+uy_all(j)^2);
        alpha(i,j)=atand(uy_all(j)/ux_all(i));
        if ux_all(i)==0 & uy_all(j)==0
            alpha(i,j)=0;
        end
        Fin_alpha(i,j)=(Fin_0*Fin_90)/(Fin_0*(sind(alpha(i,j)))^2+Fin_90*(cosd(alpha(i,j)))^2);
        kf_alpha(i,j)=(kf_0*kf_90)/(kf_0*(sind(alpha(i,j)))^2+kf_90*(cosd(alpha(i,j)))^2);
        k0_alpha(i,j)=(k0_0*k0_90)/(k0_0*(sind(alpha(i,j)))^2+k0_90*(cosd(alpha(i,j)))^2);
        Fx_alpha(i,j)=(Fin_alpha(i,j)+kf_alpha(i,j)*u_crush(i,j))*(1-exp((-k0_alpha(i,j)*u_crush(i,j))/Fin_alpha(i,j));
        Fy_alpha(i,j)=F_alpha(i,j)*cosd(alpha(i,j)); % force component parallel to the grain
        ux_crush(i,j)=ux_all(i); % displacement component parallel to the grain
        uy_crush(i,j)=uy_all(j); % displacement component perpendicular to the grain
    end
end

%% Figure checks
%figure(2)
%mesh(ux_crush,uy_crush,abs(Fx_alpha));
%xlabel('ux [mm]')
%ylabel('uy [mm]')
%zlabel('Fx [N]')
%grid on
%
%figure(3)
%mesh(ux_crush,uy_crush,abs(Fy_alpha));
%xlabel('ux [mm]')
%ylabel('uy [mm]')
%zlabel('Fy [N]')
%grid on
APPENDIX 2: Matlab function for the definition of non-linear elastic embedment behavior of the OSB sheathing

function
[Fx_alpha_2,Fy_alpha_2,ux_crush,uy_crush]=OSB_embedment_functions
_2(naildiameter,deltal1,woodtype)
uy=[(0.00:0.05:1),(1.5:0.5:29)];
ux=[(0.00:0.05:1),(1.5:0.5:29)];

uy=zeros(size(uy));
part1= (0.00<=uy) & (uy<=0.75);
Fx(part1)=(1366.67*uy(part1))/(2.5*11);

part2=(0.75<=uy) & (uy<=9.75);
Fx(part2)=(152.78*uy(part2) + 910.42)/(2.5*11);

part3=(9.75<=uy) & (uy<=22);
Fx(part3)=(3991.84-163.27*uy(part3))/(2.5*11);

part4=(22<=uy) & (uy<=29);
Fx(part4)=(1500-50*uy(part4))/(2.5*11);
%
Fy=zeros(size(ux));
part1x= (0.00<=ux) & (ux<=0.75);
Fx(part1x)=(1866.67*ux(part1x))/(2.5*11);

part2x=(0.75<=ux) & (ux<=12);
Fx(part2x)=(57.778*ux(part2x) + 1356.67)/(2.5*11);

part3x=(12<=ux) & (ux<=21.5);
Fx(part3x)=(4134.21-173.684*ux(part3x))/(2.5*11);

part4x=(21.5<=ux) & (ux<=29);
Fx(part4x)=(1285.3-41.176*ux(part4x))/(2.5*11);
%
%
for i=1:length(ux)
  for j=1:length(uy)
    u_r(i,j)=sqrt(ux(i)^2+uy(j)^2);
    alpha(i,j)=atand(uy(j)/ux(i));
    if ux(i)==0.00 & uy(j)==0.00
      alpha(i,j)=0.00;
    end
    Fin_alpha(i,j)=(Fx(i)*Fy(j))/(Fx(i)*(sind(alpha(i,j)))^2+Fy(j)*(cosd(alpha(i,j)))^2);
    if Fx(i)==0.00 & Fy(j)==0.00 & alpha(i,j)==0.00
      Fin_alpha(i,j)=0.00;
    end
    Fx_alpha_3(i,j)=Fin_alpha(i,j)*cosd(alpha(i,j)); % force component parallel to the grain
    Fx_alpha_3(1,:)=zeros;
  end
end

Appendix 2: page 1
Winston Mnari
for p=1:length(Fx)
    Fx_alpha_3(p,1)=Fx(p);
end
Fy_alpha_3(i,j)=Fin_alpha(i,j)*sind(alpha(i,j));
% force component perpendicular to the grain
for q=1:length(Fy)
    Fy_alpha_3(1,q)=Fy(q);
end
Fy_alpha_3(:,1)=zeros;
ux_crush(i,j)=ux(i);
uy_crush(i,j)=uy(j);
end
end
Fx_alpha_2=Fx_alpha_3;
Fy_alpha_2=Fy_alpha_3;

%% Graph check
figure (12)
mesh(ux_crush,uy_crush,abs(Fx_alpha_2));
xlabel('ux [mm]')
ylabel('uy [mm]')
zlabel('Fx [N]')
grid on

figure(13)
mesh(ux_crush,uy_crush,abs(Fy_alpha_2));
xlabel('ux [mm]')
ylabel('uy [mm]')
zlabel('Fy[N]')
grid on
APPENDIX 3: Matlab function for the definition of plastic hardening embedment behavior of wood

function [disp,force] = connectorproperties_plastic(doweldiameter,delta_l,woodtype,alpha1)
if woodtype==1
    % embedment behaviour nail in WOOD
    % nail diameter d=2.5 mm
    Fin_0=45.08;    % fh_in0
    Fin_90=26.913;  % fh_in90
    kf_0=0.1128;
    kf_90=4.1998;
    k0_0=71.156;
    k0_90=59.356;
elseif woodtype==2
    % embedment behaviour nail in OSB
    % nail diameter d=2.5 mm
    Fin_0=52.084;
    Fin_90=33.987;
    kf_0=2.011;
    kf_90=5.347;
    k0_0=126;
    k0_90=135.033;
end

%% 2dimensional definition of the slip behavior
ux_all=[0:0.1:2.5,3:1:30];
yy_all=[0:0.1:2.5,3:1:30];

for i=1:length(ux_all)
    Fin_alpha(i)=(Fin_0*Fin_90)/(Fin_0*(sind(alpha1))^2+Fin_90*(cosd(alpha1))^2);
    kf_alpha(i)=(kf_0*kf_90)/(kf_0*(sind(alpha1))^2+kf_90*(cosd(alpha1))^2);
    k0_alpha(i)=(k0_0*k0_90)/(k0_0*(sind(alpha1))^2+k0_90*(cosd(alpha1))^2);
    F_alpha1(i)=(Fin_alpha(i)+kf_alpha(i)*ux_all(i))*(1-exp((-k0_alpha(i)*ux_all(i))/Fin_alpha(i)));
    Fx_alpha1(i)=F_alpha1(i)*cosd(alpha1);  % force component parallel to the grain
    Fy_alpha1(i)=F_alpha1(i)*sind(alpha1);  % force component perpendicular to the grain
end

if alpha1==0
    figure(1)
    plot(ux_all,F_alpha1);
    hold on;
    plot(ux_all,Fx_alpha1,'r');
\begin{verbatim}
plot(uy_all,Fy_alpha1,'g');
grid on;

u_ell=0.5;

k=F_alpha1(6)/u_ell;  \% Initial elastic stiffness

for i=1:length(ux_all);
    ux_pl(i)=(ux_all(i))-(F_alpha1(i)/k);
end

help=[ux_pl',Fx_alpha1'];

u_F=help(6:length(F_alpha1),:);

figure(2)
plot(u_F(:,1),u_F(:,2));
hold on;
grid on;

elseif alpha1==90
    figure(1)
    plot(ux_all,F_alpha1);
    hold on;
    plot(ux_all,Fx_alpha1,'r');
    plot(uy_all,Fy_alpha1,'g');
    grid on;

    u_ell=0.5;

    k=F_alpha1(6)/u_ell;  \% Initial elastic stiffness

    for i=1:length(ux_all);
        ux_pl(i)=(ux_all(i))-(F_alpha1(i)/k);
    end

    help=[ux_pl',Fx_alpha1'];
    u_F=help(6:length(F_alpha1),:);

    figure(2)
    plot(u_F(:,1),u_F(:,2));
    hold on;
    grid on;
end

disp=u_F(:,1);
force=u_F(:,2);
\end{verbatim}
function
[disp_OBS, force_OBS]=OSB_embedment_functions_plasticity(naildiameter, delta11, woodtype)
uy=[(0.00:0.05:1), (1.5:0.5:29)];
ux=[(0.00:0.05:1), (1.5:0.5:29)];

Fy=zeros(size(uy));
part1= (0.00<=uy) & (uy<=0.75);
Fy(part1)=(1366.67*uy(part1))/(2.5*11);

part2=(0.75<=uy) & (uy<=9.75);
Fy(part2)=(152.78*uy(part2) + 910.42)/(2.5*11);

part3=(9.75<=uy) & (uy<=22);
Fy(part3)=(3991.84-163.27*uy(part3))/(2.5*11);

part4=(22<=uy) & (uy<=29);
Fy(part4)=(1500-50*uy(part4))/(2.5*11);
%
Fx=zeros(size(ux));
part1x= (0.00<=ux) & (ux<=0.75);
Fx(part1x)=(1866.67*ux(part1x))/(2.5*11);

part2x=(0.75<=ux) & (ux<=12);
Fx(part2x)=(57.778*ux(part2x) + 1356.67)/(2.5*11);

part3x=(12<=ux) & (ux<=21.5);
Fx(part3x)=(4134.21-173.684*ux(part3x))/(2.5*11);

part4x=(21.5<=ux) & (ux<=29);
Fx(part4x)=(1285.3-41.176*ux(part4x))/(2.5*11);
%
%
u_mean=0.5*(ux+uy);
F_mean=0.5*(Fx+Fy);

u_ell=0.75;
k=F_mean(16)/u_ell;   % Initial elastic stiffness

for i=1:length(u_mean);
    u_pl(i)=(u_mean(i))-(F_mean(i)/k);
end

help=[u_pl',F_mean'];

F_u=help(16:length(help(:,1)),:);

help=F_u(:,1),F_u(:,2))
disp_OSB=F_u(:,1);
force_OSB=F_u(:,2);
APPENDIX 5: Connection capacity calculations according to Eurocode 5 (Matlab script)

clear all;
clc;

%% Calculation of strength of nail connections - not predrilled
% according to EN 1995-1-1

%% Nail fastener properties
% ultimate strength
fu=866;
% Nail diameter
d=2.5;
% Yield Moment (cf. Eq. 8.14 in EC5 [9])
Myrk=0.3*fu*d^2.6

%% OSB side member
% Thickness of member
t1=11;
% Mean density of OSB
rhom_OSB=600;
% Embedment strength of OSB (cf. Eq. 8.22 in EC5 [9])
fh1k=65*d^(-0.7)*t1^(0.1)

%% Wood side member
% Depth of penetration
t2=60-11;
% Mean density of wood according to EN 338 for C24
rhom=420;
% Embedment strength of Wood (cf. Eq. 8.15 in EC5 [9])
fh2k=0.082*rhom*d^(-0.3)

%% Axial strength of connector
tpen=60-11;  % Penetration depth
dh=5;        % Nail head diameter
% Axial withdrawal strength for other than smooth nails
%(cf. OENORM B 1995-1-1:2015) [34].
faxk=50*10^(-6)*rhom^2;
% Axial pull-through strength for other than smooth nails
%(cf. OENORM B 1995-1-1:2015) [34].
fheadk=100*10^(-6)*rhom_OSB^2;

% Connection withdrawal capacity (cf. Eq. 8.23 in EC5)
Faxrk1=faxk*d*tpen
Faxrk2=fheadk*dh^2;
Faxrk_all=[Faxrk1; Faxrk2]
Faxrk=min(Faxrk_all)

%% Calculation of failure modes
beta=fh2k/fh1k;

% Single shear plane failure modes (cf. Eq. 8.6 in EC5)
Fvrk1=fh1k*t1*d;        % Mode (a)
Fvrk2 = fh2k*t2*d; % Mode (b)
Fvrk3 = (fh1k*t1*d)/(1+beta)*(sqrt(beta+2*beta^2*(1+t2/t1+(t2/t1)^2)
+beta^3*(t2/t1)^2)-beta*(1+t2/t1)) + Faxrk/4;
% Mode (c)
Fvrk4 = 1.05*(fh1k*t1*d)/(2+beta)*(sqrt(2*beta^2*(1+beta)+4*beta*(2+beta)*Myrk/(fh1k*d*t1^2)) - beta) + Faxrk/4;
% Mode (d)
Fvrk5 = 1.05*(fh1k*t2*d)/(1+2*beta)*(sqrt(2*beta^2*(1+beta)+4*beta*(1+2*beta)*Myrk/(fh1k*d*t2^2)) - beta) + Faxrk/4;
% Mode (e)
Fvrk6 = 1.15*sqrt(2*beta/(1+beta))*sqrt(2*Myrk*fh1k*d) + Faxrk/4;

Fvrk_all = [Fvrk1; Fvrk2; Fvrk3; Fvrk4; Fvrk5; Fvrk6];

% Connection capacity
Fvrk = min(Fvrk_all)