Dissertation

Master in Civil Ingeneering - Building Constructions

DESIGN OF WOOD CONNECTIONS WITH DOWEL TYPE FASTENERS

Luis Enrique Chávez Rubio

Leiria, *July of 2018*

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DESIGN OF WOOD CONNECTIONS WITH DOWEL TYPE FASTENERS

Luis Enrique Chávez Rubio

Dissertation developed under the supervision of Doctor Florindo José Mendes Gaspar, professor at the School of Technology and Management of the Polytechnic Institute of Leiria and co-supervision of Master Wilson Santiago Medina Robalino, professor at the Facultad de Ingeniería Civil y Mecánica of the Universidad Técnica de Ambato.

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Resumo

Este trabalho tem como objetivo descrever os diferentes tipos de conectores e fixadores que são feitos para o dimensionamento e dimensionamento de conexões em estruturas de madeira. Para qual, uma descrição de cada um deles e suas características principais é feita.

A seguir, é descrito o uso do programa com as planilhas e como usá-lo para inserir as informações e como os resultados são apresentados usando o Eurocódigo 5. Neste explica a seqüência que deve ser seguida e as diferentes seções da planilha para dimensionamento conexões com diferentes conectores do tipo tarugo. Além disso, indica as variáveis envolvidas no dimensionamento, que é utilizado para descrever os diferentes tipos de conexões a serem analisadas.

O trabalho conclui apresentando todos os resultados da capacidade de resistência dos diferentes tipos de conexões através de tabelas de gráficos e porcentagens que ajudam a perceber como diferentes fatores intervêm na resistência da conexão.

Palavras-chave: ligacões, estruturas de madeira, Eurocódigo 5, ligadores tipo cavilha, dimensionamento.

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Abstract

This work aims to describe the different types of connectors and fasteners that is made for the design and dimensioning of connections in wooden structures. For which, a description of each of them and their main characteristics is made.

Next, the use of the program with the spreadsheets is described, and how to use it to enter the information and how the results are presented using the Eurocode 5. It explains the sequence that must be followed and the different sections of the spreadsheet for dimensioning connections with different dowel-type connectors. In addition, it indicates the variables involved in the dimensioning, which is used to describe the different types of connections to be analysed.

The work concludes, presenting all the strength capacity results of the different types of connections through graphs and percentages tables that help to perceive how different factors intervene in the resistance of the connection.

Keywords: connections, wooden structures, Eurocode 5, dowel-type fasteners, dimensioning.

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Table of Contents

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List of Figures

List of Tables

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List of Acronyms

Latin upper case letters

$F_{ax,Rd}$ - Design value of axial withdrawal capacity of the fastener;

Fed - Bearing strength of the peg

Fem - Dowel-bearing strength of the wood;

Fes - Dowel-bearing strength of the wood in the side members

F_{vp} - Effective dowel shear strength;

Fyb - Yield strength of the fastener

$F_{v,Rd}$ - Design load-carrying capacity per shear plane per fastener;

G_p - Specific gravity for peg;

G_t - Specific gravity for timber member;

$M_{y,Rk}$ - Characteristic yield moment of fastener;

Z - Capacity of the connection

Latin lower case letters

$f_{h,i,k}$ - Characteristic embedment strength of timber member i;

$f_{t,0,k}$ - Characteristic tensile strength along the grain;

k_{mod} - Modification factor for duration of load and moisture content;

n_{ef} - Effective number of fasteners;

t_{pen} - Penetration depth;

Greek lower case letters

α - Angle between a force and the direction of grain; Angle between the direction of the load and the loaded edge (or end);

γ_M - Partial factor for material properties;

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1. Introduction

1.1. Background

The connections are frequently the critical locations of timber structures, being responsible for the reduction of the continuity and the global structural strength, requiring oversized structural elements. About 80% of failures observed in timber structures are due to connections (Santos, et al., 2009).

The strength and stability of any structure depend heavily on the fastenings that hold its parts together. One main advantage of wood as a structural material is the ease with which wood structural parts can be joined together with a wide variety of fastenings—nails, spikes, screws, bolts, lag screws, drift pins or dowels, staples, and metal connectors of various types (Rammer, 2010).

The present dissertation take into account the Eurocode 5 to design the connections, which considers two types of limit states are considered: ultimate limit states and serviceability limit states. In the Eurocode 5, the safety verification is on base of the partial factor method.

Ultimate limit states are associated with the forms of structural failure where include: loss of equilibrium; failure through excessive deformations, etc.

Serviceability limit states are associated with the adverse effect on the durability of the structure where include: vibrations which cause discomfort to people or damage to the structure, damage (including cracking).

The principles of limit state design take into account the following aspects (EUROCODE 5, 2008):

- Different material properties (e.g. strength and stiffness);

- Different time-dependent behaviour of the materials (duration of load, creep);

- Different climatic conditions (temperature, moisture variations);

- Different design situations (stages of construction, change of support conditions).

The three main parameters which influence the load-carrying capacity behaviour of joints with dowel-type fasteners are:

- Embedding Strength (fh,k)
- Fastener Yield Moment (My,k)
- Withdrawal strength (Fax,Rk)

In Europe, the design of the connections is the main part of the structure that has been analysed and tested to resist the forces acting as wind, self-weight, and in certain countries the forces generated by the seismic actions. The connections are a fundamental part for the stabilization of the structure against the forces caused by different actions.

The design of the connections leads to opt for several alternatives from what type of connection (Timber - Timber or Timber - Steel), wood material, service class, load duration, and the different types of fasteners for the joint of the elements. Therefore, several factors intervene in the design that its effect on the strength of the connection is generally unknown.

The designer must take among several options for the design of the connection the elements that will be used so that the connection is the most efficient and economical. Having several alternatives can generate a little confusion but having a clear idea about how different factors affects to the connection, it would be most useful way to obtain a pre-dimensioning that is valid and effective.

1.2. Objectives

The main objective of this dissertation is to obtain resistance capacity values of several types of wooden connections using different dowel-type fasteners. These values will give a clear idea to the designer in making a decision for dimensioning a connection, in which several variables that directly or indirectly affect the resistance capacity of the connection will intervene. This analysis entails obtaining results that help the designer make quick and efficient decisions based on how different factors can affect the connection and choose the one that is therefore the most economical and feasible.

For the design of each type of connection to be taken into account, a program was developed using spreadsheets, to obtain results efficiently and quickly. With the use of these results it is intended to obtain illustrative graphs that help designer to understand better how the results will vary depending on the type of fastener and the conditions to which the connection is.

To obtain the results, several aspects must be defined in the dimensioning of the connection, which implies:

- Define several types of connections by altering the different variables that enter the dimensioning for different dowel-type fasteners.
- Calculate for each type of connection the resistance capacity while the number of fasteners increases.
- Perform the dimensioning and calculation of a mortise and connection using wooden dowels for comparison with the other types of connections using dowel-type fasteners.

- Propose graphs that indicate the calculated values vs. the number of fasteners for the comparison and analysis of the results.
- Determine the percentages of increase or decrease in resistance capacity that will depend on the values obtained from a type of base connection.

1.3. Structure of Dissertation

The present dissertation is developed in six chapters, where the aspects of dimensioning of connections in wooden structures as well as the different fasteners and connections that exist in the market are addressed.

The first chapter addresses the importance that should be taken in the design and dimensioning of the connections in wooden structures, the objectives that will be developed in the dissertation and the organization of it.

The second chapter describes the types of connections that companies offer through their catalogues. It describes the advantages of each one and in what situation it can be used, taking into account the kind of service and the use that will be given to the structure. In addition, the types of dowel-type connectors are presented, detailing each one of them and referring to the most important characteristics; in the same way it is added to what type of situations and connections are relatively more viable and that they add a better behaviour in terms of strength.

The third chapter includes the parameters that are taken into account for the dimensioning and design of the wooden connections mentioned in Eurocode 5. These parameters are briefly detailed but describing the main aspects of each one. Afterwards the different types of connections are presented depending on the type of fastener that will be used; describing in a general way the important aspects in the design of each of them. In addition, it mentions the factors that can affect the resistance capacity of the connection and some research that is developed with finite element programs to encompass all these factors. Finally, durability design is mentioned, an important aspect for the structure and its connections to maintain their capacity throughout their useful life.

In the fourth chapter, a description of the operation of the calculation spreadsheet is made, addressing all the aspects so that the user understands the way in which the program works. It details the sections that must be followed for data entry and how these data generate the necessary information for the design of the connection for both metal dowel-type fasteners and wooden dowels. In addition, the main types of connections to be designed and analysed are described, taking into account all the variables that will intervene in the connection and being able to perform the calculations for the comparison between them. Finally, the characteristics of each type of fastener to be used; being that they exist in catalogues to obtain real values.

In the fifth chapter an analysis is made dividing into four types of connections, where each one of them will use the different types of fasteners. These results are compared through the use of graphs. The number of fasteners used to reach it is analysed through the capacity of resistance. This allows obtaining tables that indicate the percentages that increase or decrease the values of resistance capacity with respect to the base values that are taken from each connection.

In the sixth chapter the conclusions that were obtained from the analysis of the results that were made in this research are exposed, and make some recommendations for future developments.

2. Connections for Timber

The connections for timber are usually made of steel that take different forms to adapt to the needs of the connection and with differences in shape, thickness and even aspects that include their mechanical properties. In this section, a description is made about several types of these connectors including their main characteristics:

2.1. Beam Connectors

2.1.1. Concealed Connectors

The concealed connectors have several advantages both aesthetics and strength. This kind of connectors are most used in main-to-secondary joist connection in timber structures.

The connection system is not a hinge joint, because the geometry creates an extra bending moment in the shear transfer zone. Consequently, the forces generate additional stress on the elements.

The steel connection is protected and isolated by the surrounding timber. Therefore, there is no change in the mechanical properties or strength reduction..

The concealed connectors (Figure 2.1) can have different forms depending of the design requirements. This type of connectors varies depending of the dimensions of the secondary joist, in width is between 45 mm to 290 mm, and in height between 80 mm to 1200 mm. The characteristic shear strength that can withstand varies between 20 kN to 320 kN. (Rothoblaas, 2015)

a) AluMAXI (with holes) b) DISC

Figure 2.1 Concealed beam connectors (Rothoblaas, 2015)

2.1.2. Not Concealed Connectors

There are three kinds of not concealed connectors: angle brackets, hangers, and perforated plates.

Angle Brackets

This type of connectors guarantee high stiffness because their geometry and height flexural capacity. The fasteners used are screws, nails or bolts. The slotted holes are discreet in the fixed zone. The field of use are timber-to-timber joints, timber to OSB panels, steel to timber joints, and timber to concrete joints. (Rothoblaas, 2015)

Their dimensions varies in the width between 20 mm to 100mm, in the height between 40mm to 200 mm. The angle of the plate can variety of 90° and 135° (Figure 2.2). The characteristic shear strength varies between 11 kN to 22 kN.

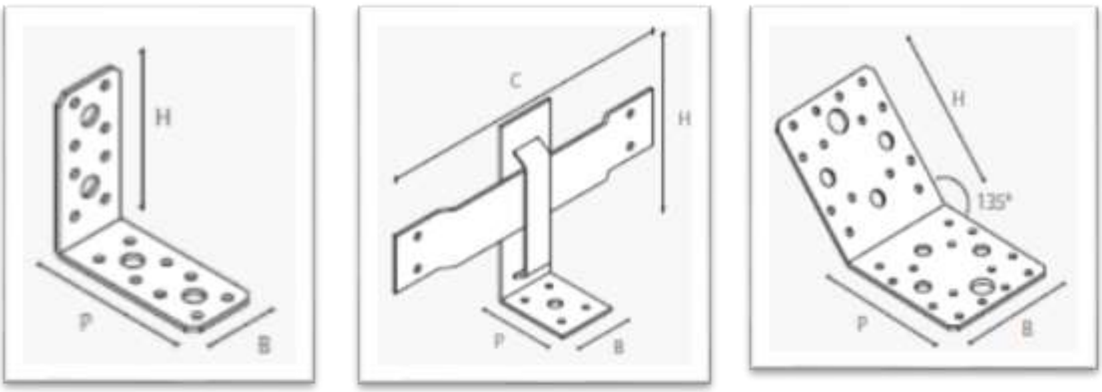


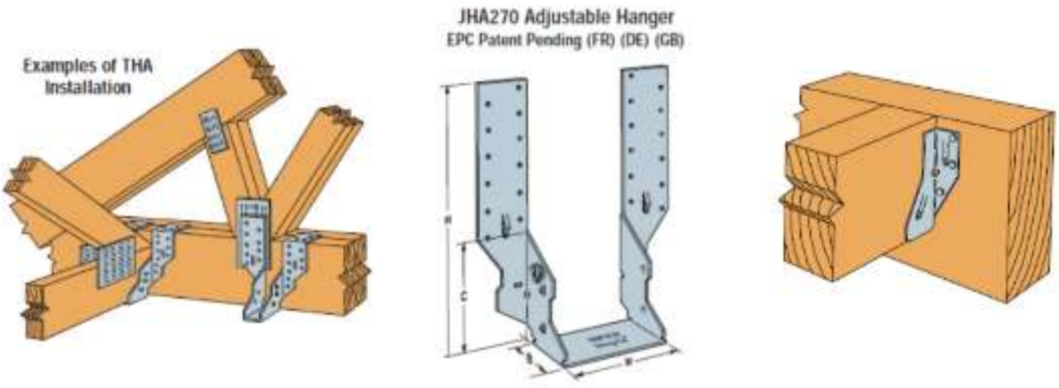
Figure 2.2 Angle brackets (not concealed connectors) (Rothoblaas, 2015)

Hangers

The hanger connectors provide joist support combined with ease installation that are adjusted to suit height of joist. There are specific hangers for supporting trussed rafters and composite timbers from timber members or attached girders to wall plates to provide wind resistant. The advantage is the extra strength due to the speed prongs and the fasteners for these connectors are screws, nails or bolts.

Their dimensions varies in the width between 32 mm to 200 mm, in the height between 100 mm to 436 mm. The characteristic shear strength varies between 2 kN to 21 kN. The

Figure 2.3 shows some connectors that can be found in the market. (Simpson Strong-Tie Company Inc., 2004)



a) Adjustable truss hangers b) Adjustable hanger c) Speed prong joist

Figure 2.3 Hanger connectors (Simpson Strong-Tie Company Inc., 2004)

Perforated plates

The perforated plates are designed for solving particular situation where requiring the transfer of tensile forces between timber elements such as beams, structural panels and cladding. (Rothoblaas, 2015)

The Figure 2.4 shows some applications on wooden structures. Their dimensions varies in the width between 40 mm to 400 mm, in the height between 120 mm to 1200 mm. The characteristic shear strength varies between 1.5 kN to 178 kN.

Figure 2.4 Perforated plates (Rothoblaas, 2015)

Punched metal plate fasteners

A 'punched metal plate' (Figure 2.5) is defined as a fastener made of metal plate, having integral projections punched out in one direction and bent perpendicular to the base of the plate, being used to joint two or more pieces of timber of the same thickness, in the same plane. They are generally manufactured from pre-galvanised mild steel strip or stainless steel strips, with thickness ranging from 0.9 to 2.5 mm (TRADA, 2012)

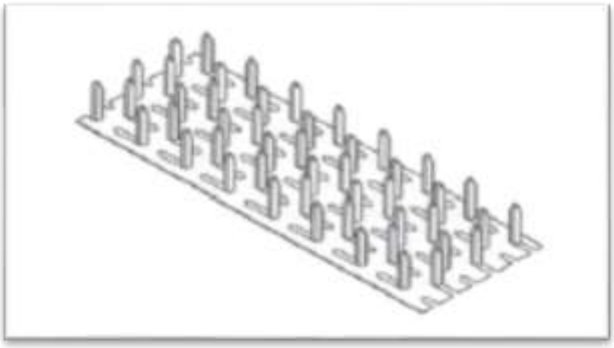
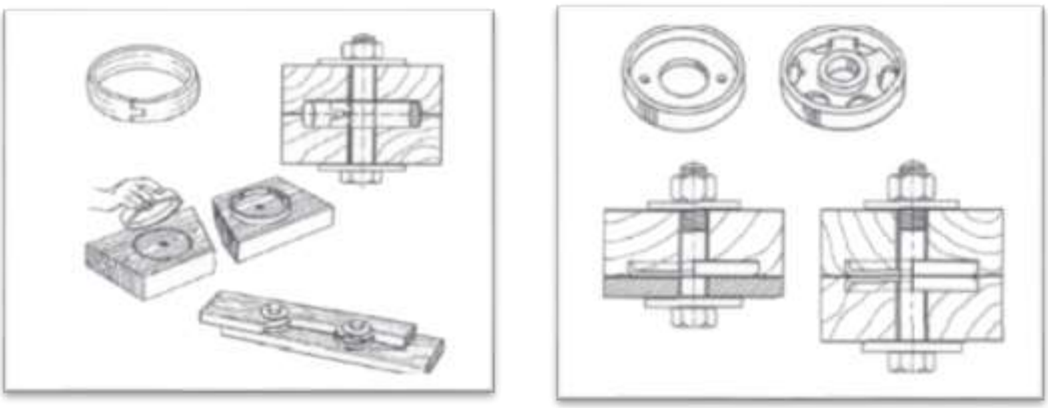


Figure 2.5 Punched metal plate fastener with teeth (TRADA, 2012)

Split-ring and Shear- plate connectors

Split-ring and shear-plate connectors (Figure 2.6) consist of one split-ring/shear-plate with a bolt, washers and nut, and the ring parallel or bevel sided form. The shear-plate joints are used in laterally loaded timber-to-timber connections as well as steel-to-timber connections, in the meantime the split-ring joints only in timber-to-timber connections. They are circular, with diameters from 60 mm to 280 mm. (TRADA, 2012)



a) Split- ring connectors

b) Shear-plate connectors

Figure 2.6 a) Split-ring connectors and Shear-plate connectors (TRADA, 2012)

Toothed-plate connectors

Toothed-plate connectors (Figure 2.7) are made from cold rolled band steel or hot dipped galvanised mild steel. They are available in a variety of shapes and sizes, with diameters ranging from 38 mm to 165 mm. The larger connectors are available for use in glued-laminated members. They are mostly circulars, but square and oval shapes are also available. The load in a double-sided toothed-plate connector joint is transferred from one timber member to the other through embedding stresses. (TRADA, 2012)

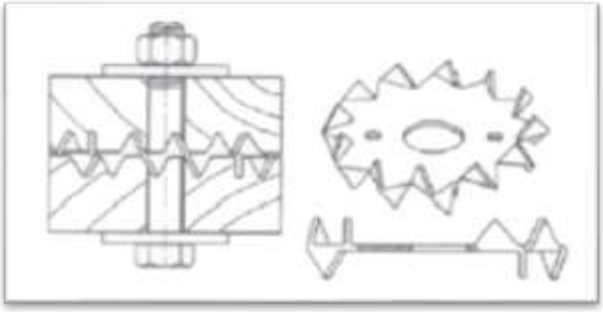


Figure 2.7 Toothed-plate connectors (TRADA, 2012)

2.2. Column to Base Connections

The column to base connections are post bases that provide an adequate distance from the ground for eliminating the risk of wood deterioration due to water splashes and stagnation with adjustable height. The joint transfer compression, tension and base shear depending on the type of base. (Rothoblaas, 2015)

Their dimensions varies in the width between 100 mm to 200 mm, in the height between 130 mm to 250 mm. The characteristic shear strength varies between 48 kN to 220 kN. The Figure 2.8 shows different types that were found in the market:

Figure 2.8 Adjustable post base (Rothoblaas, 2015)

2.3. Dowel Type Connectors

2.3.1. Nails

Nails are the most widely used dowel-type fasteners. They are used for many forms of structural timber components, such as timber frame stud walls and floor diaphragms, as well as for connecting timber or wood-based panel products together, and for connecting metal plates to timber. The use of nails in large numbers, such as in nail plates, spreads the load more evenly and for this reason has an advantage over bolts (TRADA, 2012).

Nails are usually made of steel but can also be made of stainless steel, iron, copper, aluminium, or bronze. The pointed end of a nail is called the point, the shaft is called the shank, and the flattened part is called the head.

There are many different types of nails, the types depending on the material that they are driven into and the degree of holding power that they must have. Two basic classes of nails are common nails and finishing nails (Figure 2.9).

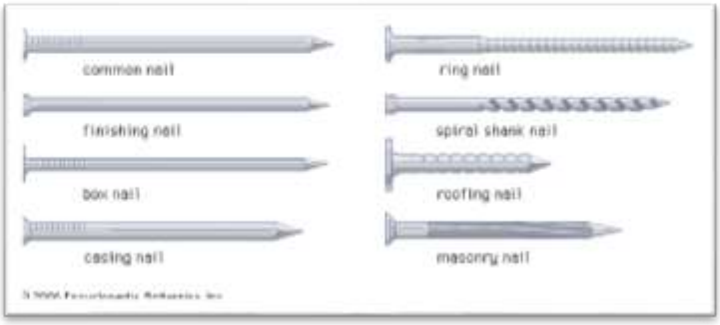


Figure 2.9 Different types of nails (Encyclopædia Britannica, 2008)

The common nail has a large, flat head that is driven in so that it is flush with the material's surface. A finishing nail has a smaller, narrower head that is driven in below the material's surface with a special tool called a nail set, or punch; the small depression remaining is filled in with putty. (Encyclopædia Britannica, 2008)

Many Simpson Strong-Tie® products are designed to use common nails, readily available to builders. Certain applications require special fasteners, such as those with length limitations or for use in hostile environments. The diameters are around of 3.75 mm – 4mm with smooth shank or square twist shank (Simpson Strong-Tie Company Inc., 2004).

2.3.2. Screws

For plain timber-to-timber joints, wood screws can be used. The metal screws are often used for steel-to-timber and panel-to-timber joints. As with nails, there are a number of different types of screws available. The most common types are countersunk, head screw, round head screw and coach screw. The screws can be used for fixing joist hangers and framing anchors. (TRADA, 2012).

Wood Screws: These have a coarser pitch (Figure 2.10) than sheet metal or machine screws, and often have an unthreaded shank. The thread-less shank allows the top piece of wood to be pulled flush against the under piece without getting caught on the threads.

Sheet Metal Screws: Usually threaded all the way to their head, these will work in wood, but wood screws should not be used in metal (this is based on hardware store employee advice, not experimental evidence). Most of these screws are self-tapping in that they only require a pre-drilled hole (pre-drill sizes).

Coach screws: are suitable for large connections and are also capable of replacing bolts for single-sided access (single shear). The thread is turned down from the original rod diameter (Figure 2.10), leaving a full diameter shank and the screws have hexagonal heads, like bolts. They are used in engineered timber structures, particularly for fastening metalwork to timber. Coach screws require a washer and must always be inserted into a pre-drilled hole.

Figure 2.10 Coach and countersunk screws (TRADA, 2012)

Apart from the screws mentioned above there are many screws designed for specific purposes – for example the self-tapping Assy screw is intended for high strength and the Topix CC screw (Figure 2.11) is intended for joining together large timbers into a tightfitting joint.

a) Assy Screw b) Topix CC

Figure 2.11 Coach screws (TRADA, 2012)

In order to gain the maximum load-carrying capacity, screws should be inserted by turning and not by driving with a hammer. Most industrial screws no longer have their traditional slotted head and proprietary head recesses allow screws to be machine driven (TRADA, 2012).

The Rothoblaas catalogue shows different types of screws for each need in the construction:

Carpentry: used timber-to-timber connection also can be used with steel plates and hooks is the type HBS. Screws with diameters between 3.0 and 5.0 mm and a length of less than or equal to 50 mm are provided with an unnotched self-perforating tip that increases the grip and hold of the screws. Ideal for using with single bits, it is easily interchanged in the bit holder to obtain the utmost screwing precision.

Screws with diameters greater than 6.0 mm have a notched self-perforating tip that avoids the risk of the wood splitting. Ideal for use with double bits directly attached to the mandrel to obtain maximum screwing force and stability.

One example is HBS + evo, ideal for use on steel plates with circular holes and hence for exterior fastening systems in service class three (pillar bases). The dimension from 4.5 mm – 8 mm of diameter and length until 200 mm.

Structures: These types of connectors distributes the stress along the entire threaded surface. High resistance connected to the wood cylinder affected by tangential stresses. The result is fewer connectors and less deformation (Figure 2.12).

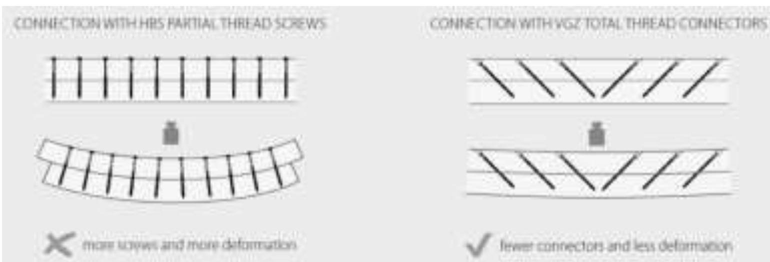


Figure 2.12 Wood – wood coupling (Rothoblaas, 2015)

The total thread distributes the perpendicular tensile stress to the fibres along the height of the beam, guaranteeing reinforcement. One example, is the VGZ that has a high resistance steel (fy,k = 1000 N/mm^2) with cylindrical head and the diameter vary between 7 mm to 9 mm.

Screws for outdoor: these types of screws have a specific application according to the wood species and the environment conditions. There are a complete array of screws that indicate for which conditions works.

The Rothoblass catalogue shows different fasteners that allow to use for the different corrosion class environmental (C1 – C5). One example, is the screw KKT A4 can be used for all corrosion class and the diameter vary between 5 mm to 9 mm and their length between 20 mm to 120 mm.

2.3.3. Bolts

Bolts are mostly used for lateral connections in glue-laminated or heavy timber construction. They transmit forces through single shear (two members) or double shear (three members) connections.

Bolts are manufactured in a variety of types based on the configuration of the bolt head. The most common types are the hexagonal head, square head, dome head, and flat head (Figure 2.14).

The standard hex or square heads are used when the bolt head is in contact with wood or steel. More specialized bolts such as the dome head and flat head provide an increased head diameter and are used when the bolt head is in wood contact (Soltis & Wilkinson, 1996).

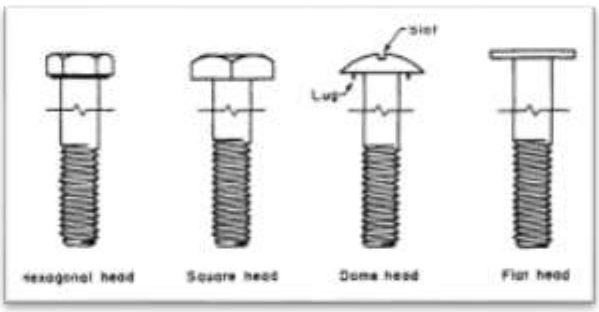


Figure 2.13 Typical Bolt (Soltis & Wilkinson, 1996)

The diameter bolts vary between 4 mm to 30 mm with length between 100 mm to 600 mm. The external diameter of washer is between 16 mm to 105 mm and the internal diameter is between 8 mm to 27 mm. The bolts strength classes according to Eurocode 3 are indicated in the Table 2.1.

Table 2.1 Bolts Strength Class according Eurocode 3

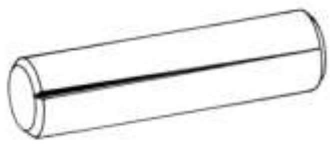
Class	4.6	5.6	6.5	6.8	8.8	10.9
fy (MPa)	240	300	300	480	640	900
fu (MPa)	400	500	600	600	800	1000

2.3.4. Dowels

Dowels are plain or ribbed rods usually circular in cross section but sometimes deformed in rectangular cross sections as well. Usually dowels have a smooth surface but are also often fluted to ease insertion. Their plain ends are neater in appearance than bolts and are also stiffer.

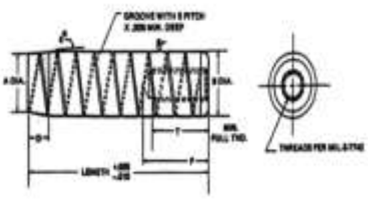
The dowel ends can be plugged which improves both the appearance and the fire performance. Some common dowel pins are shown in Figure 2.14 (Bickford & Nassar, 1998)

Straight (solid) dowel pin



Grooved dowel pin

Vented dowel pin



Drilled and tapped dowel pin with vent

Figure 2.14 Types of Dowels (Bickford & Nassar, 1998)

The Rothoblass catalogue indicates the different dowel dimensions that are offered in the market. The diameter vary between 8 mm to 12 mm with a strength class S235 (fy = 235

MPa, fu = 360 MPa) and between 16 mm to 20 mm with strength class of S355 (fy = 355 MPa, fu = 460 MPa). The length vary between 60 mm to 150 mm.

Wooden Dowels

The wooden dowels (Figure 2.15) are called wood pegs and the joints used where they works well are mortise and tenon connections. They are easy to fabricate, efficient frame assembly, and effective in transferring shear forces.

They are fabricated of different materials of wood but is necessary that the timber is a structural wood. The diameter vary between 6 mm to 60 mm and lengths between 350 mm to 1000 mm, depending of wood type. The several types of wood that were tested and the investigations confirm the use in the mortise and tenon connections are the following:

- Douglas Fir
- Eastern White Pine
- Red & White Oak
- Southern Yellow Pine
- Yellow Poplar

Figure 2.15 Wooden dowels of different diameters

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3. Design of Wood Connections

Dowel type connections is a generic term covering nails, screws, dowels and bolts transferring load perpendicular to their longitudinal axis. The design of dowel type connections consists of two relatively independent types of design criteria, a local set and a global set:

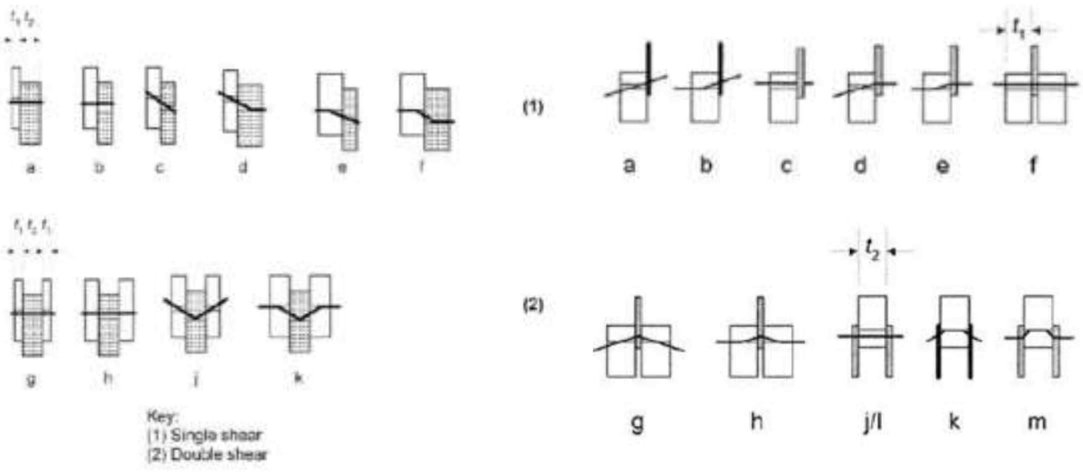
- The local design criteria consists of plasticity theory applied to the single connector, i.e. the capacity of the connector and of the wood in which it is embedded is evaluated.
- The global design criteria consists of criteria for spacing and distance between the single connectors, which are to insure global capacity of the cross section enough to withstand the forces transferred by the connectors. (Pedersen, 2002).

The local design criteria corresponds to the so called European Yield Model formulated by K. W. Johansen. These design criteria for the single connector now form the basis for the design rules given in the Eurocode 5 (EC5-1 1995).

The three main parameters mentioned in the section 1.1 are used to calculate the "Lateral load-carrying capacity" of metal dowel-type fastener taking the local design criteria. The Johansen's Theory involves the localized crushing of wood, eventually combined with formation of plastic hinges on connector.

There are different failure modes depending of the connection type. This could be timber-timber/timber-wood based connection and timber-steel connection. The failure modes are divided in two groups by single shear and double shear.

Each failure mode has an equation and the minimum value is taken for the verification of the strength of the fastener. In case of timber-steel connection there is one more important thing taking account is the thickness of the steel plate that could be "thin" or "thick" comparing with the diameter of the connector (EUROCODE 5, 2008). The Figure 3.1 shows the different failure modes.



Timber-timber/timber-wood based Timber-steel connection

Figure 3.1 Failure modes of timber connections (EUROCODE 5, 2008)

3.1. Embedment Strength

The embedment strength of timber is one of the principal parameter to calculate the design strength capacity of dowel type fasteners when using the European Yield Model (EYM) (Hettiarachchi & Nawagamuwa, 2005)

The embedment strength of timber is defined in (EN 383, 1993), fh,k, is the average compressive strength at maximum load under the action of a stiff straight dowel. Taking into account the dowel, is the fictional tension that leads to the crushing of wood. (Figure 3.2)

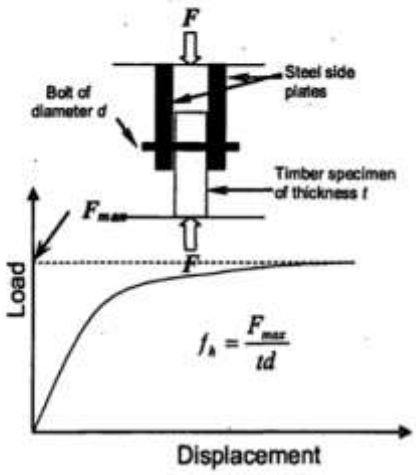


Figure 3.2 Schematic diagram showing the embedment strength tests and load-displacement (Hettiarachchi & Nawagamuwa, 2005)

The most important parameters when considering the embedding are:

- Density;
- Diameter (fastener and hole);
- Angle (between load and grain direction);
- Friction (between dowel and timber connection);
- Moisture.

3.2. Fastener Yield Moment

The yield moment was taken to be the moment at the elastic limit of the fastener and was derived from the product of the yield strength and the elastic modulus of the fastener (Porteous & Kermani, 2007).

The bending capacity (fastener yield moment) is given by the moment value which the complete plasticization of the connector section is reached. Your calculation can be experimental with tests according to normative EN 409:"Timber structures – Test methods – Determination of yield moment for dowel type fasteners – Nails" (EN 409, 1993). These tests (Figure 3.3) are based on the application of an increasing bending moment, until it reaches its maximum value or if there is a 45º angle between the two halves of the nail.

Figure 3.3 Fundamentals of the test for the determination of the yield moment on nails (EN 409, 1993)

3.3. Johansen Equations

The theory used in EC5 is based on Johansen's (1949) theory. The equation predicts the ultimate strength of a single dowel-type fastener due to either a bearing failure of the joint members or the simultaneous development of a bearing failure of the joint member and plastic hinge formation in the fastener (Debarbouille, 2011)

The ductile failure that Johansen's theory applies said that the materials of the connection (fastener, timber or wood-based material) would behave as rigid plastic materials according to strength-displacement relationships shown in Figure 3.4.

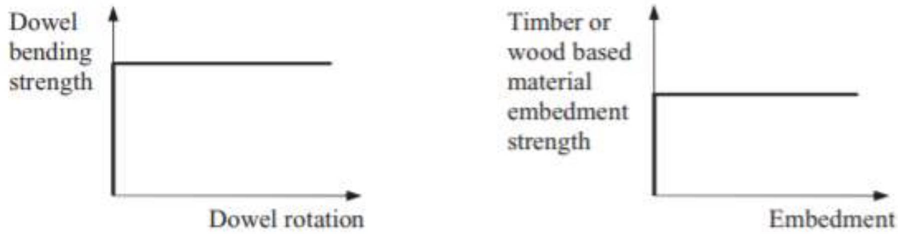


Figure 3.4 Strength/strain relationships used for dowel connections (Porteous & Kermani, 2007)

The behaviour of the connection formed with two pieces where the fastener is subjected to one plane of shear (single shear) is very different of a connection formed by three pieces, where the fastener is subjected to two plane of shear (double shear) (Branco, 2003)

The difference between these two types of connections led to the consideration and individualization of each type of rupture analytically through considerations of equilibrium of efforts.

3.3.1. Friction effects and Axial Withdrawal of the fastener

In EC5 the Johansen yield equations have been modified to include for friction and withdrawal effects. There are two types of friction effects that can arise in a connection. One will develop if the members are in contact on assembly and the other will arise when the fasteners yield and pull the members together when the fasteners deform under lateral load (Porteous & Kermani, 2007).

In EC5 the values used for the second friction type the factor is 5% where the fastener partially yields (e.g. modes (d) and (e) in Figure 3.1) and 15% where the fastener fully yields (e.g. mode (f) in Figure 3.1).

$$F_{v,Rk} = \text{friction factor} \times \text{Johansen yield load} + (\text{withdrawal capacity}/4)$$

To discriminate between the Johansen yield load and the combined withdrawal and friction forces in a connection, the latter are commonly referred to as the rope effect forces, however in EC5 reference is only made to the term $F_{ax,Rk}/4$ as the contribution from this effect. (Porteous & Kermani, 2007)

The effect of the withdrawal capacity possible to include in the total capacity of the connection is depending on the type of fastener (Debarbouille, 2011). The contribution to the load-carrying capacity due to the rope effect should be limited to following percentages of the Johansen part:

- Round nails 15 %
- Square nails 25 %
- Other nails 50 %
- Screws 100%

- Bolts 25 %
- Dowels 0 %

Fax,Rk will be the lower of the fastener head pull-through strength (including the withdrawal strength associated with the headside penetration of the fastener).

3.4. Nailed Connection

Nails are well suited for panel-to-timber and timber-to-timber shear connections. Nails are generally designed for single shear connections.

There should always be at least two nails in a connection. Nails and glue do not have a co-operative action. Unless otherwise specified, nails should be driven in at right angles to the grain.

For square and grooved nails, the nail diameter (d) should be taken as the side dimension. Smooth nails in end grain should not be considered capable of transmitting lateral forces. (METSÄ WOOD, 2018)

The Eurocode 5 indicates for smooth nails produced from wire with a minimum tensile strength of 600 N/mm2, the following characteristic values for yield moment should be used:

$$M_{y,Rk} = \begin{Bmatrix} 0.3 * fu * d^{2.6} \; for \; round \; nails \\ 0.45 * fu * d^{2.6} \; for \; sqaure \; and \; grooved \; nails \end{Bmatrix}$$

Where:

$M_{y,Rk}$ = is the characteristic yield moment, in N.mm;

fu = is the tensile strength of the wire, in mm;

d = is the nail diameter, in N/mm^2.

For nails with diameters up to 8 mm, the following characteristic embedment strengths apply:

Table 3.1 Characteristic embedment strengths on Nailed Connections

Timber and LVL	Plywood
-Without predrilled $f_{h,k} = 0.082 * pk * d^{-0.3}$ -With predrilled $f_{h,k} = 0.082 * (1 - 0.01 * d) * pk$	$f_{h,k} = 0.11 * pk * d^{-0.3}$

Hardboard	Particleborad and OSB
$f_{h,k} = 30 * d^{-0.3} * t^{0.6}$	$f_{h,k} = 65 * d^{-0.7} * t^{0.1}$

Where:

$f_{h,k}$ = is the characteristic embedment strength, in N/mm^2;

pk = is the characteristic timber density, in Kg/m^3;

d = is the nail diameter, in mm;

t = is the panel thickness, in mm.

3.5. Screwed Connection

Timber screws are well suited for steel-to-timber and panel-to-timber connections but they can also be used for timber-to-timber connections. Screw connections are generally designed for single shear connections. Screws are good at transmitting axial loads (METSÄ WOOD, 2018).

Eurocode 5 (2008), states that the effect of the threaded part of the screw shall be taken into account in determining the load-carrying capacity, by using an effective diameter (def).

For smooth shank screws, where the outer thread diameter is equal to the shank diameter, the rules given in section 8.2 of Eurocode 5 apply, provided that:

- The effective diameter (def) is taken as the smooth shank diameter;
- The smooth shank penetrates into the member containing the point of the screw by not less than 4d.

Where the conditions above are not satisfied, the screw load-carrying capacity should be calculated using an effective diameter (def) taken as 1.1 times the thread root diameter.

For smooth shank screws with a diameter d > 6 mm, the rules in bolted connection apply but for smooth shank screws with a diameter of 6 mm or less, the rules of nailed connection apply.

For the verification of strength of axially loaded screws, the following failure modes shall be taken into account:

- the withdrawal failure of the threaded part of the screw;
- the tear-off failure of the screw head of screws used in combination with steel plates, the tear-off resistance of the screw head should be greater than the tensile strength of the screw;
- the pull-through failure of the screw head;
- the tensile failure of the screw;
- the buckling failure of the screw when loaded in compression;
- failure along the circumference of a group of screws used in conjunction with steel plates (block shear or plug shear).

3.6. Bolted Connections

Bolts should be tightened so that the members fit closely, and they should be re-tightened if necessary when the timber has reached equilibrium moisture content. If re-tightening cannot be done, and there is a possibility that the timber can dry by over 5 % of its weight after installation of the bolts, only 80 % of the calculated capacity of the bolt connection can be utilized.

Washers with a side length or an external diameter of at least 3d (where d is the diameter of the bolt) and a thickness of at least 0.3d should be used under the head of bolts and nuts. Washers should have a full bearing area.

Bolt holes in timber should have a diameter no more than 1 mm larger than the bolt. Bolt holes in steel plates should have a diameter no more than 2 mm or 1.1d (whichever is greater). If the connection is designed using thick steel plate ($t \geq d$) equations and bolt diameter $d < 20$ mm, the maximum allowed hole in the steel plate should not be more than 1.1d. (METSÄ WOOD, 2018)

For bolts the following characteristic value for the yield moment should be used:

$$M_{y,Rk} = 0.3 * fu * d^{2.6}$$

Where:

d = is the bolt diameter, in mm;

fu = is the tensile strength, in N/mm^2

For bolts up to 30 mm diameter, the following characteristic embedment strength values in timber and LVL should be used, at an angle α to the grain:

$$f_{h,a,k} = \frac{f_{h,0,k}}{k_{90} * sin^2 a + cos^2 a}$$

$$f_{h,0,k} = 0.082 * (1 - 0.01 * d) * pk$$

Where:

$$k_{90}\begin{Bmatrix} 1.35 + 0.015 * d \quad for\ softwoods \\ 1.30 + 0.015 * d \quad for\ LVL \\ 0.90 + 0.015 * d\ for\ hardwoods \end{Bmatrix}$$

$f_{h,0,k}$ = is the characteristic embedment strength parallel to the grain, in N/mm^2;

pk = is the characteristic timber density, in kg/m^3;

a = is the angle of the load to the grain;

d = is the bolt diameter, in mm.

When is used in timber-wood based connections the following characteristic embedment strength values change:

Plywood	**Particleboard and OSB**
$f_{h,0,k} = 0.11 * (1 - 0.01 * d) * pk$	$f_{h,0,k} = 50 * d^{-0.6} * t^{0.2}$

The axial load-bearing capacity and withdrawal capacity of a bolt should be taken as the lower value of:

- The bolt tensile capacity;

- The load-bearing capacity of either the washer or (for steel-to-timber connections) the steel plate;

- The bearing capacity of a washer should be calculated assuming a characteristic compressive strength on the contact area of 3*fc,90,k;

- The bearing capacity per bolt of a steel plate should not exceed that of a circular washer.

3.7. Dowelled Connection

The dowel diameter (d) should be greater than 6 mm and less than 30 mm. Dowel holes (D) in timber members should have a diameter of 0.95d ≤ D ≤ d. (METSÄ WOOD, 2018)

The end of the dowel can be bevelled to make installation easier. The bevel is usually 2 mm. Dowel holes in steel plates should have a diameter no more than 1 mm or 1.1d (whichever is greater)

The rules given in bolted connections of the Eurocode 5 except 8.5.1.1(3) are applied.

3.7.1. Wooden Dowelled Connection

Design for transfer of shear forces can be done using one of two international codes, the National Design Specification for Wood connection (NDS) and the Eurocode 5 but in the Europe normative does not specific the pegged connections.

Some investigations get the necessary equations based on the Johansen theory for calculating the shear forces. In some cases, during a frame erection or to resist wind loads, the mortise and tenon joints suffer tension loads.

NDS for Wood Construction (National Design Specification)

Joint Strength

Schmidt (2006), considers an adjustment to the yield model approach. First, the dowel bearing strength of the timber accounts the fact that load is transferred through a wood peg rather than steel dowel, the result is likely a decrease in the values of F_{es} y F_{em} (dowel bearing strengths). Second, the value F_{yb} needs to describe the flexure yield strength of the wood peg. Third, an additional yield mode must be considered.

Dowel Bearing Strength

Dowel bearing strength depends of the combined deformation of the peg and the timber. There are two approaches to determine the F_{es} for a peg bearing in the mortise side wall and F_{em} a peg bearing in the tenon.

Yield Strength in Bending of a Peg

Dowel bending yield strength F_{yb} for wood pegs may be taken as the value of modulus of rupture at 12% moisture content contained in the Wood Handbook. (Forest Products Lab, 1999)

Peg Shear Strength

Mode V is a new yield mode for representing a common failure observed in mortise and tenon joints. The allowable working-level shear stress F_{vp} in a wood peg is given by:

$$F_{vp} = 1365 * G_p^{0.926} * G_t^{0.778}$$

Where:

F_{vp} = effective dowel shear strength (psi)

G_p = specific gravity for peg

G_t = specific gravity for timber

This equation was developed for joints with $G_p > G_t$

The corresponding mode V allowable load is:

$$Z = \frac{\pi * D^2}{2} * F_{vp}$$

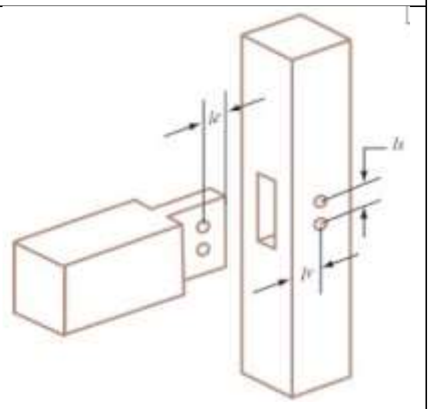
Where:

D = peg diameter that passes through two shear planes in the joint

Detailing Requirements

Specifications of end distance (le), edge distance (lv) and spacing (ls) of pegs in a mortise and tenon connection is critical to prevent brittle failure under tension load. Detailing dimension in Table 3.2 have been shown to achieve the full strength of a pegged connection.

Table 3.2 Minimum Detailing Dimension of Pegged Connection (Schmidt, 2006)

Timber Species	End Distance (le)	Edge Distance (lv)	Spacing (ls)	Joint Detaling
Douglas Fir	2D	2.5D	2.5D	
Eastern White Pine	4D	4D	3D	
Red & White Oak	3D	2D	2.5D	
Southern Yellow Pine	2D	2D	3D	
Yellow Popular	2.5D	2.5D	3D	

In the NDS exist different failure modes similar to the failure modes according to the Johansen's theory. According to the yield model, double shear connection will fail by one of five possible modes shown in Figure 3.5.

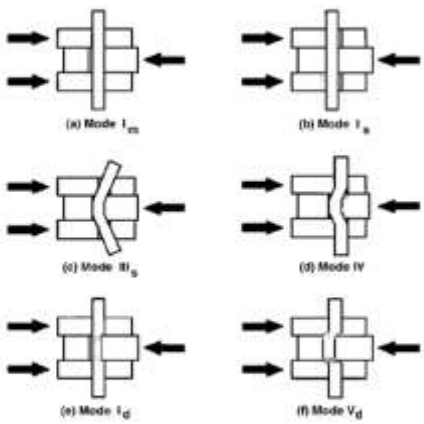


Figure 3.5 Possible failure modes for wood peg joints

A mode I_m and mode I_s failure are bearing-dominated yield of the main member wood fibres that are in contact with the fastener. A mode III_s failure is characterized by fastener yield in bending at one plastic hinge point per shear plane. A mode IV results from the formation of two plastic hinges per shear plane, but is not considered cause is not observed in practice or in laboratory. A mode Id occurs if the dowel-bearing strength of the members is greater than that of the peg itself. A mode V_d is a cross-grains shear failure of the peg. The Table 3.3 shows the different equations that use NDS in the failure modes to calculate the capacity of the connection. (Sandberg, et al., 2000)

Table 3.3 Equations for the different failure modes according to NDS

Mode I_m	$Z_{I_m} = D * t_m * F_{em}$	Z = capacity of the connection D = fastener diameter Fem = dowel-bearing strength of the wood
Mode I_s	$Z_{I_s} = 2D * t_s * F_{es}$	ts = thickness of each side member Fes = dowel-bearing strength of the wood in the side members
Mode III_s	$Z_{I_s} = \frac{2D * t_s * F_{em} * F_{es}}{2F_{es} + F_{em}} * \left(\sqrt{Q} - 1\right)$ $Q = \frac{2(F_{es} + F_{em})}{F_{em}} + \frac{2F_{yb} * (2F_{es} + F_{em}) * D^2}{3F_{em} * F_{es} * t_s^2}$	Fyb = yield strength of the fastener
Mode I_d	$Z_{I_d} = lesser\ of\ \{D * t_m * F_{ed}\}\ or$ $\{2D * t_s * F_{ed}\}$	Fed = bearing strength of the peg
Mode V_d	$Z_{V_d} = 2\frac{\pi D^2}{4} * F_{vp}$	Fvp = cross-grain shear strength of the dowel

The NDS Code use a reduction factor (Rd) to calibrate yield capacity to allowable capacity. This factor is divided for the different failure modes.

The reduction factor depends of the angle (θ) between the direction of the load and the direction of the grain. The table 3.4 indicate the reduction factor for each failure mode.

Table 3.4 Reduction Term, Rd

Failure Mode	Reduction Term (Rd)
Mode I_m , I_s , I_d	$4K_\theta$
Mode III_s	$3.2K_\theta$

Mode V_d	3.5
$K_\theta = 1 + \theta/360$ ($1 \le K_\theta \le 1.25$)	

The bearing strength of the dowel itself can be estimated from an empirical equation developed by Schmidt and Daniels (1999) for nominal 25.4 mm white oak pegs: (Sandberg, et al., 2000)

$$F_{ed} = 39 * (G_{12})^{2.04}$$

Where:

Fed = bearing strength of the dowel (Mpa)

G_{12} = specific gravity at 12% moisture content

Requirements

The following requirements is due to the limitation of the formula, cause the testing data and modelling has not been conducted for outside of these range and the equations may not be valid. (Chappell, 2011)

- The peg specific gravity must be greater than or equal to the timber specific gravity and at least 0.57 and not exceed 0.73
- The peg diameter is between 0.75 inches (19 mm) and 1.25 inches (30 mmm)
- Mortise and Tenon connections such that the main (tenoned) member is loaded by the pegs parallel to the grain.

Final design

The nominal design capacity for a single peg is the minimum of the five yield models shown in Table 3.3. The final design capacity of the connection is calculated by multiply for all the factors that consider NDS and to determine a connections consisting of multiple pegs, multiplied by the total number of pegs (Chappell, 2011)

Eurocode 5

The force required to calculate the load-carrying capacity in double shear connection depends of the minimum of the equations linked to the failure modes. The failure mode IV represents the failure of the pegged connection (Branco, et al., 2011).

$$F_{v,Rk} = 1.15\sqrt{\frac{2\beta}{1+\beta}} * \sqrt{2M_{y,Rk} * f_{h,1,k} * d}$$

Fukuyama based on Johansen's theory developed some equations to calculate the pegged connection obtained the more approximated numerical results with the experimental.

$$P_{y,EYM,cal} = \sqrt{\frac{4d * F_{ecp} * M_y * \beta}{1+\beta}}$$

$$F_{ecp} = \min(F_{e,exp} * \alpha_F * F_{cvf})$$

$$F_{e,exp} = \frac{P_{max,exp}}{d * L_1}$$

$$M_y = \frac{\pi * d^3}{32} * Fb$$

Where:

F_{ecp} = the embedment strength

$F_{e,exp}$ = embedment strength in joint components in N/mm^2

α_F = amplification coefficient on embedment yield stress

F_{cvf} = embedment yield stress in dowel

β = is the ratio between embedding wood strength of the joinst components 1 and 2

$P_{max,exp}$ = experimental maximum force in N

My = plastic capacity of the dowel in N.mm

Fb = bending strength of the dowel in N/mm^2

Branco, et al., (2011) carried out a study where evaluate the mechanical properties of dowel type wooden joints, with wooden dowels kept in different moisture content (8% and 12%) and compare with the equations from the Eurocode 5 and other researches, one of them is of Fukuyama. The results of the approaches comparing them with the experimental results the difference is greater. The analytical values are lesser than experimental results. The approach developed by Fukuyama is the only one that is approximate to the experimental result.

3.8. Effective number of fasteners

The connection strength depends of the characteristic load-carrying capacity of the rows of fasteners parallel to the grain. It consists that fasteners of the same type and dimension, may be lower than the summation of the individual load-carrying capacities of each fastener.

The factor that take into account the load-carrying capacity of a multiple fastener connection is explained in the equation below:

$$F_{v,ef,Rk} = n_{ef} * F_{v,Rk}$$

Where:

$F_{v,ef,Rk}$ = effective characteristic load-carrying capacity of one row of fasteners parallel to the grain

n_{ef} = effective number of fasteners in line parallel to the grain

$F_{v,Rk}$ = characteristic load-carrying capacity of fastener parallel to the grain

The effective number (n_{ef}) depends of type of fastener, diameter, fastener spacing and edge and end distances in the connection. This factor is reviewed in some investigations due to the overestimated value.

Wilkinson (1980) carried out an investigation about the unequal distribution of load among load applied to the row of bolts or timber connectors, comparing two analytical methods Lantos (1969) and Cramer (1968). These methods can predict the proportional limit load for a row of fasteners but is difficult to determine experimentally. Both methods overestimate the failure load due to do not take into account the nonlinear load-slip behaviour of a single fastener.

Soltis & Wilkinson (1987), who compare results found in literature, using the European Yield Theory, verified these conclusions like a base. The results indicate that current design values for the proportional limit of single-bolt connections are generally correct but that information on the load-slip behaviour and the distribution of load among bolts is inadequate if the data are to be used for limit-states design or multiple-bolt connections.

Years later, Tan & Smith (1999) proposed the hybrid elasto-plastic model. The model is an accurate and computationally efficient tool for predicting whether failures will be brittle or ductile (global failure), and ultimate capacities of connections in which a row of stocky bolts load a timber member. The prime limitation of the model is that it neglects bending deformation in the bolts, and thus cannot be applied when relatively slender bolts are used.

3.8.1. Principal factors affecting the connection strength

Moisture Content

The moisture content is the principal factor that affects the connection strength. There is growing evidence that different strength and stiffness properties are affected to varying degrees by changing levels of moisture content (Green & Evans, 1989).

Rammer & Winistorfer (2001) carried out a experimental test to determine the embedment strength and how the moisture content affects it:

- Dowel-bearing strength increases with decreasing moisture content, much like other wood properties
- The relationship between dowel-bearing strength and moisture content is independent of species type for the three tested species and fastener diameter for the two diameter tested
- Parallel-to-grain dowel-bearing strength is highly positively correlated with ultimate parallel-to-grain compression strength and is estimated by a linear regression relationship

High Temperatures

The behaviour of timber joints subjected to fire is complex and still not fully understood. The assessment of the joint failure time, the influence of the type of joint and the existence of metal elements within the joint on its thermal field and the modes of failure require more research.

Moraes & Rodrigues (2011) developed an experimental test in bolted timber connections with temperatures about 20, 50, 100, 150, 200, and 230 °C. The results confirm:

- The design criteria of timber joints are currently presented in EN 1995-1-2 (2004) for fire and in EN1995-1-1 (2004) for room temperature case. However, the application of these methods can present problems for temperatures of 300°C
- Heating of the connections causes a linear reduction of the moisture content up to 150 °C, alterations in the colour of the specimens and drops of resin at the top of the elements.
- Temperature increase leads to the non-monotonic decrease of the embedment strength parallel to the timber grain
- Specimen failure occurs by embedment or splitting. Between 50 and 100 °C there is an increase in plastic deformation.
- The reduction of the load-bearing capacity of the joints as a function of the temperature is affected by the plastic behaviour. This reduction is also explained by the appearance of cracks inside the specimens during the drying process.

3.9. Comparison between the European and the American method

Codes in the U.S. and Europe all base the design of joints with dowel-type fasteners on Johansen's yield model, it is referred to as the European Yield Model (EYM) in North America. The majority of engineers design timber structures based on the ASD (Allowable Stress Design) code "National Design Specification for Wood Construction" (NDS) that was last published in 1997.

Alternatively, the American Society of Civil Engineers has published a ''Standard for Load and Resistance Factor Design for Engineered Wood Construction'' that is technically equivalent to international LRFD (Load and Resistance Factor Design) codes. Informal information implies that at present very limited use is made of LRFD in the U.S.

As defined in the U.S., the yield limit load and material properties that enter the equations have a very specific and unique meaning, embedment strength of wood beneath a fastener and the yield moment for a fastener are 5% offset values (Smith & Foliente, 2002). The yield point (Figure 3.6) lies between the proportional limit and the ultimate strength of the connection.

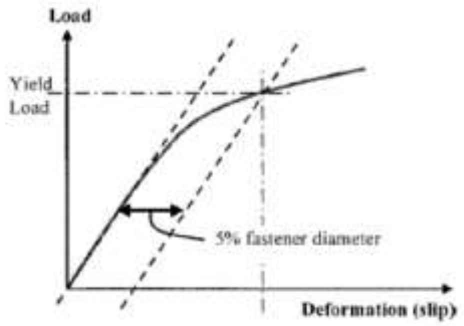


Figure 3.6 Five percent offset method for defining joint "yield limit load" (Smith & Foliente, 2002)

The European Committee for Standardisation based on Belgium has published a model design code ''Structural Timber Design Code'' with the designation Eurocode 5, which is in LRFD format. The dowel bearing strength is called in European code as embedment strength.

Wilkinson (1991) carried out a study about the dowel bearing strength. The authors defined bearing strength as the maximum test load. Results showed that bearing strength for bolts loaded parallel to grain is related to specific gravity; for bolts loaded perpendicular to grain, bearing strength is related to specific gravity and bolt diameter. Bearing strength for nails is dependent upon specific gravity and is independent of loading direction and nail diameter.

The likeness between these two codes led to the consideration and individualization of each type of rupture analytically through considerations of equilibrium of efforts. The different modes of rupture or failure modes considered by the American Code are showed in the Figure 3.7.

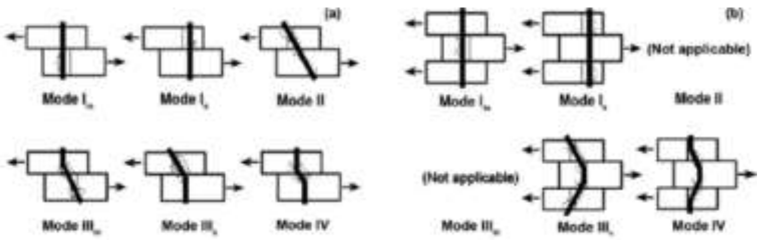


Figure 3.7 Various combinations of wood-bearing and fastener-bending yields for (a) two member connections and (b) three member connections (Rammer, 2001)

3.10. Numerical Models in Timber Connections

The embedding strength of wood and the yield moment of the dowel depend on the method of evaluation. Some studies have compare the values calculated by the yield theory (Johansen's Theory) with the experimental results. However, this theory does not consider the plastic behaviour (e.g. hardening of the dowel and embedding of wood) after yielding. (Sawata & Yasumura, 2002)

The finite element (FE) nonlinear analysis is a numerical analysis that can approximate the load-slip behaviour of dowel-type joints considering the elastoplastic behaviour of wood and dowels. Sawata & Yasumura (2002) carried out a study using FE nonlinear analysis of bolted timber joints, where the yielding of the bolt appears at the boundry between steel plate and the wood. In this study shows that the yield and the ultimate strenghts of the joiny can be stimated by the yield theory when is properly applied.

Other investigation carried out by Hong & Barrett (2010) use a 3D FE analysis of single nail connections for simulating the wood crushing behaviour under a dowel. This phenomen is difficult using the conventional methods. The application of 3D models help to simulate the loacalized wood crushing behaviour under a dowel.

By other hand, the load-bearing behaviour of a timber connections is a complex mechanism. Resch & Kaliske (2010) developed finite elements (FE) model that allows the failure behaivour and the possibility of simulating multiple fasteners. The advantages of FE models is the possibility to carry out comprehensive parameter studies for different boundary conditions, with the aim of determine the ultimate loads and failure mechanisms.

3.11. Design for Durability

The durability in wooden structures should be taken as a point of great importance, through the application of the project, manufacture, installation and maintenance to encompass all the precautions that may arise.

The risks of durability vary according to the environmental conditions, so the care in the material, assembly and maintenance will depend on the type of structure and the conditions to which it is exposed (Gaspar, et al., 2006)

There are several factors to take into account in the construction aspect:

- Deterioration of wood (atmospheric and biological agents);
- Degradation of the joints (humidification and drying in indoor environments);
- Corrosion in metal fasteners.

The need to take into account all these factors that intervene in the durability of the structure, is divided into three phases for the correct intervention of the measures that will be adapted to the structure. These three phases are:

- Project;
- Manufacturing;
- Maintenance.

3.11.1. Project Phase:

In this phase, the atmospheric and biological agents that affect the structure as well as the agents that affect the joints and the corrosion of the fasteners are analysed. Therefore, in the project phase the measures to be taken for durability are (Gaspar, et al., 2006):

- Limitation of water access to the structure;
- Take special measures to combat attacks by termites;
- Correct specification of the glulam timber;
- Appropriate design and protection of connections.

Limitation of water access to the structure

The structural provisions should facilitate drainage and aeration, mainly in the areas of joint. There are several phenomena associated with humidity (internal tensions, variations in the dimensions of the wood, etc.), which can increase their speed of appearance and spread, depending on the climatic conditions of the area.

The European regulations (EN 335-2) define five classes of risk of biological attack, of which four are related to the wood applied on the surface. There are four principles that contribute to the increase of the service time of the structure (Amburgey, 2002, Florida):

- Use wood with adequate moisture content;
- Keep the wood dry during the period of service;
- Avoid contact of the wood with the ground;
- Use wood with adequate natural durability or with a preservative treatment.

Wood can be found with several percentages of moisture content depending on its exposure, so it should be kept as far as possible in the average exposure conditions, in order to minimize the variations after the service time of the structure.

The Table 3.5 indicates the percentages to which the wood is when being in various conditions of service:

Table 3.5 Percentage of Moisture Content according to conditions service by (Machado, et al., 1997)

Conditions of Service	Percentage of Moisture Content
Wood applied indoors	8% - 14%
Exterior wood with protection	12% - 18%
Exterior wood without protection	18% - >30%

Four types of measures must be adopted to keep the wood in a dry state during its useful life (American Wood Council, 2006):

- Protection of the surfaces of the elements of the structures;
- Separation of the elements among themselves;
- Creation of drainage media;
- Use of ventilation measures for the structure.

Special measures to combat the attack of termites

The use of steel plates (Figure 3.8) can be used as an effective means to combat the termites, because it acts as a protective barrier to be able to divert these insects to a place where they are easily detected (American Wood Council, 2006).

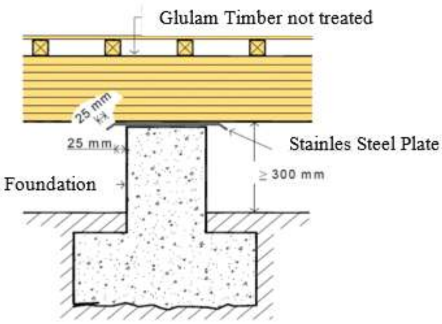


Figure 3.8 Protection against termites by (Gaspar, et al., 2006)

Other techniques are chemical barriers, usually the use of fabrics impregnated with termiticide products, or the treatment of the soil what protects the exterior surroundings of the structure.

Specification of Glulam Timber

A type of glue suitable for the service conditions to which the wood will be exposed must be used. There is a classification in the glue: type I and type II; the glue type I is suitable for the three classes of service that indicate the Eurocode 5 and type II glue are for conditions that do not exceed a temperature of 50 ° C and a relative humidity not greater than 85%.

The low natural durability of wood or the lack of treatment begins a punctual degradation by putrescence fungi. To analyse the need for a treatment, the Class of Risk of biological attack must be identified. The following table indicates the treatment to be taken according to the Hazard Class for low to medium durability wood:

Table 3.6 Treatment for durability according to the Class of Risk by (EN 350 - 2, 1994)

Class of Risk	Treatment
1	Insecticity surface protection
2	Insecticide and fungicide surface protection
3 and 4	Preservative treatment in depth avoiding contact with the ground

Conception of connections

It must be taken into account that metal fasteners have a protection against corrosion according to the class of service to which they are exposed. In addition, avoid the appearance of cracks due to the excessive development of the perpendicular tension to the grain of the wood (Gaspar, et al., 2006).

The following recommendations should be followed for a good conception of the connections (National Association of Forest Industries, 2004):

- Metal parts resistant to corrosion
- Minimize water accumulation in the contact areas
- Avoid retraction of wood, allowing differential movements

3.11.2. Manufacturing Phase:

The increase in the cross sections of the sheets of wood will cause greater dimensional variations, which would cause delamination due to the increase in tensions in the joint (Gaspar, et al., 2006). The standard EN 386 describes the maximum values of the cross sections of the sheets.

The control in the position of the sheets intervenes directly in the durability of the wood. Thus, normative 386 likewise indicates how they should be placed according to the kind of service to which they are exposed. This control is mainly due to the retraction fissures that occur in the wood, and if they are exposed, they will facilitate the entry of water and the production of harmful agents already mentioned. The Figure 3.9 indicates how the sheets are positioned according to their exposure:

a) General orientation b) Orientation for a class of service 3

Figure 3.9 Orientation of the sheets in the section by (Gaspar, et al., 2006)

3.11.3. Maintenance Phase:

It is essential to verify the wooden structures during the service period. It is necessary to follow some recommendations that will improve the durability. The following requisites should be done in the phase of maintenance as resources for the control of the durability of wood:

- Unblock and clean the drainage channels;
- Repair protections and small damages;
- Repaint necessary places;
- Add protection in places not previously intervened.

4. Methodology

4.1. Introduction

The present research work was established in a calculation plane for the design of dowel-type connections using spreadsheets, based on Eurocode 5 for connections using metal fasteners, and NDS code and other investigations made by several authors for mortise and tenon connection using wooden dowels to obtain the results.

Although there is some software for the design of dowel-type connections, it has been necessary to carry out a program. The program facilitates obtaining efficient results of the strength capacity of several types of connections, where different variables are involved that were taken into account to obtain illustrative graphics to help knowing about a previous design, besides understanding the factors that affect the strength of the connection.

The variables take into account are: the type of connection, single or double shear, the strength class of the timber, the thickness of splice piece, the type of connectors, force application angle, connector diameter, number of connectors and different service class, is described afterwards.

4.2. Excel Spreadsheet

It was necessary the use of two spreadsheets for the design of dowel-type connections. The reason is that the first spreadsheet was to obtain the values for metal dowel-type fasteners using Eurocode 5, and the second spreadsheet is for wooden dowels using the NDS for Wood Construction and other researches carried out by different authors. The format of input information and output results are the same for both spreadsheets that is describe in this section.

Input Data

In these cells, the basic information necessary is given for the program to perform the respective operations. It is presented in two ways the way to input the information, manually when the data to be entered can have an unlimited range or through lists limiting specific data. The format used a grey background and blue letters (Figure 4.1), and when there is no title in the cell, the data entered is not taken into account in the calculation.

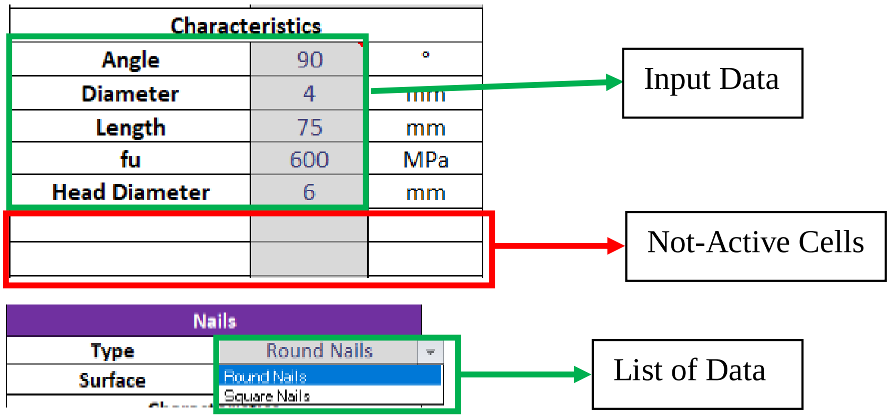


Figure 4.1 Characteristic of input data cells

<u>*Output Data*</u>

In these cells, data calculated by the program is showed, based on the input data and that was used to obtain the final results of the connection. This data is a verification of whether the input data is generating correct information for the calculation. The format used is a blue background and white letters (Figure 4.2).

ρk (kg/m³)	330
Type	Solid Timber
ft,0,k	12.0 MPa
fv,k	3.6 MPa
Ym	1.3

Figure 4.2 Characteristics of output data cells

<u>*Output Result*</u>

In these cells, the final values of the design of connection are shown. The final strength capacity of the connection as well as the minimum spacings and the effective number of fasteners involved in the connection are indicates in these cells. The format used is a green background and white letters (Figure 4.3).

RESULTS	
Fv,Rk (Connector)	1132 N
Fv,Rk (Connection)	17777 N
knef	0.85
nef	3.93
Fv,Rd (Connector)	522 N
Fv,Rd (Connection)	8205 N

Figure 4.3 Characteristics of cells output results

4.2.1. Spreadsheet for Metal Dowel-Type Fasteners

This spreadsheet is divided into seven tables, which follow a sequence for inputting data and obtaining results. It is an easy and appreciable way for the user to be sure that no data will be overlooked.

Geometry Connection (1st Table)

In this table, three important data is inserted (Figure 4.4): "Type": in this cell insert if the connection is composed of 2 or 3 pieces, that means if is one or two splice piece. "N^{er} Connectors": in this cell the number of connectors per line is inserted. "N^{er} Lines" enter the number of lines on only one side of the connection.

GEOMETRY CONNECTION	
Type	3 Pieces
Ner Connectors	5
Ner Lines	2
Ner Total Lines	4

Figure 4.4 Cells of the Geometry Connection

Main Timber Member (2nd Table)

In this table, five data is inserted (Figure 4.5): "Strength Class", from a list is chosen the different strength classes of the main timber member. "Species", the material of which it is made (Softwood, Hardwood, LVL). "Thickness", "Width" and "Length" are values of the dimensions of the main timber member.

The output data that they give are the density of the material, the timber type, the characteristic tensile strength parallel to the grain (ft,0,k) and the characteristic resistance to the shear (fv, k), and the safety coefficient (Ym).

MAIN TIMBER MEMBER	
Strength Class	C20
Species	Softwoods
Thickness (b)	75 mm
Width (h)	100 mm
Length (L)	2400 mm
ρk (kg/m³)	330
Type	Solid Timber
ft,0,k	12.0 MPa
fv,k	3.6 MPa
Ym	1.3

Figure 4.5 Cells of the Main Timber Member

Load Characteristics (3rd Table)

In this table, three data is entered (Figure 4.6): "Load Duration", from a list the options presented by Eurocode 5 are displayed (Permanent, Long Term ...). "Service Class" from a list is chosen if it is 1,2 or 3 service class depending on the moisture content of the timber. "Anlge" is the angle of the force to which the connection is subjected. The output data that show is the reduction coefficient (Kmod) and the safety factor for connections (Ym).

LOAD CHARACTERISTICS	
Load Duration	Permanent
Service Class	1
Angle (α)	0
Kmod	0.6
YM	1.30

Figure 4.6 Cells of Load Characteristics

Joint Characteristics (4th Table)

In this table, six data is inserted and they vary according to the first two cells (Figure 4.7): "Joint" of what type is the connection (Timber – Timber or Timber - Steel) and "Material" is what type of material is the joint (Timber, LVL ...). "Thickness" of the joint. "Position" is where the splice piece is located (Lateral, Central). "Shear" is the shear plane of the connection (Single, Double). "Density" of the joint. "Species" of the splice piece. “Steel Class" of the steel plate.

JOINT CHARACTERISTICS	
Joint	Timber - Timber
Material	Timber - LVL
Thickness (c)	38 mm
Position	Lateral
Shear	Single
	S275
Density (kg/m³)	330
Species	Softwoods
Fv, Rd (max)	44862 N

a) Timber – Timber Joint

JOINT CHARACTERISTICS	
Joint	Timber - Steel
Material	Steel Plate
Thickness (c)	38 mm
Position	Lateral
Shear	Single
Steel Class	S275
Fv, Rd (max)	44862 N
Steel Type	Thick
fu (Mpa)	430
fy (Mpa)	275

b) Timber – Steel Joint

Figure 4.7 Cells of Joint Characteristics

The output data is the maximum strength value that the connection can support (Fv, Rd (max)). The steel plate can be thick, thin or an average between both, which depend on the diameter of the fastener and the thickness of the steel plate. In addition, the values of ultimate tensile strength (fy) and tensile strength at rupture (fu) are shown.

Type of Fastener (5th Table)

The input data that needs to be inserted depends on the type of fastener from which it is chosen, and the characteristic data of the fastener is shown as indicated in Figure 4.8:

Fastener	Dowels

Screws		
Characteristics		
Angle	90	°
Nominal Diam.	4	mm
Length	75	mm
fu	600	MPa
Head Diameter	6	mm
My,k	7000	N.mm
Threaded Length	30	mm
Root Diameter	20	mm
Shank Diameter	40	mm
f head,k	17.5	N/mm²
f tens,k	17.5	kN
f ax,k	11.5	N/mm²
Diameter Eff.	4.00	mm
Shank Length	45	mm
tpen (mm)	37	mm

Nails		
Type	Round Nails	
Surface	Smooth Nails	
Characteristics		
Angle	90	°
Diameter	4	mm
Length	75	mm
fu	600	MPa
Head Diameter	6	mm
tpen (mm)	37	mm

Bolts		
Strength Class	4.6	
Characteristics		
Angle	90	°
Diameter	4	mm
Length	75	mm
Head Diameter	12	mm
Stress Area	353	mm2
fu	400	MPa
fy	240	MPa
tpen (mm)	37	mm

Dowels		
Strength Class	S235	
Characteristics		
Angle	90	°
Diameter	4	mm
Length	75	mm
fu	360	MPa
fy	235	MPa
tpen (mm)	37	mm

Figure 4.8 Cells of Type of Fastener

DATA (6th Table)

In this table, the output data generated by the basic information that was entered in the previous sections are showed (Figure 4.9), and they are necessary to obtain the different values of the Johansen's Equations depending on the shear plane as well as the characteristics of the fastener. The different failure modes with graphs are shown, in the case of not complying with some type of failure, the word "Not Apply" is indicated.

DATA	
Pre - Drilling	Apply
Characteristic Embedment Strenght, fh,1,k	0.0 MPa
Characteristic Embedment Strenght, fh,2,k	26.0 MPa
Fastener Yield Moment, My	3970 N.mm
Withdrawal capacity	0 N
Axial Load Bearing Capacity	0 N
Tensile resistance of the connection	-
Block Shear	13986 N

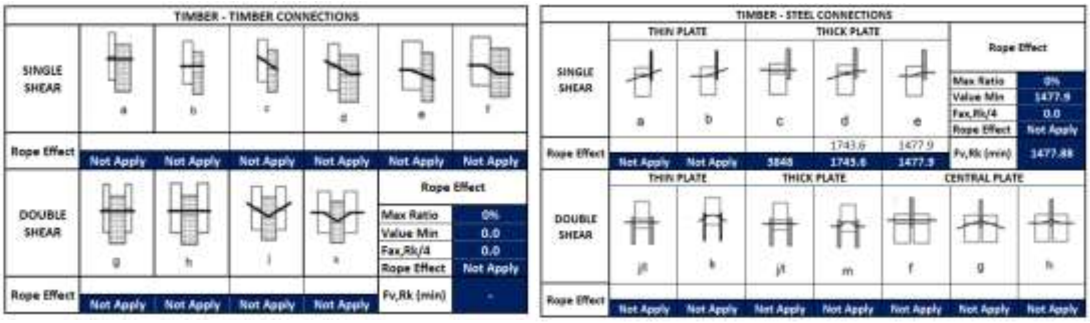


Figure 4.9 Cells Data and Modes of Failure

RESULTS (7th Table)

In this table, the final results of the connection are shown (Figure 4.10). The design strength values for the connector and for the entire connection, as well as the minimum spacing that must be taken into account are indicated. The effective number of connectors are calculated in this section:

RESULTS	
Fv,Rk (Connector)	1478 N
Fv,Rk (Connection)	13986 N
knef	-
nef	3.35
Fv,Rd (Connector)	481 N
Fv,Rd (Connection)	6455 N

MINIMUM SPACINGS		
Spacing	Angle (α)	mm
a1	0 ≤ α ≤ 360	20.00
a2	0 ≤ α ≤ 360	12.00
a3,t	(-90) ≤ α ≤ 90	80.00
a3,c	210 ≤ α ≤ 270	-
a4,t	0 ≤ α ≤ 180	12.00
a4,c	180 ≤ α ≤ 360	-

Figure 4.10 Cells of Results

4.2.2. Spreadsheet for Wooden Dowels

The spreadsheet is divided into four tables, which follow a sequence for entering data and obtaining results.

Wooden Dowels (1st Table)

In this table, three data is inserted (Figure 4.11): "Material" of the peg / wooden dowel. "Diameter" of the peg and "Number" of pegs in the connection. The output data is the specific gravity of the peg (Gp), the specific gravity for a moisture content of 12% (G12), and the values of bearing strength of the wooden dowel (Fed) and allowable shear stress in peg (Fvp).

Wooden Dowels		
Material	Douglas Fir	
Diameter	3/4 in	OK
Number	2	u
Gp	0.50	
G12	0.48	
Fed	1266	psi
Fvp	303	psi

Figure 4.11 Cells of Wooden Dowels

Mortise and Tenon Connection (2nd Table)

In this table, the strength class of the mortise and tenon is entered from a list (Figure 4.12). The output data are: "Tenon and Mortise Thickness", specific gravity (Gm, Gs), bearing strength of the mortise and tenon (Fem, Fes) and dowel bending yield strength (Fvy).

Mortise and Tenon Connection		
Material	C20	
Tenon Thickness	1 3/8	in
Mortise Thickness	3 3/8	in
Gm	0.33	OK
Fem	1400	psi
Gs	0.33	OK
Fes	1400	psi
Fvy	1056	psi

Figure 4.12 Cells of Mortise and Tenon Connection

General Data (3rd Table)

In this table, four data is entered corresponding to the load angle, moisture content, moisture condition and temperature of the environment (Figure 4.13). The output data are the reduction coefficients of the NDS for Wood Construction code.

General Data		
Angle Load	0	ø
Moisture	19	%
Moisture Cond.	Dry	%
Temperature	100	°F
Cm	1.00	
Ct	1.00	
Cg	1.00	
CΔ	1.00	

Figure 4.13 Cells of General Data

Final Detailing of The Connection (4th Table)

In this table, the final values of the connection are shown; the design strength of the connection, as well as the spaces and dimensions of the mortise and tenon connection (Figure 4.14).

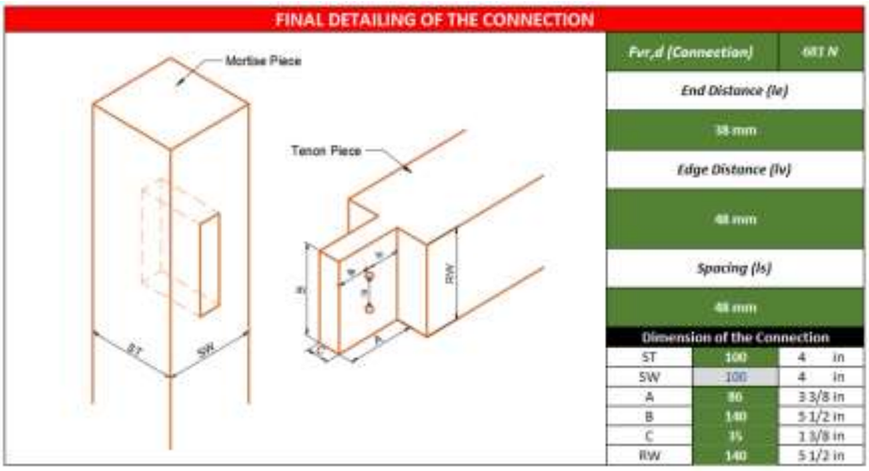
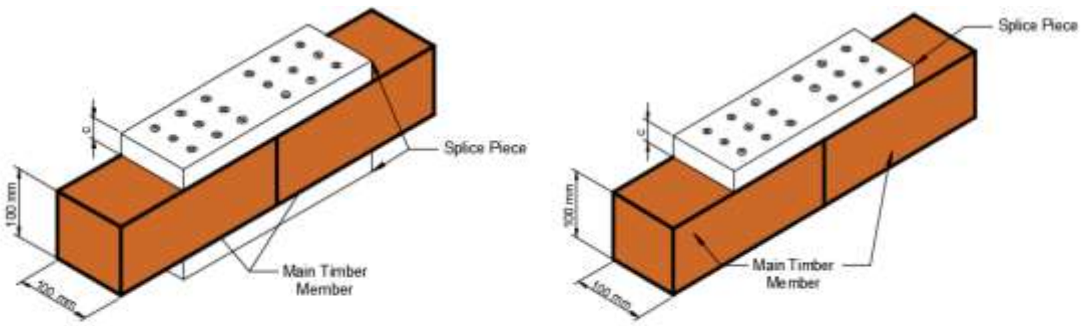


Figure 4.14 Cells of Results

4.3. Materials and design

The Main Timber Characteristics

A single dimension was chosen for the main timber member for all connections with 100 mm thick and 100 mm width (Figure 4.15). The dimension of splice piece depending of the type of the connection. It is analysed for the two main types: Timber – Timber connections and Timber - Steel connections.



a) Connection with 2 splice piece

a) Connection with 1 splice piece

Figure 4.15 Detailing of the Connection

Wood Strength Class

The Table 4.1 shows the strength classes taken into account for the design of the connections with their main characteristic properties.

Table 4.1 The Main Timber Member Strength Class

Strength Class	F t,o,k (MPa)	F v,k (MPa)	Density (gr/cm^3)	Maximum Tensile Strength (KN)
C18	11.0	3.4	320	55
C20	12.0	3.6	330	60
C24	14.0	4.0	350	70
C35	21.0	4.0	400	105

For the calculation of the resistance capacity values of the connections, strength class of the timber C20 was used as reference, and a comparison was made with the other strength classes, obtaining the percentages for the increase or decrease in their strength.

Angle of maximum load

It was analysed for three different angles: 0 °, 45 ° and 90 ° with respect to the direction of the grain. These angles were taken into account to acquire average values that indicate how it affects the capacity values of the connection and the minimum spacings.

Service Class

The Table 4.2 shows the conditions of each service class indicated by Eurocode 5:

Table 4.2 Service Class by Eurocode 5

SERVICE CLASS	**For All Woods**	**For Most Softwoods**
	Relative Humidity of Environment	***Moisture Content of Wood***
1	> 65% (at 20°C)	< 12%
2	> 85% (at 20°C)	< 20%
3	more sever situations	> 20%

Load Duration

The Eurocode 5 indicates five load duration. However, in this study the permanent duration was chosen because is the most unfavourable situation that the connection can be exposed. This factor and the service class indicate the coefficient k_{mod} that involves the strength design value of the connection.

Steel Strength Class

In the Timber – Steel connections and Timber – Central Steel connections, the strength class of the steel plate is S275 (fu = 430 MPa, fy = 275 MPa) for thicknesses less than 40 mm. The reason to choose only one strength class was because this factor is not affecting considerably in the strength value of the connection.

Number of Lines and Fasteners

The number of lines is maximum number that can be placed in the dimension of main timber member (100mm x 100mm) and depends on the diameter and type of fastener. The minimum number of fastener per line considered for nails is three and for the other fasteners is two. The number of lines indicated next to the fastener is the total number of lines, for example:

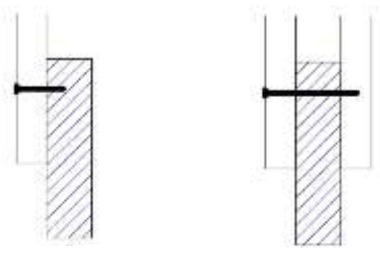
2.7 x 60 R – S (4 lines)

When the type of connection uses two-splice piece the number of lines indicates that there are 2 lines of fasteners in top side and 2 lines of fasteners in the bottom side. However, if the connection type uses one-splice piece the number indicates that there are 4 lines of fasteners in the splice piece.

4.3.1. Type of Connection

Timber – Timber Connection

This type of connection was used for the five types of fasteners: nails, screws, bolts, dowels and wooden dowels. Depending on the type of fastener, there is single shear and double shear as indicated in Figure 4.16.



a) Single Shear b) Double Shear

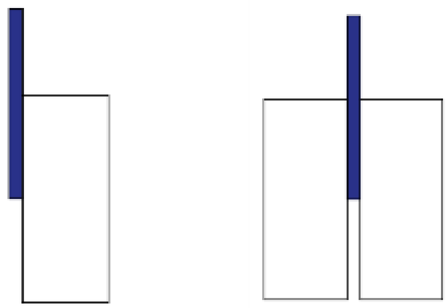
Figure 4.16 Single Shear and Double Shear Connection

The thickness of splice piece for the analysis is 30 mm, 50 mm and 70 mm, and its strength class is equal to the main timber member.

Timber – Steel Connection

This type of connection is used for the four types of metal fasteners: nails, screws, bolts, and dowels. In the same way, single shear or double shear is applied depending on the type of fastener.

The splice piece is a steel plate with a thickness of 2 mm, 3 mm, 5 mm and 10 mm, and the strength class is S275 (fy = 275 MPa, fu = 430 MPa). The steel plate is placed in lateral and central position as indicated in Figure 4.17.



a) Lateral Position b) Central Position

Figure 4.17 Position of the Steel Plate

4.3.2. Dowel Type Fasteners

Nails

The values of diameters and lengths are taken from the Rothoblass catalogue; vary between 3.75 mm to 6.00 mm and 65 mm to 120 mm respectively. These values will depend on the thickness of the connection so that they meet the minimum penetration and overlapping requirements. The tensile strength considered was 600 MPa.

The nails have two specific shapes: round nails and square nails, as well as two different roughness surfaces: smooth nails and other type of nails (they can have a certain type of roughness). To differentiate if the nail has any of these characteristics, a symbology is used as indicated below:

2.7 x 60 R – S

- Diameter = 2.7 mm;
- Length = 60 mm;
- The first letter indicates the shape of the nail: R = round nails - S = square nails;
- The second letter indicates the roughness surface: S = smooth nails – O = other type of nails.

The nails are used for the type of connection with one and two splice pieces that can be Timber - Timber or Timber - Steel, in addition to only working in single shear.

Screws

In the Rothoblass catalogue, three types of screws were chosen: HBS, HBS + evo and VGZ. Each of these screws are mentioned and described above. However, they have different characteristics where they vary mainly their threated length and their head diameter.

The nominal diameters and lengths vary between 4.5 mm to 7 mm and 60 mm to 120 mm respectively. The tensile strength considered was 600 MPa. Below is how the type of screw and its dimensions are recognized:

a) HBSP4560C	b) HBSP550	c) VGZ7100
HBS	HBS + evo	VGZ

The numbers indicate the dimensions of the screw:

a) Diameter = 4.5 mm / Length = 60 mm

b) Diameter = 5 mm / Length = 50 mm

c) Diameter = 7 mm / Length = 100 mm

The screws will be dimensioned for the type of connection with 1 and 2 splice piece that can be "Timber - Timber" and "Timber - Steel", besides only working in single shear.

Bolts

The bolts diameter varies between 4 mm to 16 mm and its length will depend on the total thickness of the connection due to the fact that they pass along it. The strength class used in the bolts is 4.6 (fy = 240 MPa, fu = 400 MPa). The type of bolts is from M4 to M16 with their own characteristics.

The bolts will be dimensioned for the type of connection with 1 and 2 splice pieces that can be "Timber - Timber" and "Timber - Steel", besides working single shear and double shear. When using a steel plate this can be located in a lateral or central position.

Dowels

The dowels diameter varies between 8 mm to 10 mm and its length will depend on the total thickness of the connection because they pass along it. The strength class of the dowels is S275 (fy = 275, fu = 430). The nomenclature is STD followed by the diameter.

The dowels will be dimensioned for the connection type with 1 and 2 splice pieces and only in one "Timber - Steel" connection, besides working in single shear and double shear. In the case of using a steel plate this can be located lateral position and central position.

Wooden Dowels

Previously it was mentioned the requirements for the dimensioning of wooden dowels where the diameters can only be between 0.75 inches (3/4”) and 1.25 inches (1 ¼”). In addition to using the mortise and tenon connection that works in double shear. The timber type of the wooden dowels are:

- Douglas Fir;
- Beech and;
- Red Oak.

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5. Results and Discussion

The results are represented in four groups: Timber - Timber Connection, Timber - Steel Connection, Timber – Central Steel Connection and Mortise and Tenon Connection. Each group is analysed by graphs representing the influence of the splice piece thickness in the connection as well as the influence of each type of fastener.

Then, the values obtained from the capacity of the connection for each type of fastener are analysed in a more specific way. The use of graphs allows to visualize all the values for the different diameters that were used in each type of connection.

A table is presented for each graphs with values of percentages that indicate the increase or decrease of strength capacity that it acquires by changing the aforementioned variables with respect to the values of the base graph of each type of connection.

5.1. Timber – Timber Connection

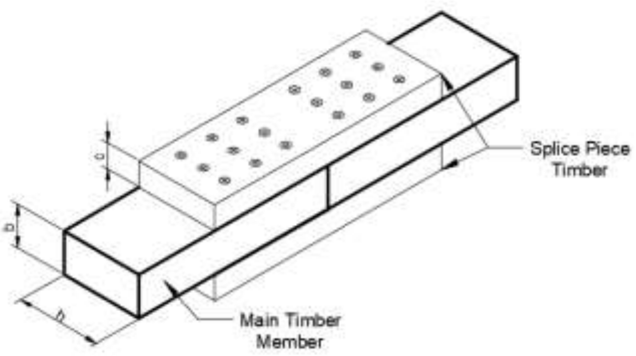

Figure 5.1 Timber - Timber Connection – two-splice piece

This type of connection is made up of a main timber member and the placement of one or two splice piece of timber (Figure 5.1). In this study, the influence of splice thickness was analysed using 30 mm, 50 mm and 70 mm.

The values obtained with tow splice piece give resistance values almost 50% more than the values obtained with one splice piece. Therefore, these results are not shown graphically but use the same percentages indicates in the tables next to the each graph.

5.1.1. Influence of Splice Piece Thickness

In Figure 5.2, the different thicknesses are analysed in a timber-timber nailed connection. Only the maximum and minimum values for each thickness are shown. The graph analyses the design strength value of the connection with respect to the total number of fasteners taken into account in the connection. Each line in the graph represents a type of nail, which represents the maximum and minimum values reached for each thickness.

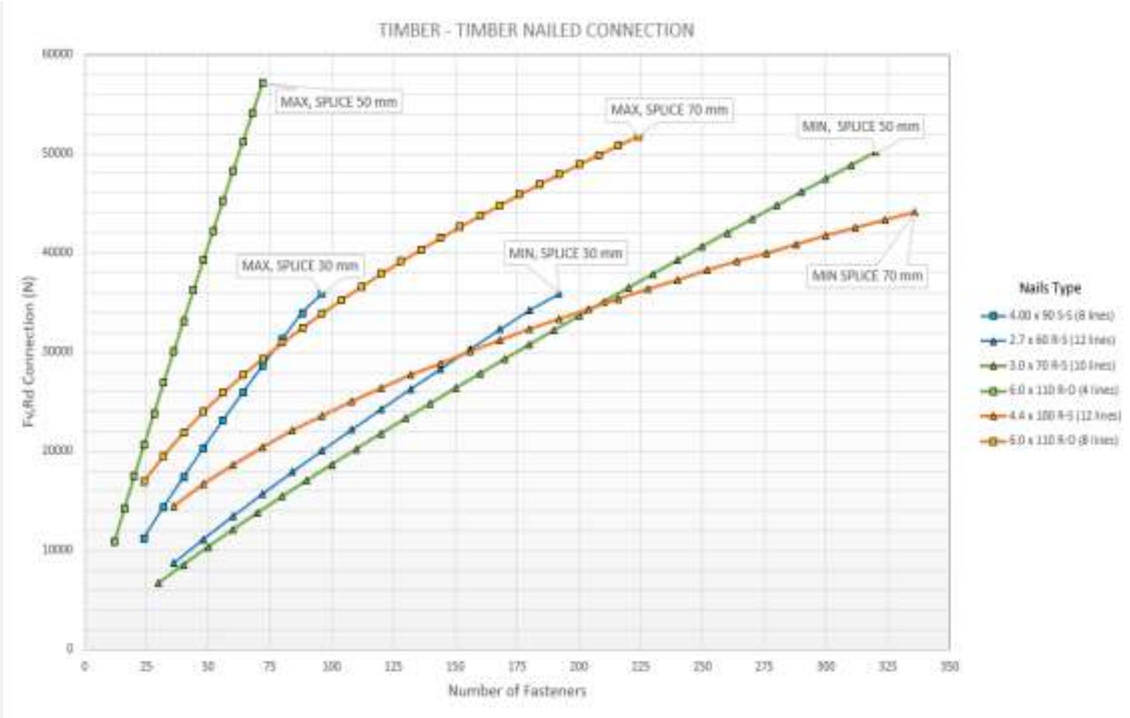

Figure 5.2 Influence of splice piece thickness in Timber – Timber Nailed Connection

The maximum strength values are reached for a thickness of 50 mm using a nail of 6.0 x 110 R - S (4 lines). The strength values achieved is around 11000 N to 60000 N using between 12 to 75 fasteners.

The thickness of 70 mm has the highest strength with respect to the minimum values using a nail 4.4 x 100 R - S (12 lines) but is less with respect to the thicknesses of 30 mm and 50 mm when the number of fasteners is higher to 150.

The thickness of 30 mm reaches resistances of 36000 N using 90 to 180 fasteners. The thickness of 50 mm reaches a strength of 58000 N to 50000 N with a number of fasteners around 75 to 325 respectively. The thickness of 70 mm reaches a strength between 14000N to 52000 N using between 24 to 330 nails.

The use of large thicknesses in the splice piece does not necessarily achieve high strength. One of the factors is the penetration length, which is taken into account in the strength of the connection. In addition, the use of larger diameters generates higher strength values despite the fact that in the use of smaller diameters the number of lines is greater.

5.1.2. Influence of Fastener Type

Figure 5.3 compares the maximum and minimum strength values of different types of fasteners (nails, bolts, screws) used in timber-timber connection with a splice piece thickness of 50 mm.

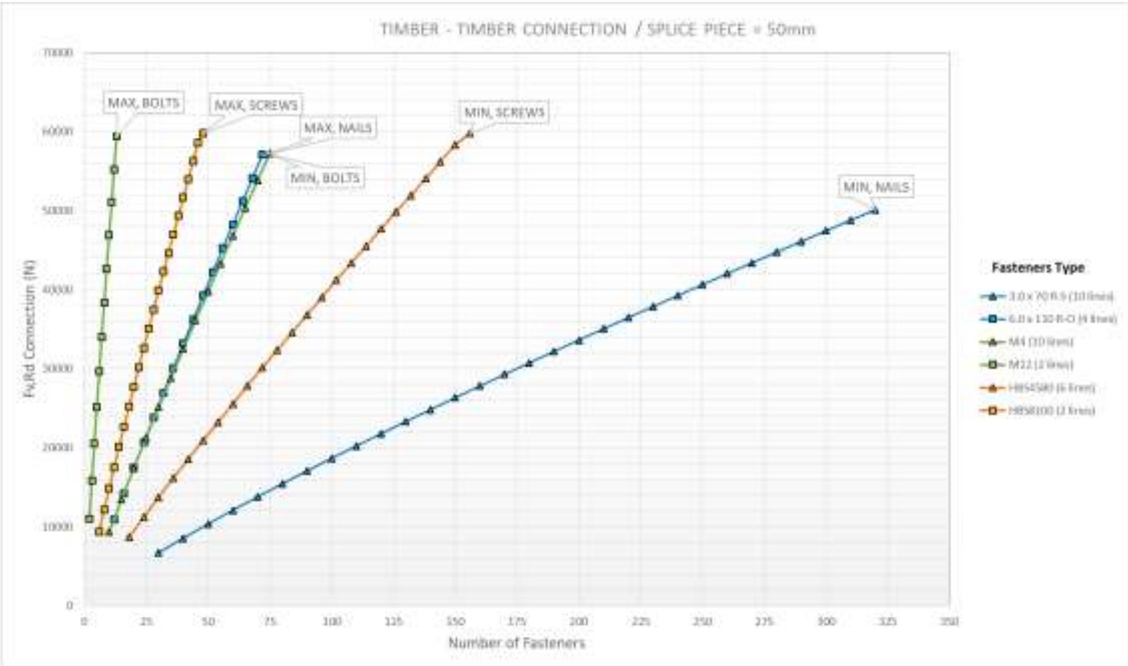

Figure 5.3 Influence of type of fastener in Timber - Timber Connection / Splice Piece = 50 mm

The maximum strength value is reached with a bolt M12 (2 lines). The number of fasteners needed to reach the maximum strength with the lower number of fasteners, between 10000 N and 60000 N is between 4 to 12 bolts.

The minimum strength with the maximum number of fasteners is reached with a nail 3.0 x 70 (10 lines). The number of fasteners needed to reach the minimum strength between 6000 N and 50000 N is between 30 to 320 nails.

The bolts achieve a strength value of 60000 N using between 12 to 75 fasteners. The screws achieve a strength value of 60000 N using between 50 to 160 fasteners. The nails achieve a strength value between 60000 N to 50000 N using between 12 to 325 fasteners.

The nail 6.0 x 110 R – O (4 lines) has almost the same strength values of a bolt M4 (10 lines). It indicates the use of large diameter can balance the number of lines used in the connection and reduce the number of fasteners.

The reason why the bolts can achieve the maximum strength values with the lower number of fasteners is because they work in a double shear so the penetration length is the total thickness of the connection and they have larger diameter range. One bolt is represented in two lines because they work in double shear.

5.1.3. Nailed Connection

Figure 5.4 compares the strength values obtained by the different diameters used in the timber – timber nailed connection with two-splice piece of 30 mm in single shear.

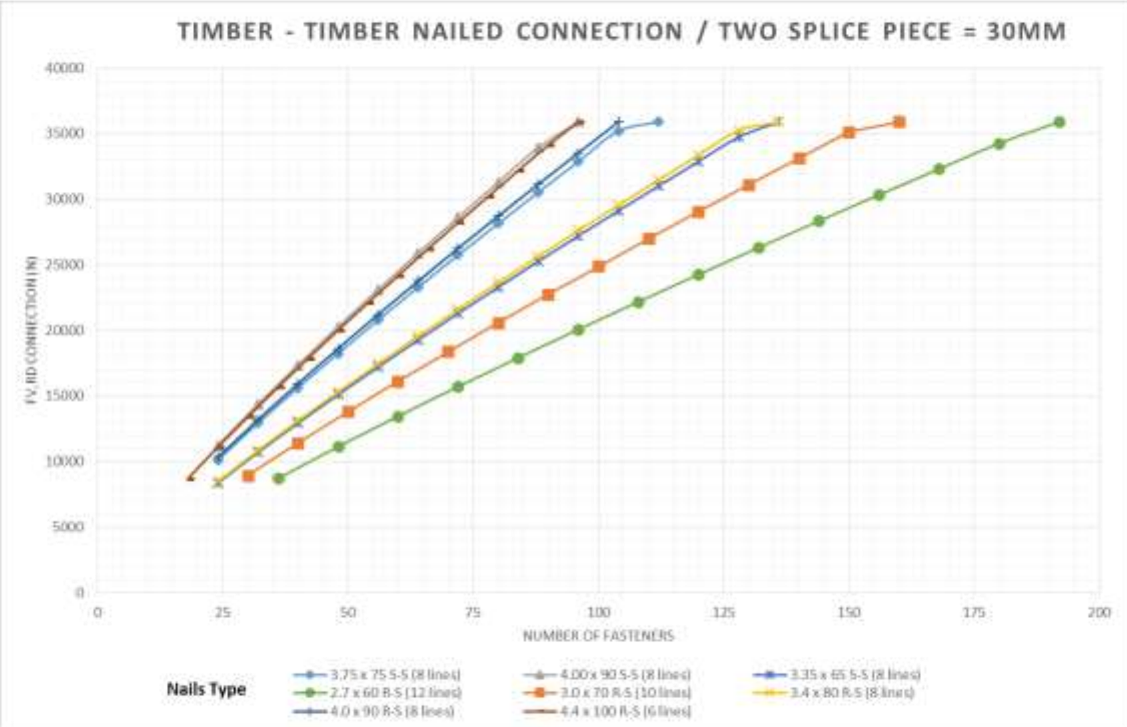

Figure 5.4 Timber - Timber Nailed Connection / Two-Splice Piece = 30 mm

The nails 4.00 x 90 S-S (8 lines) and 4.4 x 100 R-S (6 lines) achieve the maximum strength value between 9000N to 36000 N with a number of fasteners between 18 to 96 fasteners respectively. The nail 2.70 x 60 R-S (12 lines) achieve the minimum strength value between 8500 N to 36000 N with a number of fasteners around between 36 to 192 nails respectively.

The connection reaches a strength value between 8500 N to 36000 N with a number of fasteners around 18 to 192 nails. Despite of the nail 4.4 x 100 S-S has lesser number of lines than 2.70 x 60 R-S, it reaches a higher strength value.

The Table 5.1 indicates the percentages of strength with respect with the values of the Figure 5.4 for the different variables taken into account in this study.

Table 5.1 Timber - Timber Nailed Connection - Percentage of Strength for a given number of nails

TIMBER - TIMBER NAILED CONNECTION									
DIAMETER				< 4 mm		4 mm ≤ D < 5 mm		> 5 mm	
Angle	Splice Thickness	Strength Class	Service Class	MAX	MIN	MAX	MIN	MAX	MIN
0°	30 mm	C18	SC1 / SC2	-1.8%	-2.8%	-2.2%	-3.0%	-	-
			SC3	-18.1%	-19.0%	-18.5%	-19.2%	-	-
		C20	SC1 / SC2	0.0%		0.0%		-	
			SC3	-16.7%		-16.7%		-	
		C24	SC1 / SC2	6.7%	3.5%	5.4%	4.9%	-	-
			SC3	-11.1%	-13.8%	-12.2%	-12.6%	-	-
		C35	SC1 / SC2	19.5%	12.0%	18.5%	16.3%	-	-
			SC3	-0.4%	-6.7%	-1.2%	-3.1%	-	-
	50 mm	C18	SC1 / SC2	-11.1%	-26.8%	12.0%	3.9%	73.9%	21.8%
			SC3	-25.9%	-39.0%	-6.6%	-13.4%	45.0%	1.5%
		C20	SC1 / SC2	-9.0%	-25.0%	14.1%	5.9%	77.5%	25.3%
			SC3	-24.2%	-37.5%	10.1%	-11.8%	47.9%	4.3%
		C24	SC1 / SC2	-4.1%	-21.7%	18.4%	9.1%	84.6%	32.2%
			SC3	-20.0%	-34.8%	-1.3%	-9.1%	53.7%	10.2%
		C35	SC1 / SC2	6.0%	-12.8%	28.7%	17.7%	100.7%	49.1%
			SC3	-11.7%	-27.3%	7.2%	-1.9%	67.4%	24.3%
	70 mm	C18	SC1 / SC2	-	-	61.9%	2.8%	90.5%	18.9%
			SC3	-	-	35.0%	-14.3%	58.7%	-0.9%
		C20	SC1 / SC2	-	-	66.3%	5.5%	95.0%	21.0%
			SC3	-	-	38.5%	-12.1%	62.4%	0.8%
		C24	SC1 / SC2	-	-	74.4%	10.7%	105.3%	25.1%
			SC3	-	-	45.3%	-7.8%	71.2%	4.2%
		C35	SC1 / SC2	-	-	96.2%	24.5%	128.9%	34.8%
			SC3	-	-	63.4%	3.7%	90.7%	12.3%
45°	30 mm	C18	SC1 / SC2	-12.1%	-51.1%	8.0%	-49.6%	12.4%	-57.9%
			SC3	-26.8%	-59.2%	-10.0%	-58.0%	-6.3%	-64.9%
	50 mm	C20	SC1 / SC2	-10.4%	-50.1%	10.8%	-48.4%	14.4%	-57.1%
			SC3	-25.4%	-58.4%	-7.7%	-57.0%	-4.7%	-64.2%
		C24	SC1 / SC2	-4.4%	-48.0%	16.3%	-45.9%	18.3%	-55.3%
			SC3	-20.3%	-56.6%	-3.1%	-54.9%	-1.5%	-62.8%
	70 mm	C35	SC1 / SC2	7.1%	-42.5%	30.8%	-40.0%	27.4%	-51.4%
			SC3	-10.8%	-52.1%	9.0%	-50.0%	6.1%	-59.5%
90°	30 mm	C18	SC1 / SC2	-28.4%	-71.5%	8.0%	-68.2%	-25.0%	-76.7%
			SC3	-40.3%	-76.2%	-10.0%	-73.5%	-37.6%	-80.6%
	50 mm	C20	SC1 / SC2	-26.5%	-70.7%	10.8%	-67.5%	-23.7%	-76.2%
			SC3	-38.8%	-75.6%	-7.7%	-72.9%	-36.5%	-80.2%
		C24	SC1 / SC2	-21.6%	-69.5%	16.3%	-65.9%	-21.2%	-75.2%
			SC3	-34.6%	-74.6%	-3.1%	-71.6%	-34.3%	-79.4%
	70 mm	C35	SC1 / SC2	-12.1%	-66.0%	16.3%	-62.2%	-21.2%	-73.1%
			SC3	-26.8%	-71.7%	9.0%	-68.5%	-29.2%	-77.6%

To explain the application of the table of percentages, it is presented by an example. The strength value of a nail 2.7 x 60 R-S (12 lines) with 36 fasteners is 8700 N (Figure 5.4).

Therefore, the strength with 32 fasteners in a splice piece of 50 mm, strength class of C20 and service class 1 has a strength percentage between -9.0% (MAX) and -25.0 % (MIN).

MAX	MIN
8700 N -------------- 100%	8700 N -------------- 100%
X -------------- -9.0%	X -------------- -25.0%
$= \frac{-9.0*8700}{100} = -783\ N$	$= \frac{-25.0*8700}{100} = -2175\ N$

Thus,

MAX → 8700 N – 783 N = 7917 N

MIN → 8700 N – 2175 N = 6525 N

The strength of the connection for a in a splice piece of 50 mm, strength class of C20 and service class 1 is between 7917 N and 6525 N with 32 nails of 2.70 x 60 R-S (12 lines).

The percentages for diameter higher than 5 mm is compared with the strength values of the nails 4.4 x 100 (6 lines) because the higher diameters have higher length and is not possible to place in the connection due to requirements of the Eurocode 5.

The strength capacity of the connection decrease when use diameters lesser than 4 mm in thickness of splice piece of 50 mm but when use diameter higher than 4 mm the strength capacity is higher.

The strength capacity increase when use a splice piece of 70 mm with nails higher than 4 mm but the range between maximum and minimum percentages is so long because while the number of fasteners increase the strength capacity decrease due to the penetration length that is not enough for keeping the capacity strength increasing.

When the angle of application of the force with regard of the direction of the grain is greater of 0° the strength capacity decrease in all diameters and there is not a significant difference between the thicknesses of the splice piece.

5.1.4. Screwed Connection

Figure 5.5 compares the strength values of the different screws type (HBS, HBS + evo, VGZ) in a timber – timber connection with two-splice piece of 30 mm.

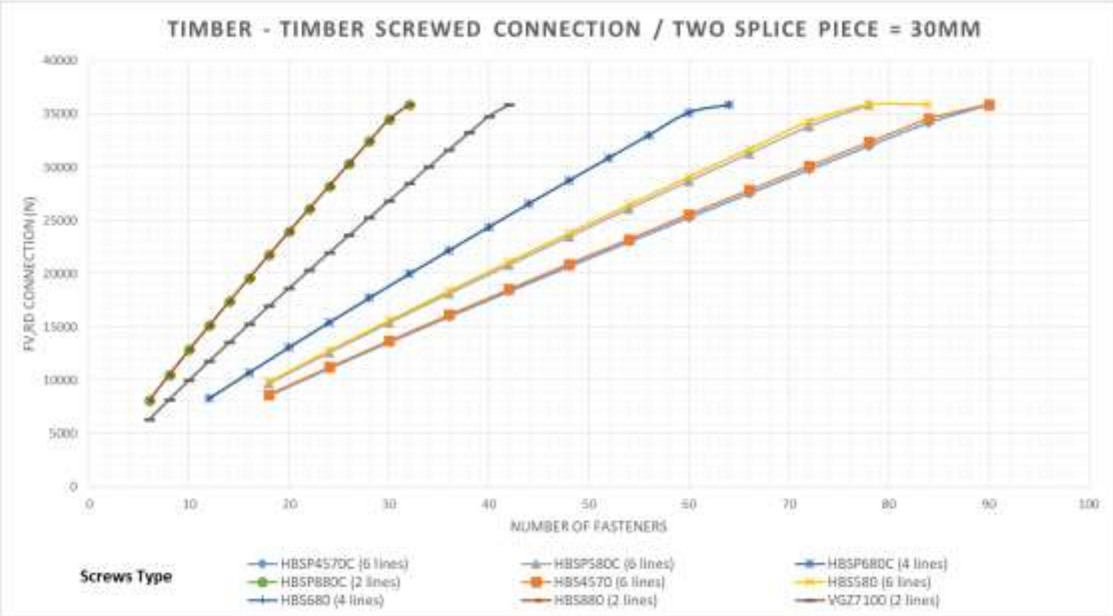

Figure 5.5 Timber – Timber Screwed Connection – Two Splice Piece = 30 mm

The screw HBS880 and HBSP880C reach the same strength values and get the maximum values in this type of connection between 8000 N to 36000 N with 6 to 32 fasteners respectively.

The screw HBSP4570C uses the greatest number of fasteners to get the maximum strength. The values is between 8500 N to 36000 N placing between 18 to 90 fasteners.

The screw VGZ7100 is placed in two lines of fasteners as HBS880 but the second one achieve greater strength than first one, despite having a shorter length. The use of larger diameters can achieve higher strength values than use larger penetration lengths.

The connection has a range of strength values between 6000 N to 36000 N placing between 6 to 90 fasteners to reach the maximum strength.

The graph indicates there is a small difference in the strength values between the screws HBS and HBS + evo, even the values are equal in the screw HBS880 and HBSP880C. The reason is due to the head diameter in HBS + evo is a little bigger than HBS. This factor intervenes in the pull through of the connection (Fax, Rk).

The number of fasteners used in a timber – timber screwed connection is almost less than half of fasteners used in a timber – timber nailed connection. The screws and nails work in a single shear but the first ones has a rough surface that helps to acquire greater strength than nails.

The Table 5.2 indicates the percentages of strength with respect with the values of the Figure 5.5 for the different variables taken into account in this study.

The percentages indicate that the use of large thicknesses of splice piece do not affect in the increase of strength. The strength in a screwed connection depends mainly of the threated length that intervenes in the main timber member. Therefore, when increase the thickness of the splice piece and the threated length is the same, the strength is equal.

The factor of the angle of application of the force affect in the strength of the connection due to the minimum spacing increase, so the number of lines is less than using angle of 0°. The use of larger diameters than 5 mm cannot use in a width connection of 100 mm when the angle is increased because the minimum spacing required are greater, and the width have to increase its dimension.

Table 5.2 Timber – Timber Screwed Connection - Percentage of Strength for a given number of screws

TIMBER - TIMBER SCREWED CONNECTION									
TYPE				**HBS**		**HBS + EVO**		**VGZ**	
DIAMETER				**4 mm < D < 8 mm**		**4 mm < D < 8 mm**		**D > 7 mm**	
Angle	**Splice Thickness**	**Strength Class**	**Service Class**	**MAX**	**MIN**	**MAX**	**MIN**	**MAX**	**MIN**
0°	30 mm	C18	SC1 / SC2	-2.5%	-2.6%	-2.5%	-2.6%	-2.6%	
			SC3	-18.7%	-18.8%	-18.7%	-18.8%	-18.8%	
		C20	SC1 / SC2	0.0%		0.0%		0.0%	
			SC3	-16.7%		-16.7%		-16.7%	
		C24	SC1 / SC2	4.9%	2.9%	4.9%	2.9%	4.8%	
			SC3	-12.6%	-14.2%	-12.6%	-14.2%	-12.7%	
		C35	SC1 / SC2	17.0%	11.3%	17.0%	11.4%	17.0%	
			SC3	-2.5%	-7.3%	-2.5%	-7.2%	-2.5%	
	50 mm 70 mm	C18	SC1 / SC2	12.3%	-2.5%	13.6%	-2.5%	8.1%	
			SC3	-6.3%	-18.7%	-5.4%	-18.7%	-10.0%	
		C20	SC1 / SC2	14.4%	0.0%	15.5%	0.0%	9.9%	
			SC3	-4.7%	-16.7%	-3.8%	-16.7%	-8.4%	
		C24	SC1 / SC2	18.3%	4.9%	19.2%	3.4%	13.3%	
			SC3	-1.4%	-12.6%	-0.6%	-13.8%	-5.6%	
		C35	SC1 / SC2	27.4%	17.0%	28.2%	11.4%	21.5%	
			SC3	6.2%	-2.5%	6.9%	-7.2%	1.2%	
45° 90°	30 mm 50 mm 70 mm	C18	SC1 / SC2	-34.7%	-67.5%	-34.7%	-67.5%	-	
			SC3	-45.6%	-72.9%	-45.6%	-72.9%	-	
		C20	SC1 / SC2	-33.3%	-66.7%	-33.3%	-66.7%	-	
			SC3	-44.5%	-72.2%	-44.5%	-72.2%	-	
		C24	SC1 / SC2	-31.1%	-65.0%	-31.1%	-65.0%	-	
			SC3	-42.5%	-70.9%	-42.5%	-70.9%	-	
		C35	SC1 / SC2	-25.8%	-61.0%	-25.8%	-61.0%	-	
			SC3	-38.2%	-67.5%	-38.2%	-67.5%	-	

5.1.5. Bolted Connection

Figure 5.6 compares all the strength values achieved by the different bolts diameters. The connection works in a double shear, so the length of the bolts depends of the total thickness of the connection.

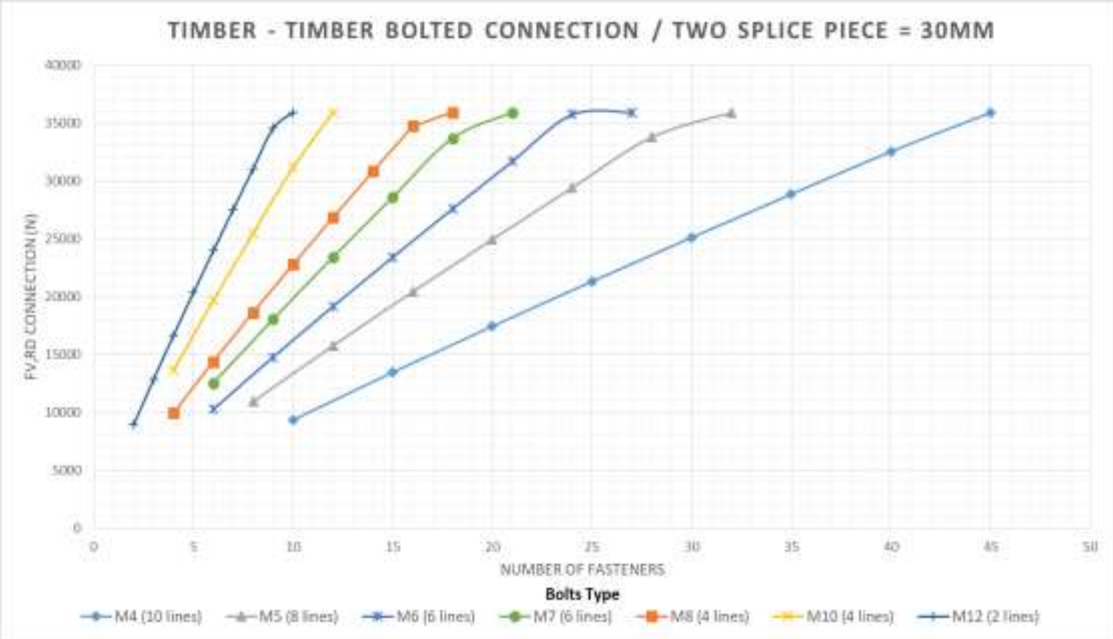

Figure 5.6 Timber – Timber Bolted Connection - Two Splice Piece = 30 mm

The bolt M12 (2 lines) achieves the maximum strength with the least number of fasteners. The value strength is between 9000 N to 36000 N using around 2 to 10 fasteners. The bolt M4 (10 lines) reaches the minimum strength with the largest number of fasteners. The value strength is between 9000 N to 36000 N using around 10 to 45 bolts.

The number of fasteners used in a timber – timber bolted connection is almost less than half of fasteners used in a timber – timber screwed connection. The bolts work in double shear consequently the strength value is greater than nails and screws due to the penetration length in bolted connection is the total thickness of the connection.

The Table 5.3 indicates the percentages of strength with respect with the values of the Figure 5.6 for the different variables taken into account in this study.

The use of smaller diameters than 7 mm the increasing of thickness of splice piece between 50 and 70 mm do not affect in the strength capacity of the connection because the connection strength does not directly depend on the length penetration but depends on the diameter of the fastener.

The application of the force with a greater angle than 0° the strength capacity decreases with smaller diameters than 7 mm. However, the use of greater diameters than 7 mm does not have a considerable decrease in strength until an angle of 45°. If the angle is greater than 45° the strength increase because the effective number is equal to number of fasteners on the connection.

Table 5.3 Timber - Timber Bolted Connection - Percentage of Strength for a given number of bolts

TIMBER - TIMBER BOLTED CONNECTION							
DIAMETER				4 mm < D < 7 mm		D > 7 mm	
Angle	Splice Thickness	Strength Class	Service Class	MAX	MIN	MAX	MIN
0°	30 mm	C18	SC1 / SC2	-1.6%	-2.6%	-1.9%	-2.4%
			SC3	-18.0%	-18.9%	-18.2%	-18.6%
		C20	SC1 / SC2	0.0%		0.0%	
			SC3	-16.7%		-16.7%	
		C24	SC1 / SC2	5.1%	3.0%	4.4%	3.9%
			SC3	-12.4%	-14.1%	-13.0%	-13.4%
		C35	SC1 / SC2	17.1%	10.1%	15.6%	13.3%
			SC3	-2.4%	-8.3%	-3.7%	-5.6%
	50 mm	C18	SC1 / SC2	18.6%	-1.6%	27.6%	20.7%
			SC3	-1.1%	-18%	6.3%	0.6%
		C20	SC1 / SC2	20.6%	0.0%	29.7%	23.5%
			SC3	0.4%	-16.7%	8.0%	2.9%
		C24	SC1 / SC2	24.0%	3.0%	33.6%	29.6%
			SC3	3.4%	-14.1%	11.3%	8.0%
		C35	SC1 / SC2	32.6%	10.1%	44.3%	40.5%
			SC3	10.5%	-8.3%	20.2%	17.2%
	70 mm	C18	SC1 / SC2	18.6%	-1.6%	42.6%	25.6%
			SC3	-1.1%	-18%	18.9%	4.6%
		C20	SC1 / SC2	20.6%	0.0%	44.8%	27.6%
			SC3	0.4%	-16.7%	20.6%	6.3%
		C24	SC1 / SC2	24.0%	3.0%	49.3%	31.4%
			SC3	3.4%	-14.1%	24.4%	9.5%
		C35	SC1 / SC2	32.6%	10.1%	59.5%	40.5%
			SC3	10.5%	-8.3%	32.9%	17.2%
45°	30 mm	C18	SC1 / SC2	-1.6%	-45.0%	21.3%	-58.4%
			SC3	-18.0%	-54.2%	1.1%	-65.3%
	50 mm	C20	SC1 / SC2	-0.1%	-43.8%	24.1%	-57.5%
			SC3	-16.8%	-53.2%	3.3%	-64.6%
		C24	SC1 / SC2	3.0%	-41.4%	30.8%	-55.9%
			SC3	-14.2%	-51.2%	8.9%	-63.2%
	70 mm	C35	SC1 / SC2	10.2%	-34.9%	39.6%	-51.8%
			SC3	-8.2%	-45.8%	16.4%	-59.9%
90°	30 mm	C18	SC1 / SC2	60.9%	-32.8%	66.2%	-48.8%
			SC3	34.1%	-44.0%	38.4%	-57.3%
	50 mm	C20	SC1 / SC2	63.7%	-31.3%	70.6%	-47.8%
			SC3	36.3%	-42.8%	42.1%	-56.5%
		C24	SC1 / SC2	68.3%	-28.5%	78.7%	-45.8%
			SC3	40.3%	-40.4%	49.0%	-54.8%
	70 mm	C35	SC1 / SC2	80.1%	-21.0%	100.2%	-40.9%
			SC3	49.9%	-34.2%	66.7%	-50.7%

5.2. Timber – Steel Connection

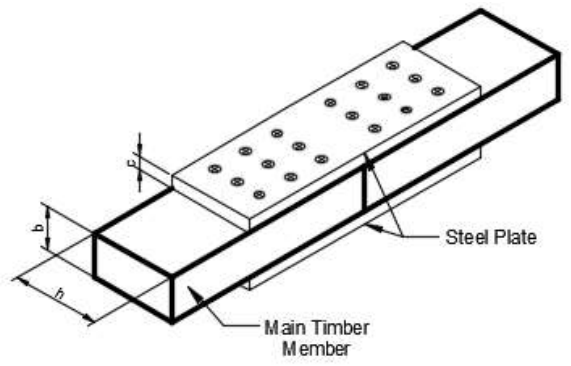

Figure 5.7 Timber – Steel Connection – two-splice piece

In this type of connection, the main timber member is placed with one or two steel plates (Figure 5.7).

In this study, it was analysed with plate thicknesses of 2 mm, 3 mm, 5 mm and 10 mm with a strength class S275.

The values obtained with two or one steel plate are different because of the failure due to called block shear. However, the percentages of increase or decrease of resistance is the same for the two cases.

5.2.1. Influence of Steel Plate Thickness

Figure 5.8 represents the maximum and minimum strength values of the different thickness of splice piece in a timber – steel nailed connection.

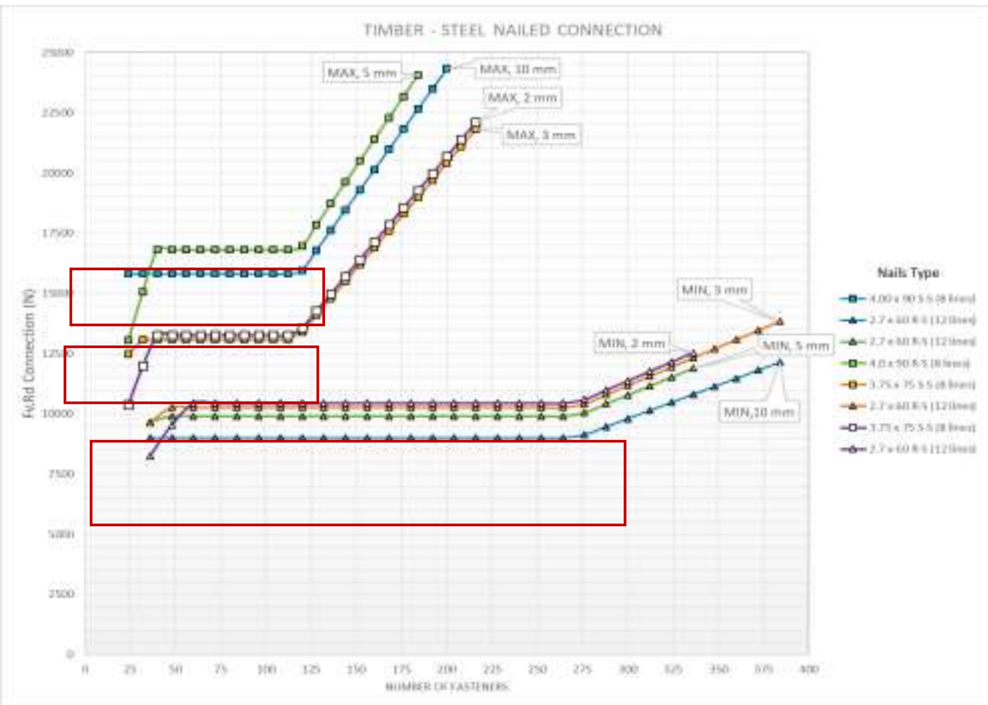

Figure 5.8 Influence of splice piece thickness in Timber – Steel Nailed Connection

There are values that keep constant even when the number of fasteners increase. The factors that intervene in this failure called block shear are the diameter size and mainly the number of the lines and number of fasteners in the connection.

The block shear in this type of connection is related to number of lines. The number of lines remains constant so the strength value does not change with the increase of number of fasteners. Therefore, there is a limitation of strength due to the block shear. This limit is between 8000 N to 17000 N using around of 24 to 48 nails.

The maximum strength values is achieved using a nail 4.0 x 90 R-S (8 lines) with a steel plate of 5 mm. The values are between 13000 N to 17000 N with a number of fasteners around of 24 to 40 nails. The steel plate of 10 mm reaches lower strength values than steel plate of 5 mm. It indicates that use of greater thickness no represent a benefit in the strength capacity of the connection.

The minimum strength values is achieved using a nail 2.7 x 60 R-S (12 lines) with a steel plate of 10 mm. The strength value is 9000 N using 36 fasteners. The penetration length and the diameter have lower dimensions regard with the others fasteners.

5.2.2. Influence of Fastener Type

Figure 5.9 compares the maximum and minimum strength values of the different type of fasteners in a timber – steel connection with a steel plate of 5 mm.

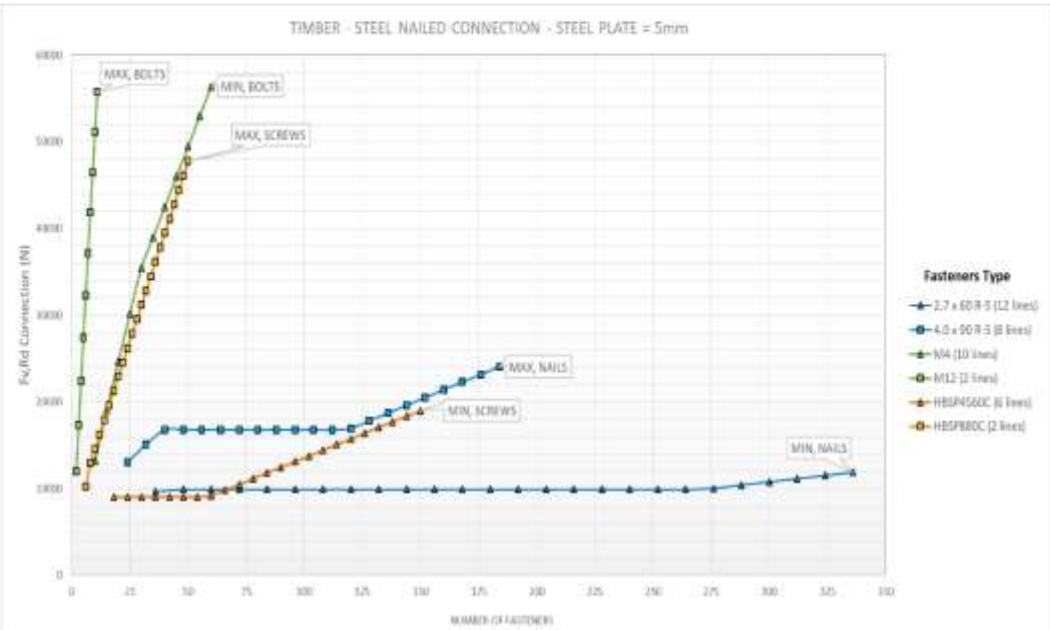

Figure 5.9 Influence of Fastener type on Timber – Steel Nailed Connection – Two Steel Plate = 5 mm

The block shear, related it the number of lines appear in the screws HBSP4560C (6 lines), and in nails 2.7 x 60 R-S (12 lines) and 4.0 x 90 R-S (8 lines). However, the bolts do not present constant values because the block shear is related with the number of fasteners.

The maximum strength values is achieved using a bolt M12 (2 lines). The values are between 12000 N to 56000 N with a number of fasteners around of 2 to 12 bolts.

The minimum strength values is achieved using a nail 2.7 x 60 R-S (12 lines). The strength value is 9000 N using 36 fasteners. The screw HBSP4560C reaches the same strength value with 18 fasteners.

5.2.3. Nailed Connection

Figure 5.10 compares the strength values of the different type of nails in a timber – steel nailed connection with two steel plate of 2 mm.

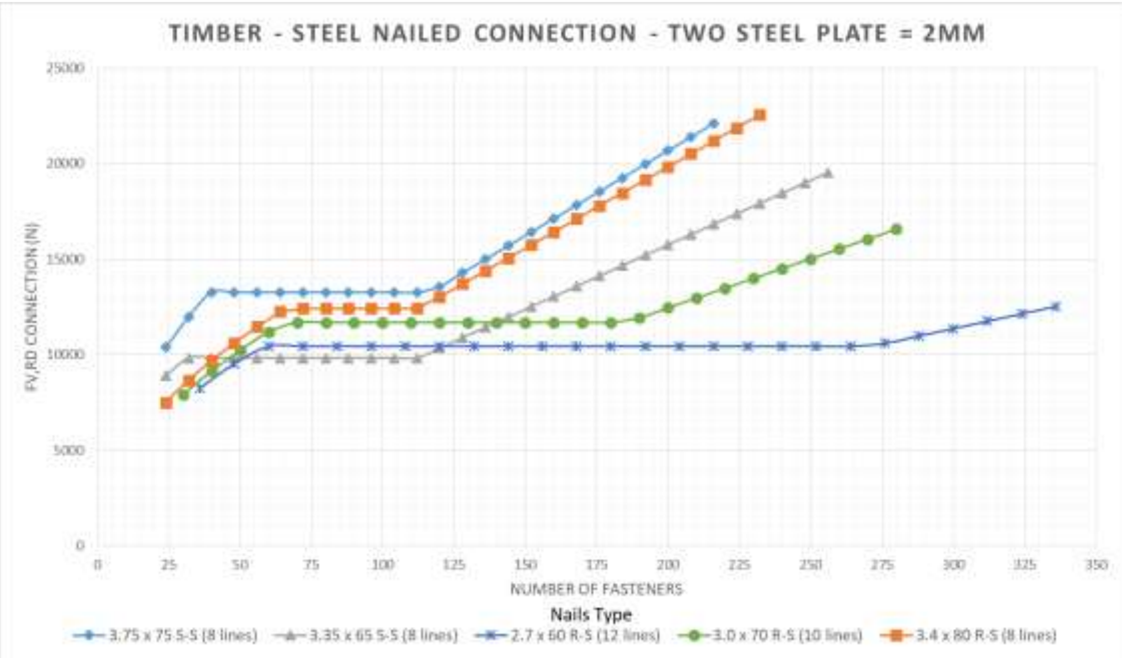

Figure 5.10 Timber - Steel Nailed Connection - Two Steel Plate = 2 mm

The block shear related with the number of lines is presented in all fasteners. This type of failure lead to a limitation on the strength. The nail 3.75 x 75 S-S (8lines) gives the maximum strength value. These values are between 10000 N to 13000 N using around 24 to 40 fasteners.

The nail 2.7 x 60 R-S (12 lines) achieves the minimum strength value. These values are between 9000 N using around 40 fasteners to 10000 N using around 64 fasteners. The limitation of connection strength is achieved using around of 24 to 64 fasteners.

The Figure 5.11 indicates the strength values for a timber – steel nailed connection with one steel plate of 2 mm.

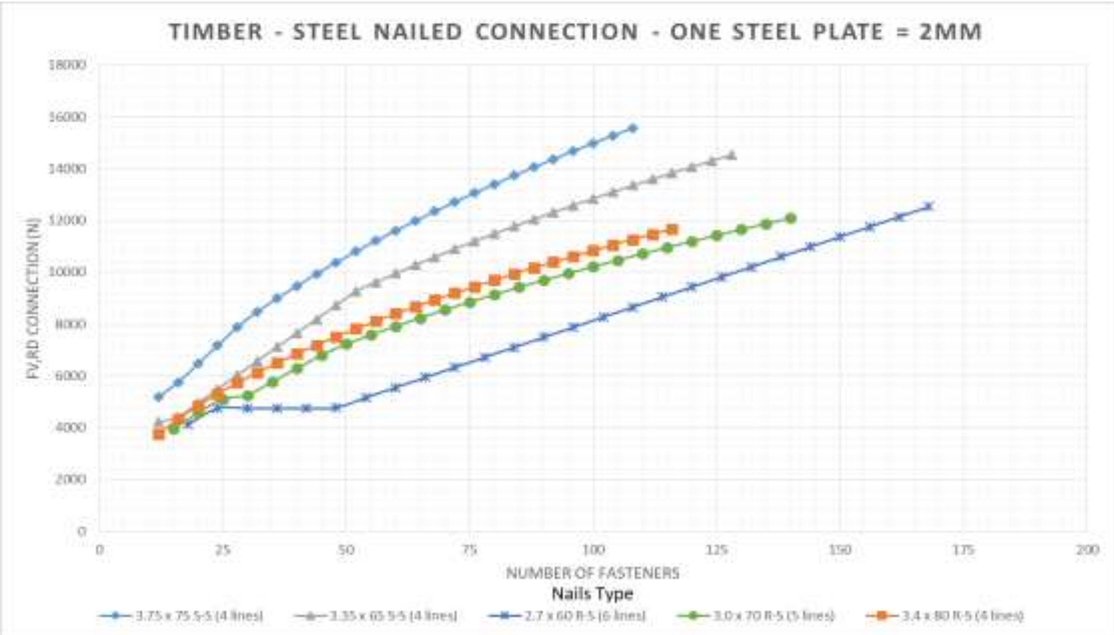

Figure 5.11 Timber - Steel Nailed Connection- One Steel Plate = 2 mm

The block shear failure related with the number of lines where the strength values are constants is on the fasteners 2.7 x 60 R-S (6 lines) and 3.0 x 70 R-S (5 lines). However, the other types of nails present a block shear failure due to number of fasteners.

The nail 3.75 x 75 S-S (4 lines) gives the maximum strength value. These values are between 5000 N to 16000 N using around 12 to 108 fasteners.

The nail 2.7 x 60 R-S (6 lines) achieves the minimum strength value. These values are between 4000 N using around 18 fasteners to 4800 N using around 24 fasteners.

The Table 5.4 indicates the percentages of strength with respect with the values of the Figure 5.11 and Figure 5.12 for the different variables taken into account in this study.

The strength increases when the thickness of the steel plate is greater in all fasteners using in this study but the minimum percentages go down and the range between the max and min percentage is larger due to the limitation of the strength by block shear change with the different characteristics.

Table 5.4 Timber - Steel Nailed Connection - Percentages of Strength for a given number of nails

TIMBER - STEEL NAILED CONNECTION					
DIAMETER				≤ 4 mm	
Angle	Steel Plate Thickness	Strength Class	Service Class	MAX	MIN
0°	2 mm	C18	SC1 / SC2	-2.0%	-8.0%
			SC3	-18.0%	-24.0%
		C20	SC1 / SC2	0.0%	
			SC3	-16.7%	
		C24	SC1 / SC2	17.0%	3.0%
			SC3	-3.0%	-14.0%
		C35	SC1 / SC2	75.0%	12.0%
			SC3	46.0%	-6.0%
	3 mm	C18	SC1 / SC2	20.7%	-9.9%
			SC3	0.6%	-24.9%
		C20	SC1 / SC2	22.7%	-1.7%
			SC3	2.2%	-18.1%
		C24	SC1 / SC2	27.1%	9.2%
			SC3	5.9%	-9.0%
		C35	SC1 / SC2	72.8%	9.3%
			SC3	44.0%	-8.9%
	5 mm	C18	SC1 / SC2	27.4%	-13.1%
			SC3	6.2%	-27.6%
		C20	SC1 / SC2	29.8%	-5.2%
			SC3	8.1%	-21.0%
		C24	SC1 / SC2	40.2%	5.4%
			SC3	16.8%	-12.2%
		C35	SC1 / SC2	68.3%	5.8%
			SC3	40.2%	-11.8%
	10 mm	C18	SC1 / SC2	71.5%	-21.0%
			SC3	42.9%	-34.1%
		C20	SC1 / SC2	74.7%	-13.8%
			SC3	45.6%	-28.2%
		C24	SC1 / SC2	81.2%	-4.2%
			SC3	51.0%	-20.2%
		C35	SC1 / SC2	122.7%	-3.0%
			SC3	85.6%	-19.2%
45°	2 mm 3 mm 5 mm 10 mm	C18	SC1 / SC2	84.6%	-29.6%
			SC3	53.8%	-41.3%
		C20	SC1 / SC2	101.4%	-25.3%
			SC3	67.8%	-37.7%
		C24	SC1 / SC2	134.9%	-16.8%
			SC3	95.8%	-30.7%
		C35	SC1 / SC2	193.2%	12.4%
			SC3	144.3%	-6.4%
90°	2 mm 3 mm 5 mm 10 mm	C18	SC1 / SC2	112.7%	-24.5%
			SC3	77.3%	-37.1%
		C20	SC1 / SC2	128.1%	-17.7%
			SC3	90.1%	-31.4%
		C24	SC1 / SC2	153.7%	-3.9%
			SC3	111.4%	-19.9%
		C35	SC1 / SC2	193.2%	12.4%
			SC3	144.3%	-6.4%

To explain in a better way the changes of the limitation of strength by block shear is presented the Figure 5.12. This Figure 5.12 indicates the strength values for a timber – steel nailed connection with two steel plate of 2 mm and application force angle of 45°.

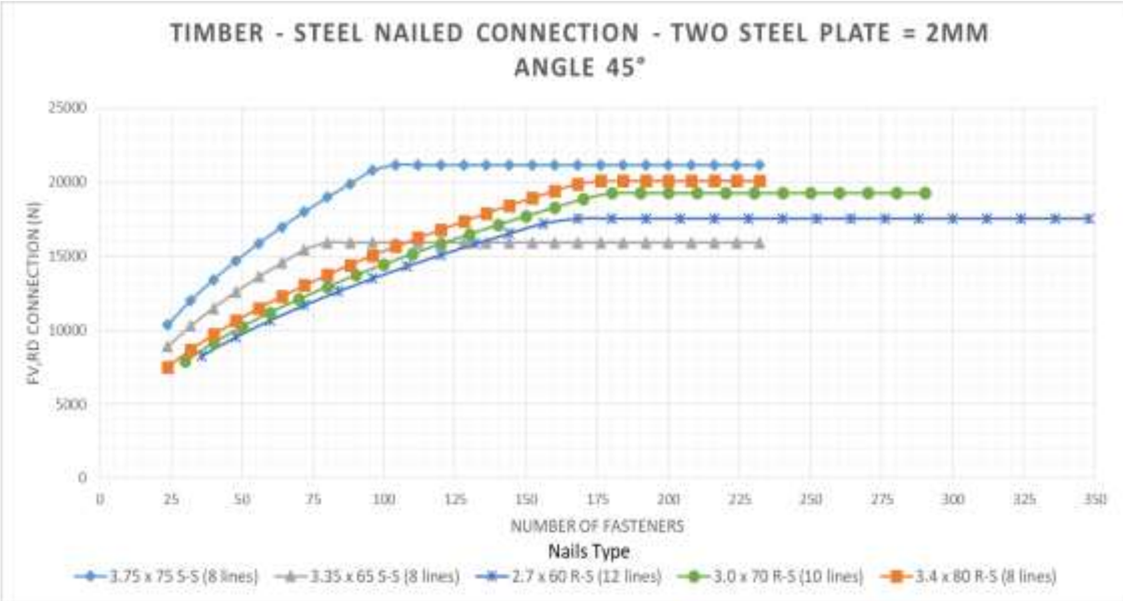

Figure 5.12 Timber - Steel Nailed Connection - Two Steel Plate = 2 mm - Angle 45°

The nail 3.75 x 75 R-S (8 lines) achieves the maximum strength values. The strength values are between 10000 N to 20000 N using around of 25 to 100 fasteners.

The limit strength of connection is imposed by the block shear due to number of fasteners between 100 to 170 fasteners. However, when the number of fasteners is greater, the block shear due to number of lines appears and the strength keeps constant.

This is the reason because the percentages of strength in timber – steel connection there is a big difference between the maximum and minimum strength percentages. The use of different application force angle give an increase of strength because the block shear due to number of fasteners.

The limitation of strength in a steel connection depends of the block shear due to number of lines or number of fasteners but the most unfavourable is due to number of lines.

5.2.4. Screwed Connection

Figure 5.13 indicates the strength values in a timber – steel screwed connection with two steel plate of 2 mm using the screw type HBS.

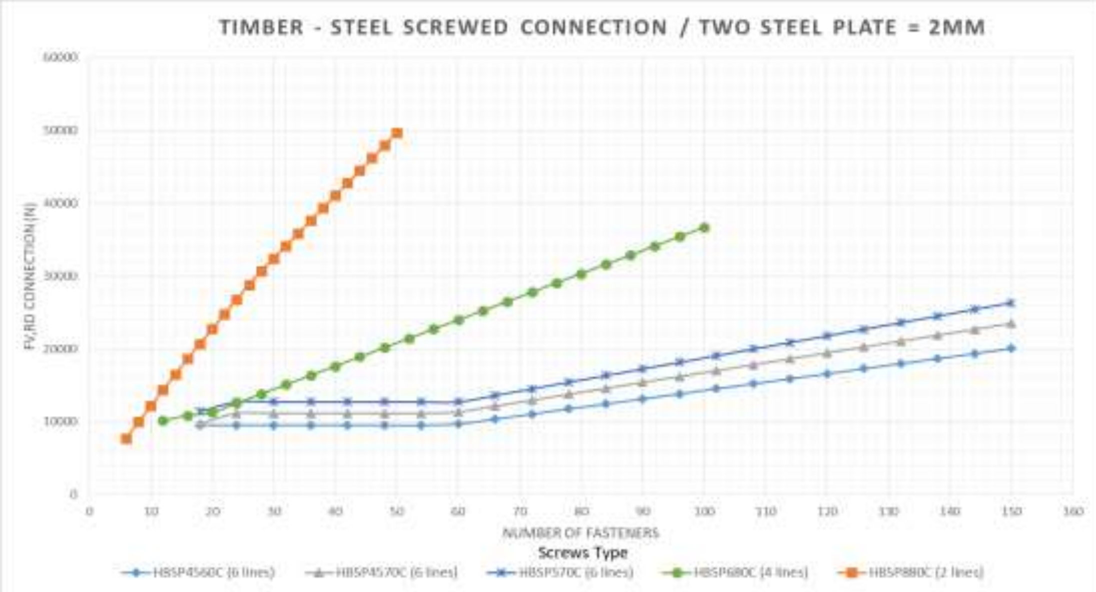

Figure 5.13 Timber - Steel Screwed Connection - Two Steel Plate = 2 mm

The screws HBS and HBS + evo achieve the same strength values due to the connection strength is given by the block shear failure.

The block shear due to number of lines appears in the screws HBSP4560C (6 lines), HBSP4570C (6 lines) and HBSP570C (6 lines). The minimum strength values are between 9000 N to 12000 N using around of 18 fasteners.

The screw HBSP880C (2 lines) achieve the maximum strength values with the least number of fasteners. The strength values are between 8000 N to 50000 N using around 6 to 50 fasteners.

The Figure 5.14 indicates the strength values for a timber – steel screwed connection with one steel plate of 2 mm.

The block shear due to the number of fasteners lead to the limit connection strength. Therefore, the constant strength values do not appear in this type of connection.

The screw HBSC4560C (3 lines) achieve the minimum strength. These strength values are between 5000 N to 20000 N using around of 8 to 75 fasteners.

The screw HBSP880C (1 line) achieve the maximum strength with the least number of fasteners. These strength values are between 4000 N to 25000 N using around of 4 to 26 fasteners.

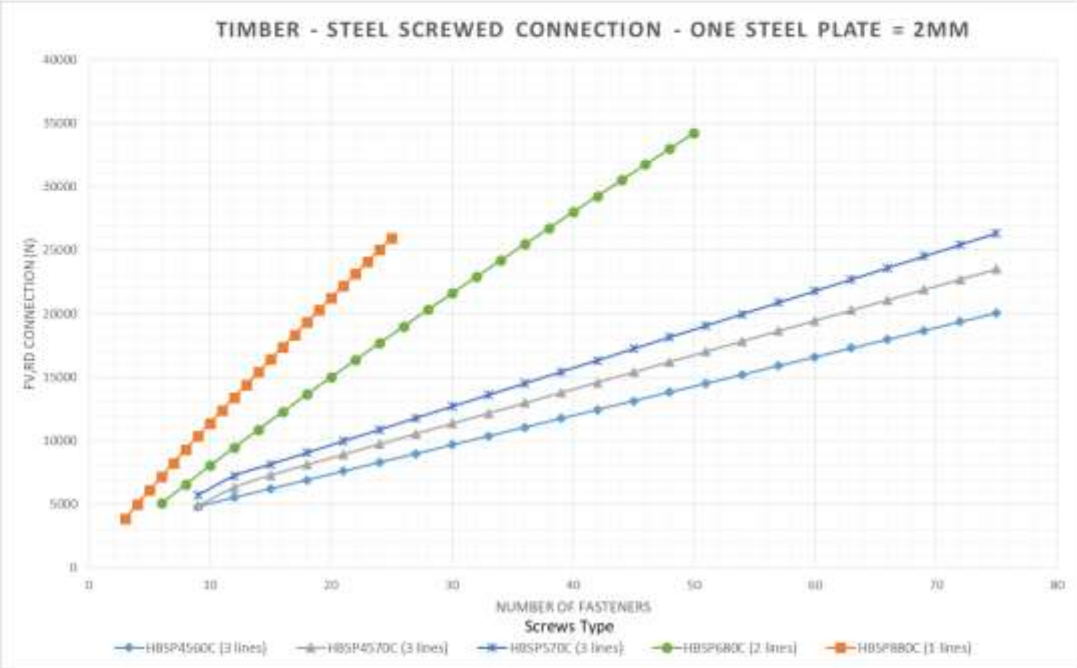

Figure 5.14 Timber - Steel Screwed Connection - One Steel Plate = 2 mm

The Table 5.5 indicates the percentages of strength with respect with the values of the Figure 5.13 and Figure 5.14 for the different variables taken into account in this study.

The percentage of strength increase when the thickness of the steel plate increase. However, the use of steel plate thickness larger than 5 mm the connection strength decrease due to the penetration length is not enough to gain strength regard with the other thickness.

The maximum strength percentages is higher regard with an angle of 0° because the limit strength is imposed by the block shear due to number of lines. The use of angles of 45° and 90° apparently could achieve a greater strength than by applying a force parallel to the grain. However, the Table 5.5 also indicates that for angles of 45° and 90° a much lower resistance is achieved than the use of an angle of 0°. These ranges too far between maximum and minimum strength is due to the block shear failure.

The limitation of strength in a steel connection depends of the block shear due to number of lines or number of fasteners but the most unfavourable is due to number of lines. When is applied a angle 0°, the block shear due to number of fasteners affects the connection strength but when the angle increases the block shear is due to number of lines. Hence when comparing the angles of 45° and 90 with the values of an angle of 0 °there is a too large variation.

Table 5.5 Timber - Steel Connection - Percentage of Strength for a given number of screws

TIMBER - STEEL SCREWED CONNECTION					
TYPE				HBS = HBS + EVO	
DIAMETER				4 mm < D < 8 mm	
Angle	**Splice Thickness**	**Strength Class**	**Service Class**	**MAX**	**MIN**
0°	2 mm	C18	SC1 / SC2	-1.5%	-8.3%
			SC3	-17.9%	-23.6%
		C20	SC1 / SC2	0.0%	
			SC3	-16.7%	
		C24	SC1 / SC2	16.7%	3.3%
			SC3	-2.8%	-13.9%
		C35	SC1 / SC2	75.0%	11.1%
			SC3	45.8%	-7.4%
	3 mm	C18	SC1 / SC2	8.9%	-9.9%
			SC3	-9.2%	-24.9%
		C20	SC1 / SC2	12.7%	-1.5%
			SC3	-6.1%	-17.9%
		C24	SC1 / SC2	20.3%	9.2%
			SC3	0.3%	-9.0%
		C35	SC1 / SC2	72.4%	9.2%
			SC3	43.7%	-9.0%
	5 mm	C18	SC1 / SC2	30.3%	-13.1%
			SC3	8.5%	-27.6%
		C20	SC1 / SC2	32.5%	-4.4%
			SC3	10.4%	-20.3%
		C24	SC1 / SC2	36.8%	5.4%
			SC3	14.0%	-12.2%
		C35	SC1 / SC2	68.3%	5.4%
			SC3	40.2%	-12.2%
	10 mm	C18	SC1 / SC2	29.3%	-21.0%
			SC3	7.7%	-34.1%
		C20	SC1 / SC2	36.9%	-11.8%
			SC3	14.1%	-26.5%
		C24	SC1 / SC2	52.1%	-4.2%
			SC3	26.8%	-20.2%
		C35	SC1 / SC2	68.3%	-4.2%
			SC3	40.3%	-20.2%
45° 90°	2 mm 3 mm 5 mm 10 mm	C18	SC1 / SC2	68.0%	-58.4%
			SC3	40.0%	-65.3%
		C20	SC1 / SC2	70.9%	-55.9%
			SC3	42.4%	-63.2%
		C24	SC1 / SC2	82.5%	-50.8%
			SC3	52.0%	-59.0%
		C35	SC1 / SC2	173.7%	-31.6%
			SC3	128.1%	-43.0%

5.2.5. Bolted Connection

Figure 5.15 compares the strength values achieved by the different bolt types in a timber – steel bolted connection with two steel plate of 2 mm.

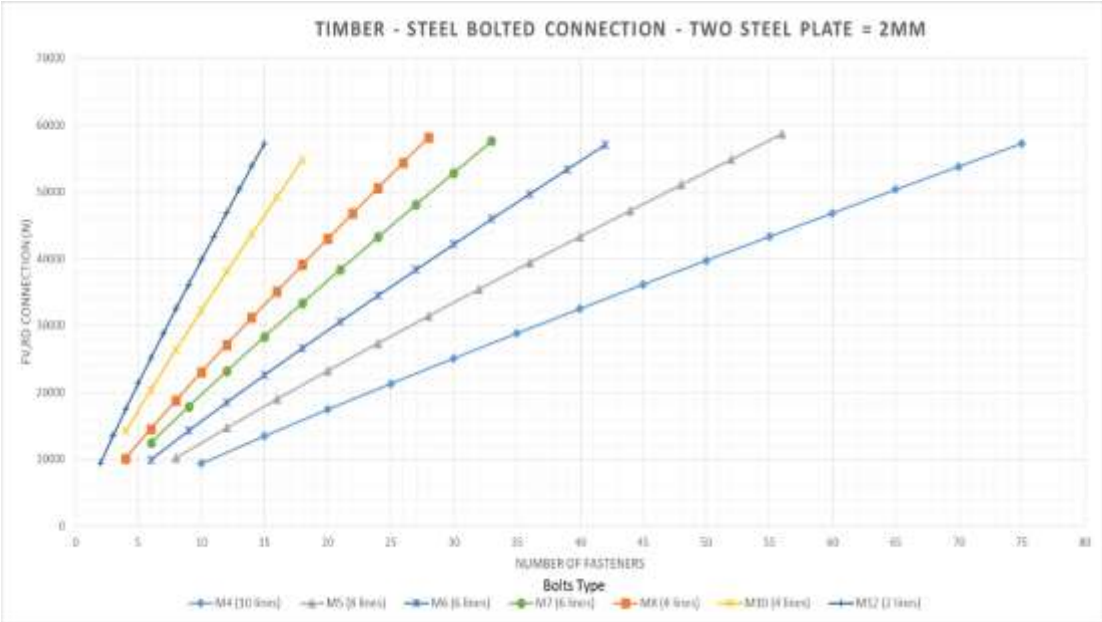

Figure 5.15 Timber - Steel Bolted Connection / Two Steel Plate = 2 mm

The block shear due to number of lines does not appear in this type of connection. The minimum strength values are between 10000 N to 58000 N using around of 10 to 75 fasteners given by the bolts M4 (10 lines)

The bolt M12 (2 lines) achieve the maximum strength values with the least number of fasteners. The strength values are between 9000 N to 58000 N using around 4 to 35 fasteners. The timber – steel bolted connection achieve strength values between 9000 to 58000 N using around 4 to 75 fasteners.

In Figure 5.16, the strength values of different bolts types in a timber – steel bolted connection with one steel plate of 2 mm is compared.

The bolt M4 (5 lines) achieves the minimum strength value. The strength is between 5000 N to 56000 N using around of 10 to 155 fasteners.

The bolt M12 (1 line) achieves the maximum strength values with the least number of fasteners. The strength is between 4000 N to 55000 N using around of 2 to 32 fasteners.

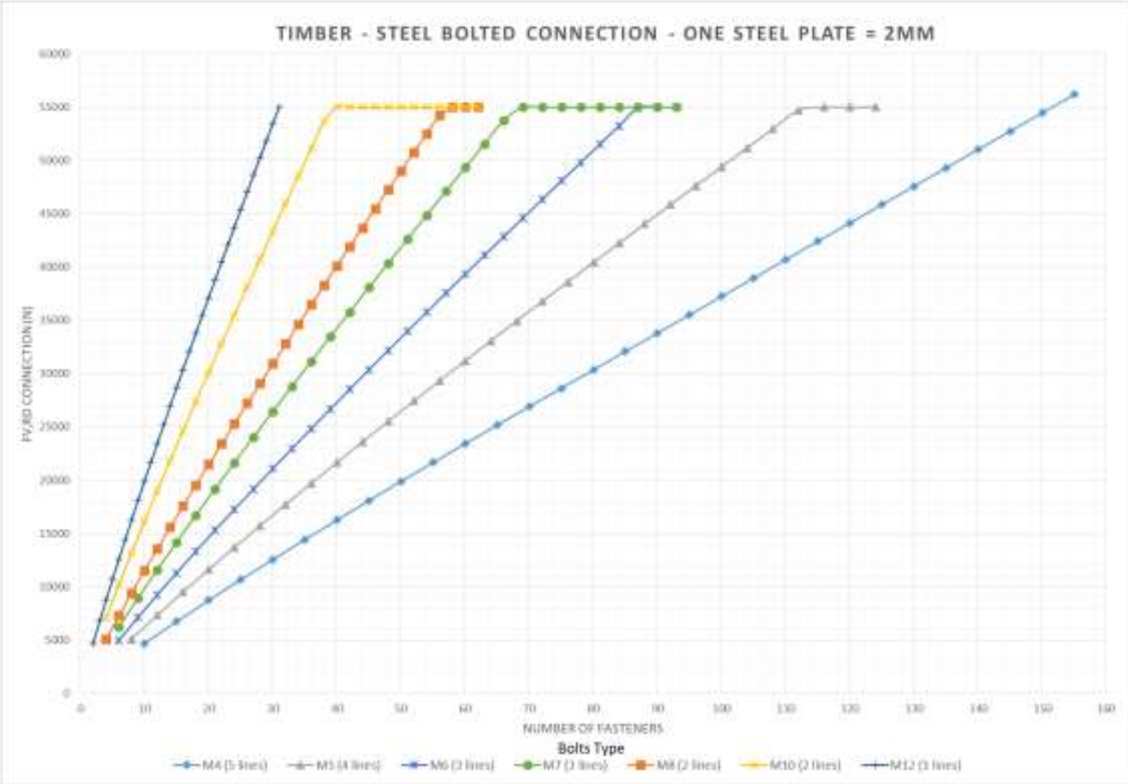

Figure 5.16 Timber - Steel Bolted Connection / One Steel Plate = 2 mm

The block shear failure due to the number of lines is presented in all fasteners except in the M4 and M12. This failure appears when the number of fasteners is between 40 to 110 bolts achieving the maximum strength of 55000 N.

The Table 5.6 indicates the percentages of strength with respect with the values of the Figure 5.15 and Figure 5.16 for the different variables taken into account in this study.

The diameters smaller than 7 mm reach higher strength percentages because they use a greater number of lines. The strength does not depend on the diameter or the penetration length because all the fasteners work in double shear and have the same penetration length.

When is applied a force with an angle between 45° and 90°, the range between the maximum and minimum strength percentages increases notably due the block shear failure, which it due to the number of lines and the strength values keep constant and that generates the increase between the percentages.

When the angle is 90° the Eurocode 5 specify that the effective number is equal to the number of fasteners on the connection. Therefore, the values of maximum percentages are greater than use a angle of 45°.

Table 5.6 Timber - Steel Bolted Connection - Percentage of Strength for a given number of bolts

TIMBER - STEEL BOLTED CONNECTION							
DIAMETER				4 mm ≤ D ≤ 7 mm		D > 7 mm	
Angle	Splice Thickness	Strength Class	Service Class	MAX	MIN	MAX	MIN
0°	2 mm	C18	SC1 / SC2	-1.4%	-1.6%	-1.5%	-1.7%
			SC3	-17.8%	-18.0%	-17.9%	-18.0%
		C20	SC1 / SC2	0.0%		0.0%	
			SC3	-16.7%		-16.7%	
		C24	SC1 / SC2	3.1%	2.9%	3.1%	2.8%
			SC3	-14.1%	-14.2%	-14.1%	-14.3%
		C35	SC1 / SC2	10.2%	10.0%	10.2%	10.0%
			SC3	-8.2%	-8.3%	-8.2%	-8.4%
	3 mm	C18	SC1 / SC2	18.8%	12.6%	11.2%	7.9%
			SC3	-1.0%	-6.2%	-7.3%	-10.1%
		C20	SC1 / SC2	20.7%	14.4%	13.1%	9.5%
			SC3	0.6%	-4.7%	-5.8%	-8.7%
		C24	SC1 / SC2	24.4%	17.7%	16.4%	12.9%
			SC3	3.6%	-1.9%	-3.0%	-5.9%
		C35	SC1 / SC2	32.9%	25.8%	24.5%	20.7%
			SC3	10.7%	4.9%	3.8%	0.6%
	5 mm	C18	SC1 / SC2	51.8%	13.7%	36.9%	26.7%
			SC3	26.5%	-5.2%	14.1%	5.6%
		C20	SC1 / SC2	54.2%	20.4%	39.2%	28.6%
			SC3	28.5%	0.4%	16.0%	7.2%
		C24	SC1 / SC2	58.9%	32.2%	43.3%	32.6%
			SC3	32.4%	10.2%	19.4%	10.5%
		C35	SC1 / SC2	69.9%	29.8%	53.3%	41.7%
			SC3	41.6%	8.1%	27.7%	18.1%
	10 mm	C18	SC1 / SC2	69.2%	13.7%	76.2%	56.9%
			SC3	41.0%	-5.2%	46.8%	30.7%
		C20	SC1 / SC2	71.9%	20.4%	86.6%	66.1%
			SC3	43.3%	0.4%	55.5%	38.4%
		C24	SC1 / SC2	77.0%	32.2%	93.5%	81.8%
			SC3	47.5%	10.2%	61.3%	51.5%
		C35	SC1 / SC2	89.2%	29.8%	106.9%	82.3%
			SC3	57.6%	8.1%	72.4%	51.9%
45°	2 mm 3 mm 5 mm 10 mm	C18	SC1 / SC2	44.1%	-41.6%	55.5%	-56.7%
			SC3	20.1%	-51.4%	29.6%	-63.9%
		C20	SC1 / SC2	46.3%	-40.8%	58.2%	-56.0%
			SC3	21.9%	-50.6%	31.9%	-63.3%
		C24	SC1 / SC2	50.8%	-39.1%	62.9%	-54.6%
			SC3	25.6%	-49.2%	35.7%	-62.2%
		C35	SC1 / SC2	61.3%	-34.7%	73.9%	-51.6%
			SC3	34.4%	-45.6%	44.9%	-59.6%
90°	2 mm 3 mm 5 mm 10 mm	C18	SC1 / SC2	83.2%	-25.9%	97.0%	-45.2%
			SC3	52.7%	-38.3%	64.2%	-54.4%
		C20	SC1 / SC2	94.1%	-24.8%	100.0%	-44.6%
			SC3	61.8%	-37.4%	66.7%	-53.8%
		C24	SC1 / SC2	99.5%	-22.7%	114.9%	-42.9%
			SC3	66.3%	-35.6%	79.1%	-52.4%
		C35	SC1 / SC2	119.7%	-17.2%	141.0%	-38.9%
			SC3	83.1%	-31.0%	100.9%	-49.0%

5.3. Timber – Central Steel Connection

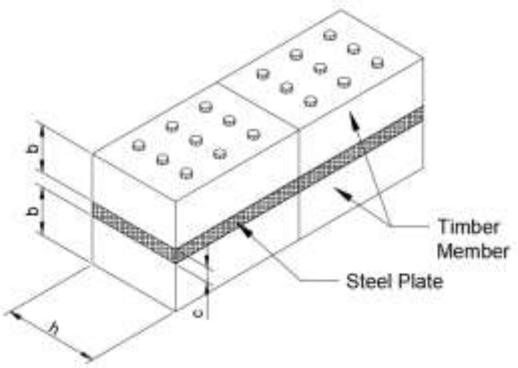

Figure 5.17 Timber - Central Steel Connection

This type of connection has a steel plate S275 in the central part (Figure 5.17) surrounded by two pieces of timber. A single thickness of steel plate is used for two types of fasteners:

- Dowels
- Bolts

The influence of thickness of the steel plate is not take into account because the Johansen's Equations do not make a difference between thick or thin, therefore, they are taken the same value for any thickness of the steel plate.

5.3.1. Influence of Fastener Type

In Figure 5.18 indicates the maximum and minimum strength values achieved by dowels and bolts in a timber – central steel connection.

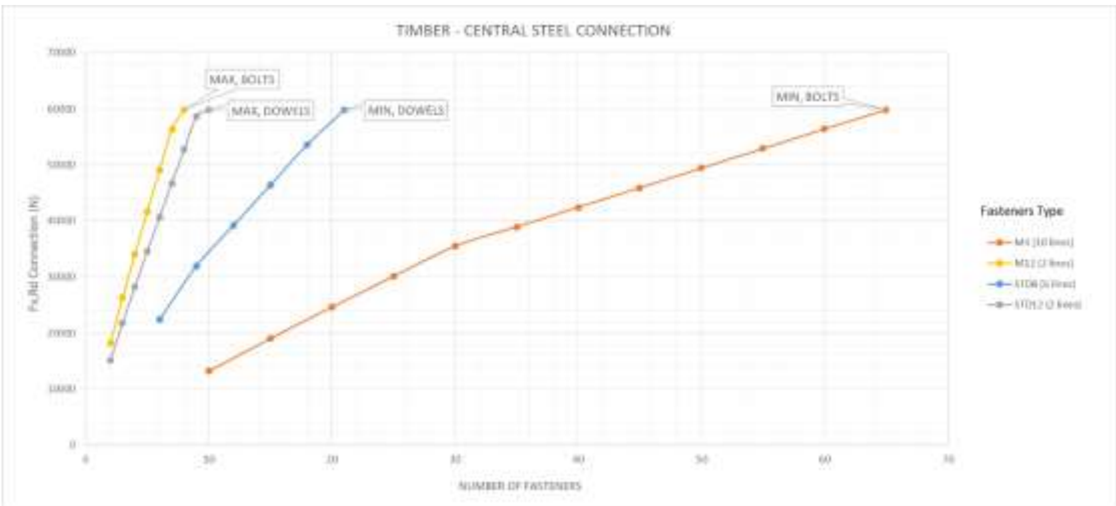

Figure 5.18 Influence of Fastener Type in a Timber – Central Steel Connection

The maximum strength with the least number of fasteners is achieved by bolts M12 (2 lines). The strength values are between 18000 N and 60000 N using around of 2 to 8 fasteners.

The maximum strength with the greatest number of fasteners is achieved by bolts M4 (10 lines). The strength values are between 13000 N and 60000 N using around of 10 to 65 fasteners.

The reason why the bolts have a greater strength values is that they have an additional strength due to withdrawal capacity (Fax, Rk) that take into account 25% of this strength. By other hand, the dowels do not have any withdrawal capacity.

5.3.2. Dowelled Connection

In Figure 5.19 indicates the strength values reached by the different type of dowels in a timber – central steel connection.

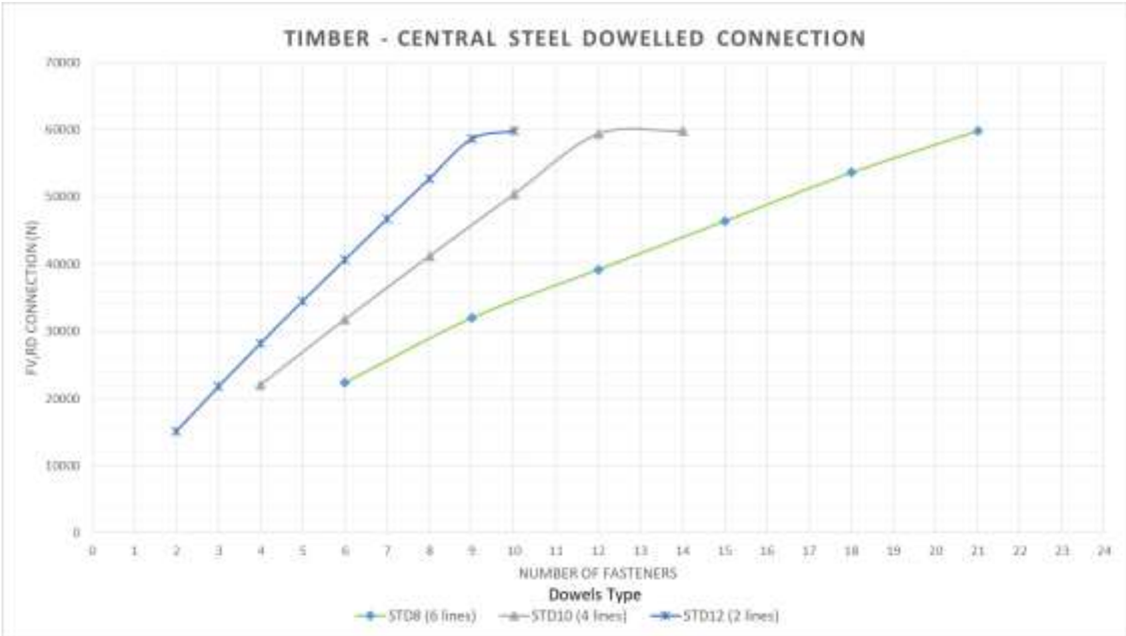

Figure 5.19 Timber - Central Steel Dowelled Connection

The dowel STD12 (2 lines) reaches the maximum strength values with the least number of fasteners. The strength values are between 15000 N and 60000 N using between 2 and 10 fasteners.

The dowel STD8 (6 lines) reaches the maximum strength values with the greatest number of fasteners. The strength values are between 22000 N and 60000 N using between 6 and 21 fasteners.

The Table 5.7 indicates the percentages of strength with respect with the values of the Figure 5.19 for the different variables taken into account in this study.

Table 5.7 Timber – Central Steel Dowelled Connection - Percentage of Strength for a given number of dowels

TIMBER - CENTRAL STEEL DOWELLED CONNECTION								
Diameters			STD8		STD10		STD12	
Angle	Strength Class	Service Class	MAX	MIN	MAX	MIN	MAX	MIN
0°	C18	SC1 / SC2	-1.6%	-5.6%	-1.7%	-	-1.5%	-
		SC3	-18.0%	-21.3%	-18.0%	-	-17.9%	-
	C20	SC1 / SC2	0.0%		0.0%		0.0%	
		SC3	-16.7%		-16.7%		-16.7%	
	C24	SC1 / SC2	11.1%	3.0%	2.8%	-	3.1%	-
		SC3	-8.5%	-14.2%	-14.3%	-	-14.1%	-
	C35	SC1 / SC2	11.1%	10.1%	10.0%	-	10.2%	-
		SC3	-7.4%	-8.2%	-8.4%	-	-8.2%	-
45°	C18	SC1 / SC2	-11.7%	-40.6%	-11.3%	-41.0%	-12.2%	-45.4%
		SC3	-26.4%	-50.5%	-26.1%	-50.9%	-26.8%	-54.5%
	C20	SC1 / SC2	-6.2%	-36.4%	-10.0%	-37.6%	-10.9%	-42.2%
		SC3	-21.8%	-47.0%	-25.0%	-48.0%	-25.7%	-51.8%
	C24	SC1 / SC2	0.1%	-28.7%	-2.8%	-29.4%	-8.1%	-34.0%
		SC3	-16.5%	-40.6%	-19.0%	-41.2%	-23.4%	-45.0%
	C35	SC1 / SC2	14.2%	-1.3%	12.4%	-1.5%	-1.1%	-17.4%
		SC3	-4.8%	-17.8%	-6.3%	-17.9%	-17.6%	-31.1%
90°	C18	SC1 / SC2	-26.4%	-39.2%	-30.8%	-45.4%	13.0%	-0.6%
		SC3	-38.6%	-49.3%	-42.3%	-54.5%	-5.9%	-17.2%
	C20	SC1 / SC2	-23.3%	-35.6%	-28.3%	-44.6%	16.2%	5.2%
		SC3	-36.1%	-46.4%	-40.3%	-53.8%	-3.1%	-12.3%
	C24	SC1 / SC2	-19.0%	-28.5%	-26.2%	-42.9%	24.2%	13.3%
		SC3	-32.5%	-40.4%	-38.5%	-52.4%	3.5%	-5.6%
	C35	SC1 / SC2	-14.7%	-28.5%	-21.0%	-38.9%	30.0%	15.3%
		SC3	-29.0%	-40.4%	-34.1%	-49.0%	8.3%	-3.9%

The dowel STD8 (6 lines) when an angle of 0 is applied presents a range of strength percentages. This is because it has a block shear failure due to the number of lines and in a certain number of fasteners the strength remains constant, so it generates a range between maximum and minimum. On the other hand, the dowels STD10 (4 lines) and STD12 (2 lines) the increase or decrease of percentage strength is equal by any number of fasteners.

The use of an angle of 90°, it result low strength capacity. Therefore, as long as the angle is less than 90°, the strength capacity is increased.

The application of an angle of 45° can generate a high range between the minimum and maximum values. It could be caused by the block shear failure because the values do not increase in a constant way.

5.3.3. Bolted Connection

Figure 5.20 compares the strength values achieved by the different type of bolts in a timber – central steel connection.

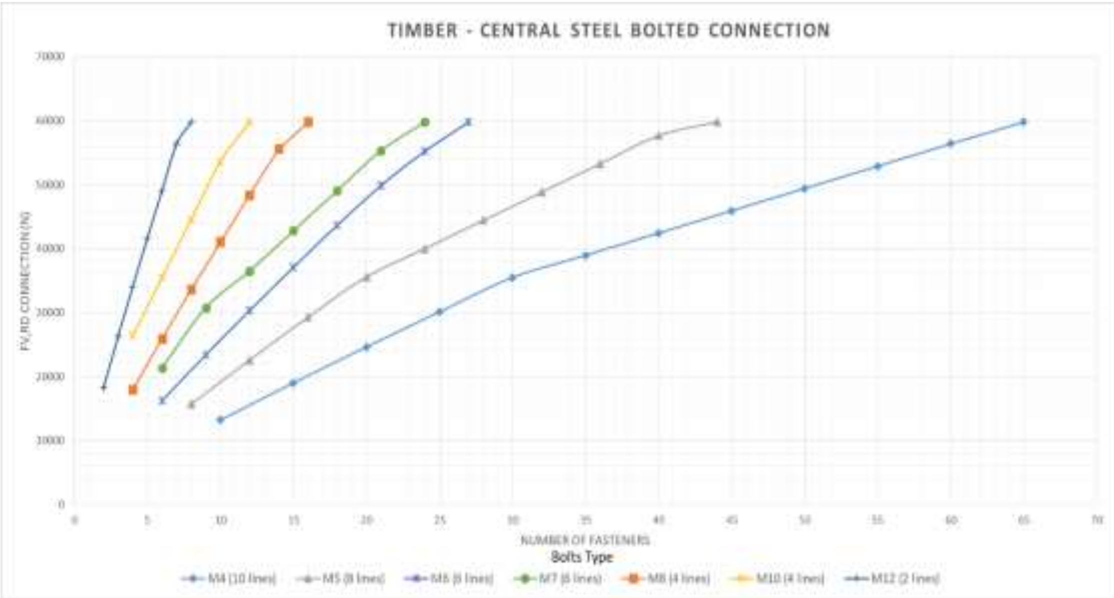

Figure 5.20 Timber - Central Steel Bolted Connection

The bolt M12 (2 lines) reaches the maximum strength values with the least number of fasteners. The strength values are between 18000 N and 60000 N using between 2 and 8 fasteners.

The dowel M4 (10 lines) reaches the maximum strength values with the greatest number of fasteners. The strength values are between 13000 N and 60000 N using between 10 and 65 fasteners.

The Table 5.8 indicates the percentages of strength with respect with the values of the Figure 5.20 for the different variables taken into account in this study.

In the application of a force with an angle of 0°, the percentages of strength are similar for diameters greater than 4 mm. However, when the angle increase, the use of diameters greater than 7 mm have a lower strength capacity than the use of smaller diameters.

The use an angle of 90° in a bolted connection can achieve higher strength values because the number effective is equal to the number of fasteners on the connection.

Table 5.8 Timber - Central Steel Bolted Connection - Percentage of Strength for a given number of bolts

TIMBER - CENTRAL STEEL BOLTED CONNECTION						
DIAMETER			4 mm ≤ D ≤ 7 mm		D > 7 mm	
Angle	Strength Class	Service Class	MAX	MIN	MAX	MIN
0°	C18	SC1 / SC2	-1.4%	-5.6%	-1.6%	-5.6%
		SC3	-17.8%	-21.3%	-18.0%	-21.3%
	C20	SC1 / SC2	0.0%		0.0%	
		SC3	-16.7%		-16.7%	
	C24	SC1 / SC2	11.1%	2.9%	11.1%	3.0%
		SC3	-7.4%	-14.2%	-7.4%	-14.2%
	C35	SC1 / SC2	25.3%	10.0%	18.9%	10.1%
		SC3	4.4%	-8.3%	-1.0%	-8.3%
45°	C18	SC1 / SC2	-11.3%	-57.4%	-12.8%	-74.6%
		SC3	-26.1%	-64.5%	-27.4%	-78.8%
	C20	SC1 / SC2	-6.2%	-54.5%	-11.3%	-73.1%
		SC3	-21.8%	-62.1%	-26.1%	-77.6%
	C24	SC1 / SC2	0.1%	-46.9%	-8.7%	-70.1%
		SC3	-16.5%	-55.8%	-23.9%	-75.1%
	C35	SC1 / SC2	14.2%	-36.4%	-2.5%	-70.1%
		SC3	-4.8%	-47.0%	-18.7%	-75.1%
90°	C18	SC1 / SC2	21.0%	-25.9%	10.5%	-25.1%
		SC3	0.9%	-38.3%	-8.0%	-37.6%
	C20	SC1 / SC2	22.7%	-24.8%	12.1%	-23.8%
		SC3	2.3%	-37.4%	-6.6%	-36.5%
	C24	SC1 / SC2	29.2%	-22.7%	20.5%	-21.6%
		SC3	7.6%	-35.6%	0.4%	-34.7%
	C35	SC1 / SC2	47.9%	-17.2%	28.6%	-16.1%
		SC3	25.6%	-31.0%	7.2%	-30.1%

5.4. Mortise and Tenon Connection

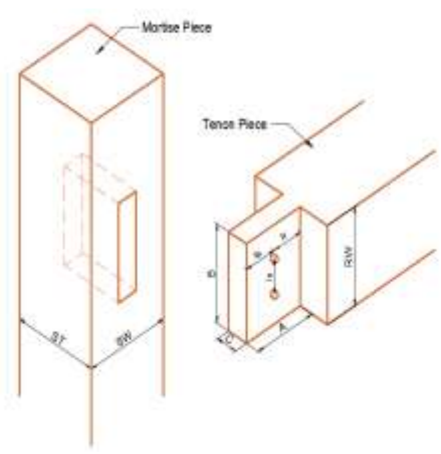

Figure 5.21 Mortise and Tenon Connection

This type of connection uses wooden dowels or also called pegs (Figure 5.21), with diameters from ¾ inches to 1 ¼ inches. The wood class of the fasteners considered in this work are:

- Beech,
- Douglas fir
- Red oak.

5.4.1. Influence of Fastener Type

In figure 5.22 indicates the strength values achieved by the wooden dowels and metal dowels. The first one are used in a mortise and tenon connection. The second one are used in a timber – timber connection where the main timber member is applied a force with an angle of 0° and the splice piece with an angle of 90°. The reason why is applied two different angle is to compare in the similar way in which the mortise and tenon works.

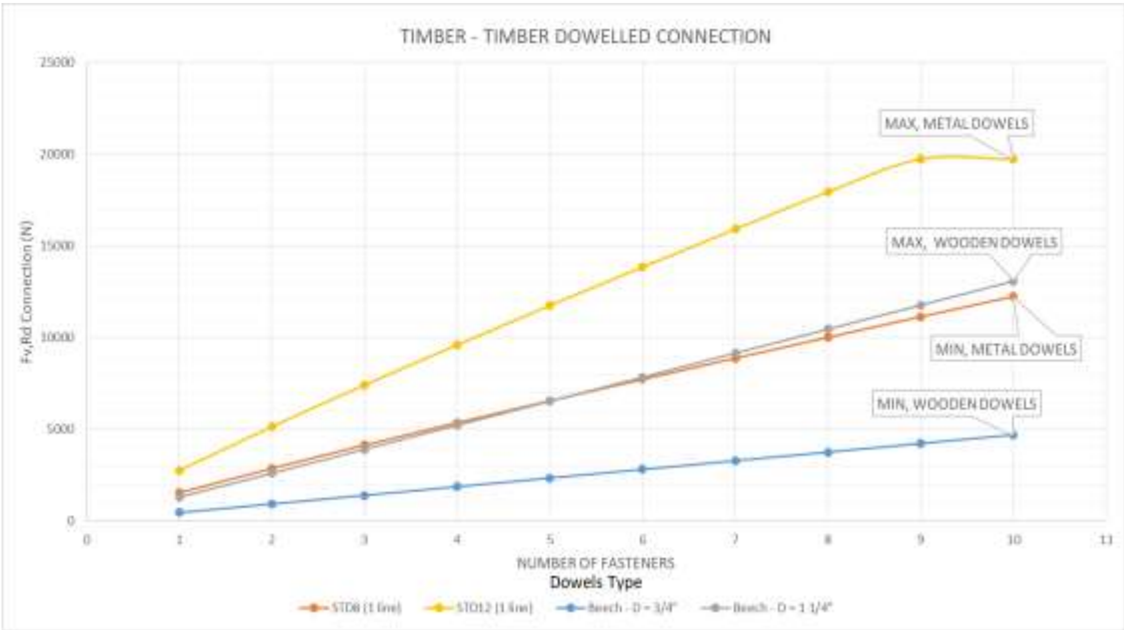

Figure 5.22 Influence of Type of Fastener in a Timber – Timber Dowelled Connection (Mortise and Tenon Connection)

The dowel STD12 (1 lines) reaches the maximum strength values with the least number of fasteners. The strength values are between 2700 N and 20000 N using between 1 and 9 fasteners.

The wooden dowel Beech – D = ¾” reaches the minimum strength values with the greatest number of fasteners. The strength values are between 471 N and 5000 N using between 1 and 10 fasteners.

Despite the metal dowels can reach greater strength values than wooden dowels. The advantage of use a mortise and tenon connection is the durability of it. Avoid the corrosion in the connection can guarantee that the strength capacity is kept during the useful life of the connection.

5.4.2. Influence of Wooden Dowel Timber Type

Figure 5.23 compares the strength values achieved by the different types of wooden dowel in a mortise and tenon connection.

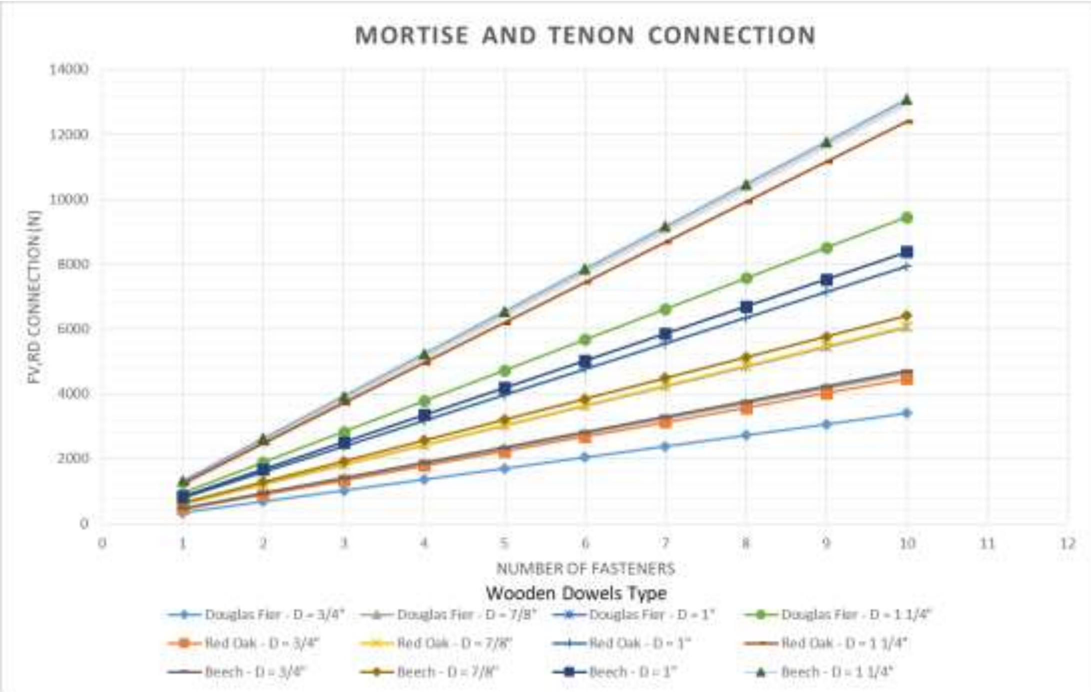

Figure 5.23 Influence of Wooden Dowel Type on Mortise and Tenon Connection

The wooden dowel Beech – D = 1 ¼" reaches the maximum strength values. The strength values are between 1300 N and 13000 N using between 1 and 10 fasteners. The values between Beech and Red Oak there is not a big difference.

The wooden dowel Douglas Fier – D = ¾" reaches the minimum strength values. The strength values are between 340 N and 3400 N using between 1 and 10 fasteners.

The Table 5.9 indicates the percentages of strength regard with the values of the Figure 5.23 taking into account the different strength class used in the mortise and tenon members.

The use of a higher strength class results in an increase of strength. The percentages are equal for all diameters because the increase of strength is constant and do not present any type of failure that decrease the strength.

The use of wooden dowel with high values of specify density can reach higher strength values. In the same way, the use of large diameters can reach higher capacity strength.

Table 5.9 Mortise and Tenon Connection - Percentage of Strength for a given number of wooden dowels

MORTISE AND TENON CONNECTION		
Wooden Dowels	**Strength Class**	**Diameter 3/4" - 1 1/4"**
Douglas Fier	C18	-2.4%
	C20	0.0%
	C24	4.7%
	C35	16.1%
Red Oak	C18	28.0%
	C20	31.1%
	C24	37.3%
	C35	52.2%
Beech	C18	35.0%
	C20	38.4%
	C24	44.9%
	C35	60.6%

6. Conclusions and future developments

The present work of investigation was done to research the influence of various parameters on the strength capacity of the connections in the wooden structures with dowel type fasteners. The analysis focused on the variation of strength with regard to the number of fasteners involved in the connection for four groups of connections taking into account different characteristics and conditions. The calculations were based on a cross section of 100 mm by 100 mm that was chosen for the main timber member for all connections.

The first conclusion is that among the four groups those that presented the highest strength capacity with the lowest number of fasteners is Timber - Central Steel Connection. In addition, it is a type of connection that improves aesthetics because the steel plate is hidden in the timber member, which is also benefit for fire protection. The large plate thicknesses are not required because there is no relationship whit his thickness in the Johansen's Equations, and the strength values with respect to the thickness variable are not altered.

The Timber - Timber Connection group has the peculiarity that the thickness of the splice piece and the penetration length of the fastener influences the strength capacity of the connection. The nailed connection achieves its maximum capacity of strength until a certain thickness of splice piece (30 mm and 50 mm) because the penetration length is enough to reach the maximum capacity of each fastener. However, when the thickness is too large (70 mm), the strength values decrease and the maximum strength is not reached. The screwed and bolted connection regardless of the thickness of the splice piece is achieved the maximum capacity of each connection. The screws, although they work in single shear as the nails, they can reach higher strength values because their threated length improves their strength capacity.

In the Timber - Steel Connection group, there is a common failure in steel plates and it is the block shear. This failure occurs due to the shear force generated by the fasteners in the steel plate. The block shear is presented in nailed and screwed connection, which causes its strength values to remain constants and does not increase while increasing the number of fasteners.

The block shear depends mainly by two factors: the number of lines and the number of fasteners. If the block shear appears due to number of lines, the strength values keep constants and the strength connection is lower than the block shear due to the number of fasteners.

Another factor that influences the presence of the block shear is the angle of application of the force because the angle is related with the minimum spacings. Hence the angle increases the minimum spacing, and the spacing increase the area affected by the block shear.

In the Timber - Central Steel Connection group, the bolts reach the values of greater strength. The reason why the bolts have a greater strength values is that they have an additional strength due to withdrawal capacity (Fax, Rk) that take into account 25% of this strength. By other hand, the dowels do not have any withdrawal capacity.

In the Mortise and Tenon Connection group, which uses wooden dowels, its strength values depend a lot on the type of timber of the wooden dowels (specify density). The maximum strength reached is by beech dowels. The disadvantage of using wooden dowels is that the equations are applied to a specific group of materials that were tested in laboratories and that must follow certain requirements.

Despite of metal dowels can reaches greater strength values than wooden dowels. The advantage of use a mortise and tenon connection is the durability of it. Avoid the corrosion in the connection can guarantee that the strength capacity is kept during the useful life of the connection.

The use of one or two splice piece was also taken into account. The strength values obtained when using two splice piece is almost double the values obtained with one splice piece in the Timber - Timber Steel Connection group. However, in the Timber - Steel Connection group the values are different mainly due to the block shear failure.

Tables were obtained for each type of connection that indicated percentages of increase or decrease in strength with respect to the values of the main connection. These percentages vary according to the variables that were taken into account for the analysis in this study. The resistance increased according to these factors:

- Superior strength class
- Service class minor

- Splice piece minor
- Angle of force equal to 0°
- Larger diameters
- Larger penetration lengths
- Double shear

This dissertation carried out an analysis on the connections strength in wooden structures with different types of fasteners subjected to different characteristics and conditions, leaving, some points to be determined and that a deeper analysis must be made. As a complement to the work carried out, the following suggestions for future developments are described:

- Carry out an analysis on how the dimension of the main timber member intervened in the strength capacity;
- Determine how the block shear is presented and the factors that intervene to avoid this type of failure to obtain a more efficient connection;
- Analysis of the number of lines of fasteners that are placed in the connection. This factor can greatly influence the resistance of the connection and depends mainly on the minimum spacing required according to the characteristics of each type of fastener;
- Analysis of materials and geometries influence the design of moment resisting connections;
- Experimental evaluation of the strength capacity of wooden dowel connections.

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