Master's thesis

NTNU
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Department of Structural Engineering

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Review of the new rules for connections on Eurocode 5 - Part 1-1

Master's thesis in Structural Engineering
Supervisor: Haris Stamatopoulos
June 2023

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ACCESSIBILITY

OPEN

MASTER THESIS 2023

SUBJECT AREA:	DATE:	NO. OF PAGES:
Timber Structures	11.06.2023	183

TITLE:

Review of the new rules for connections on Eurocode 5 – Part 1-1

Gjennomgang av de nye reglene for forbindelser på Eurokode 5 – Del 1-1

BY:

Biniam Tsegai Haile

SUMMARY:
"CEN/TC 250/SC 5 N 1650: prEN 1995-1-1_FOR ENQ (working draft to CIB)", which is referred to as New Eurocode 5 in this thesis, is a revised Eurocode 5 draft created by the European Committee for Standardization (CEN) as a further development of the Eurocode 5 – Part 1-1 to achieve a further improvement of design rules for timber structures in Europe. The "Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings" (EN 1995-1-1), which is referred to as Present Eurocode 5 in this thesis, is nowadays implemented and applied for the design of timber structures in all European countries. One of the most important and most difficult aspects of the design of timber structures is the design of timber connections. This thesis is aimed at reviewing the design rules for connections in timber structures on the New Eurocode 5 and comparing them to the Present Eurocode 5. A comparison study is performed, and example cases are also included in the comparison. The changes or differences between the design rules for connections in timber structures on the New Eurocode 5 and the Present Eurocode 5 are explored and highlighted in this thesis and one of them is given below.

For the determination of the characteristic value of the dowel-effect contribution of a fastener, the New Eurocode 5 provides the same set of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is treated as a member in steel-to-timber connections. The Present Eurocode 5 provides different sets of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is not treated as a member in steel-to-timber connections. For connections with more than two shear planes, four compatible failure mode combinations (A), (B), (C) and (D) are given by the New Eurocode 5, but the compatibility between failure modes must be checked according to the Present Eurocode 5.

RESPONSIBLE TEACHER: Associate Professor Haris Stamatopoulos

SUPERVISOR: Associate Professor Haris Stamatopoulos

CARRIED OUT AT: Department of Structural Engineering

Abstract

"CEN/TC 250/SC 5 N 1650: prEN 1995-1-1_FOR ENQ (working draft to CIB)", which is referred to as New Eurocode 5 in this thesis, is a revised Eurocode 5 draft created by the European Committee for Standardization (CEN) as a further development of the Eurocode 5 – Part 1-1 to achieve a further improvement of design rules for timber structures in Europe. The "Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings" (EN 1995-1-1), which is referred to as Present Eurocode 5 in this thesis, is nowadays implemented and applied for the design of timber structures in all European countries. The aim of this thesis is to review and explore the design rules for connections in timber structures on the New Eurocode 5 and comparing them to the Present Eurocode 5. A comparison study is performed, and example cases are also included in the comparison. The changes or differences between the design rules for connections in timber structures on the New Eurocode 5 and the Present Eurocode 5 are explored and highlighted in this thesis and some of them are as follows:

- For the determination of the characteristic value of the dowel-effect contribution (Johansen's part) of a fastener, the New Eurocode 5 provides the same set of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is treated as a member in steel-to-timber connections. The Present Eurocode 5 provides different sets of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is not treated as a member in steel-to-timber connections. For connections with more than two shear planes, four compatible failure mode combinations (A), (B), (C) and (D) are given by the New Eurocode 5, but the compatibility between the failure modes must be checked according to the Present Eurocode 5.

- When determining the characteristic withdrawal capacity of connections with axially loaded screws and rods with wood screw thread, the range of diameters is changed from 6 mm $\leq d \leq$ 12 mm to 3.5 mm $\leq d \leq$ 22 mm and the minimum withdrawal length is also changed from $6d$ to $5d$ in the New Eurocode 5.

- In the New Eurocode 5, the design splitting capacity of a connection with fasteners loaded perpendicular to the grain must be equal to the sum of the values of the two shear forces on the sides of the connection and does not depend on the position of the connection along the beam length. In the Present Eurocode 5, it must be equal to or greater than the maximum of the shear force values on the sides of the connection and depends on the position of the connection along the beam length.

- The New Eurocode 5 give provisions for the compression (buckling) resistance of a connection with axially loaded screws and rods with wood screw thread, but the Present Eurocode 5 does not.

- For laterally loaded metal dowel-type fasteners and shear connectors, the expressions provided by the New Eurocode 5 for determining the minimum values of spacing and end and edge distances do not include the load to grain angle α, but the load to grain angle α is included in the Present Eurocode 5.

Sammendrag

"CEN/TC 250/SC 5 N 1650: prEN 1995-1-1_FOR ENQ (working draft to CIB)", som refereres til som ny Eurokode 5 i denne oppgaven, er et revidert Eurokode 5-utkast utviklet av Den europeiske standardiseringskomiteen (CEN) som en videreutvikling av Eurokode 5 – Del 1-1 for å oppnå en ytterligere forbedring av dimensjoneringsregler for trekonstruksjoner i Europa. " Eurokode 5: Prosjektering av trekonstruksjoner - Del 1-1: Allmenne regler og regler for bygninger" (EN 1995-1-1), som refereres til som nåværende Eurokode 5 i denne oppgaven, er nå for tiden implementert og anvendt for prosjektering av trekonstruksjoner i alle europeiske land. Målet med denne oppgaven er å gjennomgå og utforske dimensjoneringsreglene for forbindelser i trekonstruksjoner på den nye Eurokode 5 og sammenligne dem med den nåværende Eurokode 5. En sammenligningsstudie er utført, og eksempeltilfeller er også inkludert i sammenligningen. Endringene eller forskjellene mellom dimensjoneringsreglene for forbindelser i trekonstruksjoner på den nye Eurokode 5 og den nåværende Eurokode 5 er utforsket og gitt i denne oppgaven, og noen av dem er som følger:

- For å bestemme den karakteristiske verdien av bidraget fra såkalte dybeleffekten (Johansens del) av en forbinder gir den nye Eurokode 5 samme sett av bruddformer for tre-mot-tre - og stål-mot-tre forbindelser, og stålplaten behandles som et element i stål-mot-tre forbindelser. Den nåværende Eurokode 5 gir forskjellige sett av bruddformer for tre-mot-tre - og stål-mot-tre forbindelser, og stålplaten behandles ikke som et element i stål-mot-tre forbindelser. For forbindelser med mer enn to skjærplan er fire kompatible bruddformskombinasjoner (A), (B), (C) og (D) gitt av den nye Eurokode 5, men kompatibiliteten mellom bruddformene må kontrolleres i henhold til den nåværende Eurokode 5.

- Ved bestemmelse av den karakteristiske uttrekkskapasiteten for forbindelser med aksialt belastede skruer og gjengestenger endres diameterområdet fra 6 mm $\leq d \leq$ 12 mm til 3.5 mm $\leq d \leq$ 22 mm, og den minste inntrengningsdybden endres også fra 6*d* til 5*d* i den nye Eurokode 5.

- I den nye Eurokode 5 må den dimensjonerende splittingskapasiteten av en forbindelse med forbindere belastet vinkelrett på fiberretningen være lik summen av verdiene av de to skjærkreftene på sidene av forbindelsen og den er ikke avhengig av posisjonen til forbindelsen langs bjelkelengden. I den nåværende Eurokode 5 må den være lik eller større enn den maksimum av de skjærkraftverdiene på sidene av forbindelsen og den er avhengig av posisjonen til forbindelsen langs bjelkelengden.

- Den nye Eurokode 5 gir regler for kompresjonskapasiteten (knekking) av en forbindelse med aksialt belastede skruer og gjengestenger, men den nåværende Eurokode 5 gjør det ikke.

- For tverrbelastede stavformede metall forbindere og tømmerforbindere inkluderer uttrykkene gitt av den nye Eurokode 5 for å bestemme minimumsverdiene for innbyrdes avstand og ende- og kantavstander ikke vinkelen α mellom kraft- og fiberretning, men vinkelen α er inkludert i den nåværende Eurokode 5.

Preface

This thesis was written in the spring of 2023 in the course "TKT4950 – Structural Engineering, master's thesis" at the Department of Structural Engineering as the final part of the two-year master's degree program in "Civil and Environmental Engineering" at the Norwegian University of Science and Technology, NTNU. This thesis is aimed at reviewing and exploring the design rules for connections in timber structures on a draft of revised Eurocode 5 - Part 1-1.

I want to thank my supervisor, Associate Professor Haris Stamatopoulos, for valuable discussions and guidance throughout this semester. I would also like to thank Associate Professor Francesco Mirko Massaro for participating in interesting meetings and contributing fruitful comments.

Trondheim, June 2023

Biniam Tsegai Haile

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Table of Contents

List of figures

List of tables

Abbreviations

CEN	European Committee for Standardization
CIB	International Council for Research and Innovation in Building and Construction
CLT	Cross Laminated Timber
EFTA	European Free Trade Association
GL	Glued Laminated Timber or Glued Lumber
GST	Glued Solid/Structural Timber
GVL	Glued Laminated Veneer Lumber
LVL	Laminated Veneer Lumber
LVL-P	Laminated Veneer Lumber with Parallel Veneers
NA	National Annex
NDP	National Determined Parameter
NSB	National Standardization Body
PL	Parallel Laminated Timber
PMPF	Punched Metal Plate Fastener
PT	Project Team
SC	Subcommittee
SL	Structural Lumber
SLS	Serviceability Limit State
ST	Solid/Structural Timber
TC	Technical Committee
ULS	Ultimate Limit State
WG	Working Group

1 Introduction

1.1 Motivation and problem statement

A revised Eurocode 5 draft named as "CEN/TC 250/SC 5 N 1650: prEN 1995-1-1_FOR ENQ (working draft to CIB)", which is hereafter referred to as New Eurocode 5 [1], is created by the European Committee for Standardization as a further development of the Eurocode 5 - Part 1-1 to achieve a further improvement of design rules for timber structures in Europe. The "Eurocode 5: Design of timber structures - Part 1-1: General – Common rules and rules for buildings" (EN 1995-1-1), which is hereafter referred to as Present Eurocode 5 [2], is nowadays implemented and applied for the design of timber structures in all European countries. The chapter of connections takes up a large part of the Present Eurocode 5. One of the most important and most challenging aspects of the design of timber structures is the design of timber connections. Thus, the design rules for timber connections should be more user-friendly. What are the changes or differences between the design rules for connections in timber structures on the New Eurocode 5 and the Present Eurocode 5 and how do they influence the design of timber connections? To answer this question, a comparison study is performed on the design rules for connections in timber structures provided by the New Eurocode 5 and the Present Eurocode 5. Worked example cases are also included in the comparison. The types of timber considered in this thesis are solid/structural timber (ST), glued structural timber (GST) and glued laminated timber (GLT) to make the comparison simple and efficient.

1.2 Introduction to Eurocode 5

Eurocode 5 (EN 1995) has Part 1-1: General - Common rules and rules for buildings (EN 1995-1-1), Part 1-2: General - Structural fire design (EN 1995-1-2) and Part 2: Bridges (EN 1995-2). The International Council for Research and Innovation in Building and Construction, Working Commission W18 Timber Structures (CIB-W18), began drafting of design code for timber structures in 1973 using the National standards as the basis of discussion. The first CIB-Structural Timber Design Code was published in 1983 [3]. The CIB-Structural Timber Design Code (CIB, 1983) was the basis for the proposed Eurocode 5 [3]. A report of the European Commission, which was the predecessor to Eurocode 5, was published in 1987 and had a commenting period open for national comments until April 1989 [4]. The European Committee for Standardization (CEN) had received the work on the Eurocode 5 in 1990 [3]. The first version of Eurocode 5 was published in 1993 in the form of a prestandard ENV 1995-1-1 (ENV stands for EuroNorm Vornorm) [3]. This version was the basis for the final version of EN 1995-1-1:2004 which was published in 2004. For some European countries, it was the first ever code for timber structures [3].

National Determined Parameters (NDP) are provided by the Eurocodes to make future adjustments on the national level [5]. The National Standardization Body (NSB) is responsible for the NDP’s to be published in National Annexes (NA) to the national editions of the Eurocodes [5].

The European Commission asked CEN to develop a detailed work program for the preparation of the second generation of Eurocodes through the Mandate M/515 in December 2012 [5]. One of the demands, which were asked by the Mandate, was the "Refinement to improve the 'ease of use' of Eurocodes by practical users" [6]. In May 2013 the CEN responded to the European Commission with a work program as "Response to Mandate M/515" [7]. The CEN/TC 250 document called "Position paper on enhancing ease of use of the Structural Eurocode" [8] provides a clear definition to whom the Eurocodes are addressed [5], which are "Competent civil, structural and geotechnical engineers, typically qualified professionals able to work independently in relevant fields" [8]. The CEN/TC 250 document is intended to make the Eurocodes more user-friendly by setting principles to improve harmonization between the Eurocodes [5]. One of the principles in the CEN/TC 250 document [8] is avoiding basic changes to the approach to design and to the structure of the Eurocodes [5].

1.3 Eurocode 5 standardization committee

The European Committee for Standardization, in short CEN (Comité Européen de Normalisation), which is officially recognized by the European Union and the European Free Trade Association (EFTA), is responsible for developing and defining standards at European level [5]. There are several technical committees (TC) in charge of different subjects inside the CEN [5]. The technical committee CEN/TC 250 is dealing with developing and defining the design rules of civil engineering structures and common buildings [5]. CEN/TC 250 is divided into different subcommittees (SC) representing the existing Eurocodes [5]. The number of the subcommittee is the number of the represented Eurocode for instance Eurocode 5 is represented by SC 5 [5]. Each subcommittee has different supporting working groups (WG) intended to divide the work into specific subjects and the work for the next generation of Eurocode 5 is classified into ten WG's [5]. Table 1 shows the ten WG's with their specific subjects in CEN/TC 250/SC 5. Project Teams (PT's), which are groups of experts from different countries, are responsible for the writing process of the new standards and each Project Team (PT) has five members and one leader [5]. WG's and PT's work closely to get good outcome [5]. After working with the SC 5/WG's, the PT's write the Eurocode draft and sends the draft to the CEN/TC 250/SC 5 to be reviewed and then accepted [5]. The CEN/TC 250/SC 5 then sends the accepted draft to the CEN/TC 250 to take the final decision to accept the new Eurocode in compliance with all other Eurocodes [5].

Table 1: Ten working groups of CEN/TC 250/SC 5 with their respective subjects [5].

CEN/TC 250/SC 5	
WG 1	Cross Laminated Timber (CLT)
WG 2	Timber Concrete Composites (TCC)
WG 3	Cluster: floor vibrations, racking strength, stability of members etc.
WG 4	Fire

WG 5	Connections
WG 6	Bridges
WG 7	Reinforcement
WG 8	Seismic design
WG 9	Execution
WG 10	Basis of design and materials

1.4 Aim and structure

The main objective of this thesis is to review the design rules for connections in timber structures on the New Eurocode 5 and compare them to the Present Eurocode 5. The thesis explores and highlights the changes or differences between the design rules for connections in timber structures on the New Eurocode 5 and the Present Eurocode 5. The thesis is structured by topic and consists of 10 different topics excluding the introduction, example cases covering multiple topics and the conclusion parts. The topics covered in this thesis are axially loaded fasteners, laterally loaded fasteners, connection design with dowel-type metal fasteners, slip modulus of connections, spacing and end and edge distances, brittle failure modes of connections, bonded-in rods, shear connectors, punched metal plate fasteners and connections with interlayers. All the topics in this thesis are included under the chapter of connections in the New Eurocode 5. Some topics and subtopics in this thesis are not covered by the Present Eurocode 5. A review of the rules given by the New Eurocode 5 is provided for each topic except for the topic of connections with interlayers which is only introduced. For each of the topics and subtopics covered by both the New Eurocode 5 and the Present Eurocode 5, the changes or differences between the design rules are discussed. Reinforced connections and carpentry connections, which are covered by the New Eurocode 5, are not covered in this thesis.

2 Axially loaded fasteners

2.1 Withdrawal resistance

2.1.1 Screws and rods with wood screw thread

The New Eurocode 5 provides a more detailed expression for determining the characteristic withdrawal capacity of axially loaded screws and rods with wood screw thread. In addition to changes of symbols for some parameters, few alterations in the expression have been made in the New Eurocode 5 relative to the expression in the Present Eurocode 5. Range of diameters and ratio of inner thread diameter to outer thread diameter are changed from 6 mm ≤ d ≤ 12 mm and 0.6 ≤ d_1/d ≤ 0.75 in the Present Eurocode 5 to 3.5 mm ≤ d ≤ 22 mm and 0.55 ≤ d_1/d ≤ 0.76 in the New Eurocode 5 respectively. The withdrawal parameter ($f_{ax,k}$) for screws and rods with wood screw thread with diameters greater than 12 mm is not provided in the Present Eurocode 5 and must be determined by testing according to EN 14592. The requirement for the minimum withdrawal length is changed from 6d to 5d. In the Present Eurocode 5, the angle between the fastener axis and the grain direction α cannot be lower than 30 degrees ($\alpha \geq 30°$) to eliminate the risk of splitting failure, but in the New Eurocode 5 a withdrawal length of $l_w \leq 20d$ must be used for small angles $0° \leq \varepsilon \leq 30°$. Although no information is provided in the Present Eurocode 5, the characteristic density of the timber member in the connection cannot be greater than 700 kg/m^3 in the New Eurocode 5. Thus, the New Eurocode 5 has overcome some limitations of the Present Eurocode 5 for determining the characteristic withdrawal capacity of connections with axially loaded screws and rods with wood screw thread by increasing the range of diameters (3.5 mm ≤ d ≤ 22 mm) and by including small angles between the fastener axis and the grain direction ($0° \leq \varepsilon \leq 90°$).

The expression for the determination of the characteristic withdrawal capacity in the Present Eurocode 5 has the parameter n_{ef} as presented in Equation (*1*). Therefore, the characteristic withdrawal capacity of a connection is based on the effective number of fasteners in the connection. The expression in the New Eurocode 5, as given in Equation (*6*), is for determining the characteristic withdrawal capacity of one fastener. The characteristic withdrawal capacity of a connection is based on the actual number of fasteners acting together in the connection according to the New Eurocode 5.

Present Eurocode 5

The characteristic withdrawal capacity of connections with axially loaded screws and rods with wood screw thread of 6 mm ≤ d ≤ 12 mm and 0.6 ≤ d_1/d ≤ 0.75 is given by:

$$F_{ax,\alpha,Rk} = \frac{n_{ef} * f_{ax,k} * d * l_{ef} * k_d}{1.2 * \cos^2\alpha + \sin^2\alpha} \tag{1}$$

$$f_{ax,k} = 0.52 * d^{-0.5} * {l_{ef}}^{-0.1} * {\rho_k}^{0.8} \tag{2}$$

$$k_d = \min\begin{cases}\frac{d}{8}\\ 1\end{cases} \tag{3}$$

The effective number of screws for a connection with a group of axially loaded screws is given by:

$$n_{ef} = n^{0.9} \tag{4}$$

For all other screws that do not satisfy the inner and outer thread diameter requirement mentioned above is given by:

$$F_{ax,\alpha,Rk} = \frac{n_{ef} * f_{ax,k} * d * l_{ef}}{1.2 * \cos^2\alpha + \sin^2\alpha} * \left(\frac{\rho_k}{\rho_a}\right)^{0.8} \tag{5}$$

where all the symbols are the same as explained in Table 2:

$f_{ax,k}$ is the characteristic withdrawal parameter perpendicular to the grain in compliance with NS-EN 14592 for the associated density ρ_a, in N/mm^2;

ρ_a is the associated density for $f_{ax,k}$, in kg/m^3.

New Eurocode 5

The characteristic withdrawal resistance of screws and rods with wood screw thread of 3.5 mm ≤ *d* ≤ 22 mm and 0.55 ≤ d_1/d ≤ 0.76 is determined by:

$$F_{w,k} = \pi * d * l_w * f_{w,k} \tag{6}$$

$$f_{w,k} = k_{screw} * k_w * k_{mat} * d^{-0.33} * \left(\frac{\rho_k}{350}\right)^{k_p} \tag{7}$$

$k_{screw} = ki,$ where $i = 6,7,8,9,10$

$k6 = 6\,,\ k7 = 7\,,\ k8 = 8\,,\ k9 = 9$ and $k10 = 10$ are values for k_{screw} (8)

$$k_w = \begin{cases}1.0 & \text{for } 30° \le \varepsilon \le 90°\\ 1 - 0.01(30-\varepsilon) & \text{for } 0° \le \varepsilon < 30°\end{cases} \tag{9}$$

$$k_{mat} = \{1 + \frac{\ln(n_p)}{12} \le 1.15 \tag{10}$$

$$k_p = \begin{cases}1.10 & \text{for softwoods and } 15° \le \varepsilon \le 90°\\ 1.25 - 0.05d & \text{for softwoods and } 0° \le \varepsilon < 15°\\ 1.6 & \text{for hardwoods and } 0° \le \varepsilon \le 90°\end{cases} \tag{11}$$

$k_w = k_{mat} = 1.0$ for materials that are not specifically mentioned.

The expressions given by the Present Eurocode 5 and the New Eurocode 5 for the determination of the characteristic withdrawal capacity of axially loaded screws and rods with wood screw thread use some common parameters, which can vary, such as outer thread diameter, withdrawal length, angle between the fastener axis and the grain direction and characteristic timber density. A comparison has been made by varying one of these parameters at a time while holding the other parameters constant. The values used are diameter d = 12 mm, withdrawal length of 200 mm, angle with 90° and GL30c timber member with density ρ_k = 390 kg/m^3. The values, which are chosen for the parameters in this comparison, are conservative.

a) Withdrawal resistance using different diameters.

Fasteners of diameters 3.5 mm ≤ d ≤ 22 mm are used according to the New Eurocode 5. The Present Eurocode 5 does not include diameters of less than 6 mm. For these diameters, the graph is plotted with a dashed red line in Figure 1. The graph which represents the Present Eurocode 5 has four different slopes due to varying values of some parameters in the formulas. The first slope is due to the parameter k_d which has a varying value and reaches a maximum value of 1 (one) at the diameter of 8 mm. k_d has constant value of 1 (one) beyond the 8 mm diameter which is the cause for the second slope. For diameters greater than 12 mm, the withdrawal strength parameter is not provided in the Present Eurocode 5 and must be obtained by testing according to EN 14592. The value of the withdrawal strength parameter used in this case, $f_{ax,k}$ = 11.92 MPa, is for rods with wood screw thread of diameters d = 12 mm embedded in a GL30c timber member with associated characteristic density ρ_a = 400 kg/m^3 from an article by Stamatopoulos and Malo [9]. The third slope is due to this change of values of the withdrawal strength parameter. Finally, the fourth slope is due to the constant value of the withdrawal strength parameter.

As shown in Figure 1, the New Eurocode 5 gives higher withdrawal capacities for fasteners with diameters up to about 19 mm. At diameter of 19 mm, the Present Eurocode 5 and the New Eurocode 5 give the same value for the withdrawal capacity. For diameters greater than about 19 mm, the results for the withdrawal capacities from the Present Eurocode 5 have higher values. Therefore, the New Eurocode 5 is more significant and effective for the commonly used screws and rods with wood screw thread with diameters up to around 20 mm in terms of the withdrawal capacities.

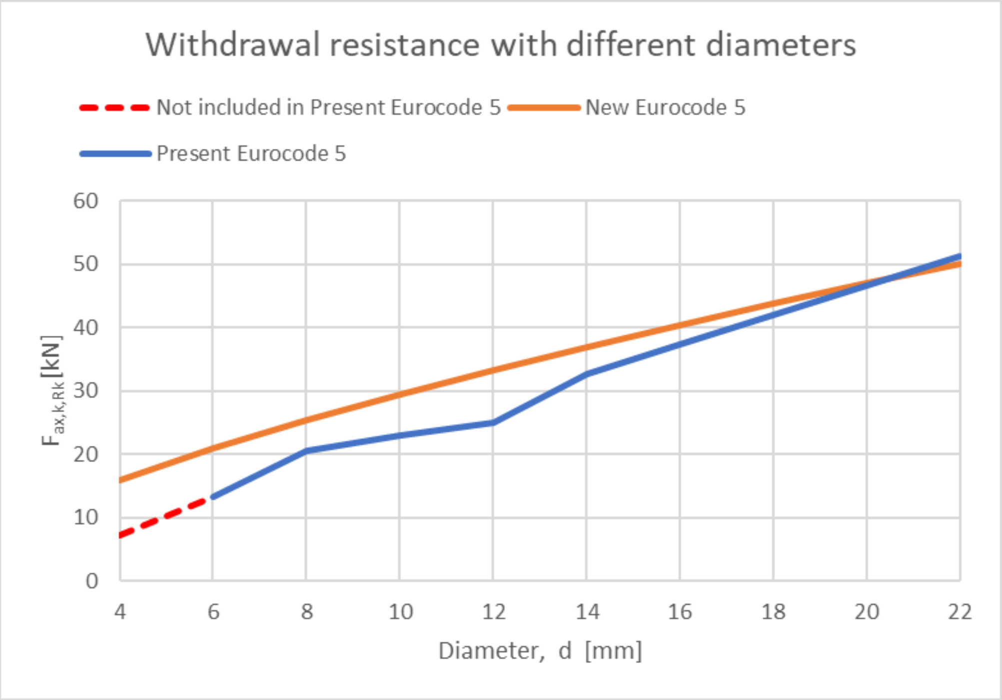


Figure 1: Withdrawal resistance using different diameters.

b) Withdrawal resistance using different withdrawal lengths.

Withdrawal length is the varying parameter in this case to determine the characteristic withdrawal capacity of axially loaded screws and rods with wood screw. Withdrawal lengths for different values of $5d \leq l_w \leq 30d$, where diameter d = 12 mm, are used. As shown in Figure 2, the New Eurocode 5 gives higher values of the withdrawal capacities for all values of withdrawal lengths. The difference between the values of the withdrawal capacities by the Present Eurocode 5 and the New Eurocode 5 is increasing as the withdrawal length increases. The New Eurocode 5 gives better results than the Present Eurocode 5 in the withdrawal capacities of screws and rods with wood screw with long withdrawal lengths.

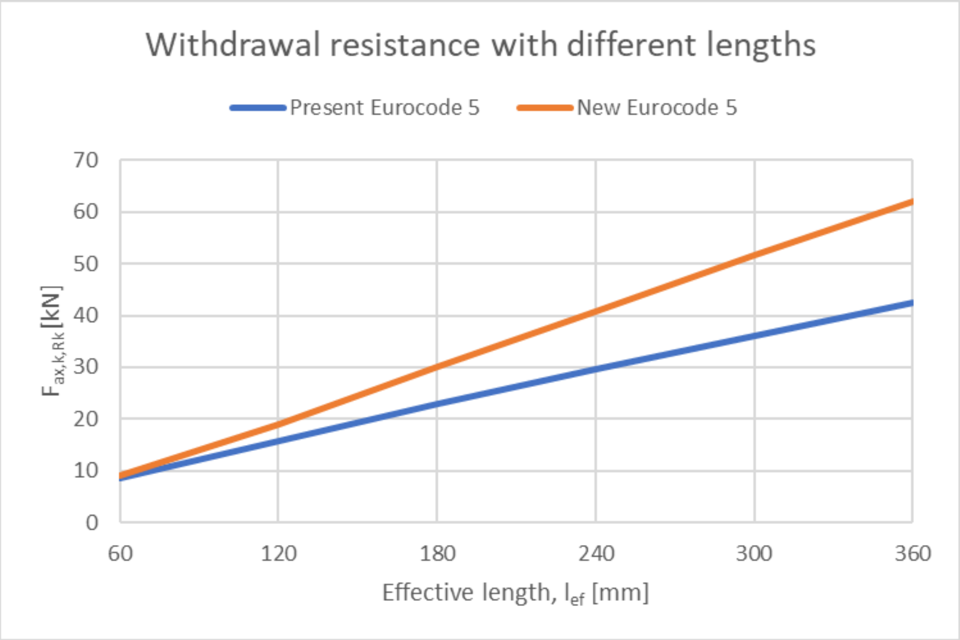


Figure 2: Withdrawal resistance using different withdrawal lengths.

c) Withdrawal resistance using different angle between the screw axis and the grain direction.

In this case, the angle is the varying parameter to determine the characteristic withdrawal capacity of axially loaded screws and rods with wood screw. The angles used are from 0° to 90°. In the Present Eurocode 5, the angle between the fastener axis and the grain direction α cannot be lower than 30 degrees ($\alpha \geq 30°$). For these angles, the graph is plotted with a dashed red line in Figure 3. When the angle increases, the value of the characteristic withdrawal capacity by the Present Eurocode 5 increases with a decreasing slope as depicted in Figure 3. The graph which represents the New Eurocode 5 has four different slopes due to varying values for some parameters in the formula for determining the characteristic withdrawal capacity of axially loaded screws and rods with wood screw. k_w and k_p depend on the angle values. The first slope is due to the value change of only k_w for the angles 0° to 10°. The second slope is due to the change of values of both k_w and k_p for the angles 10° to 20°. The change of the value of only k_w creates the third slope in the graph. The last slope is owing to the constant values of both k_w and k_p. As shown in Figure 3, the New Eurocode 5 gives better results than the Present Eurocode 5 in the withdrawal capacities of screws and rods with wood screw for all values of the angles.

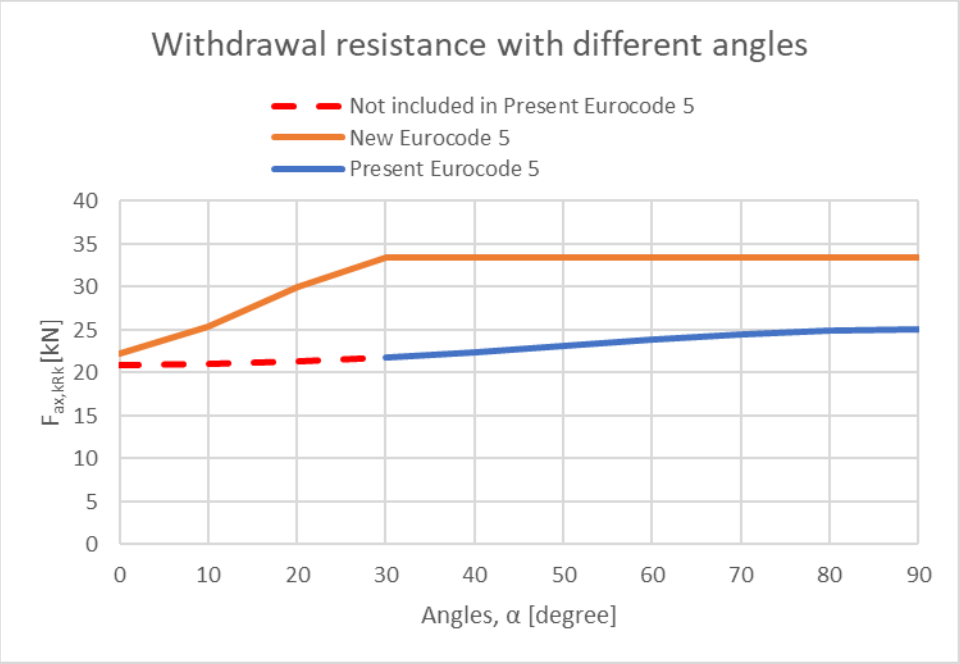


Figure 3: Withdrawal resistance using different angles between the screw axis and the grain direction.

d) Withdrawal resistance using different characteristic timber density.

The characteristic timber density ρ_k is the varying parameter in this case to determine the characteristic withdrawal capacity of axially loaded screws and rods with wood screw. The values of the characteristic timber density ρ_k from 300 kg/m^3 to 700 kg/m^3 are used. As shown in Figure 4, the New Eurocode 5 gives higher values of the withdrawal capacities for all values of characteristic timber densities. The difference between the values of the withdrawal capacities by the Present Eurocode 5 and the New Eurocode 5 increases with the increase of the values of the characteristic timber densities. The New Eurocode 5 gives better results than the Present Eurocode 5 in the withdrawal capacities of screws and rods with wood screw with higher values of the characteristic timber density.

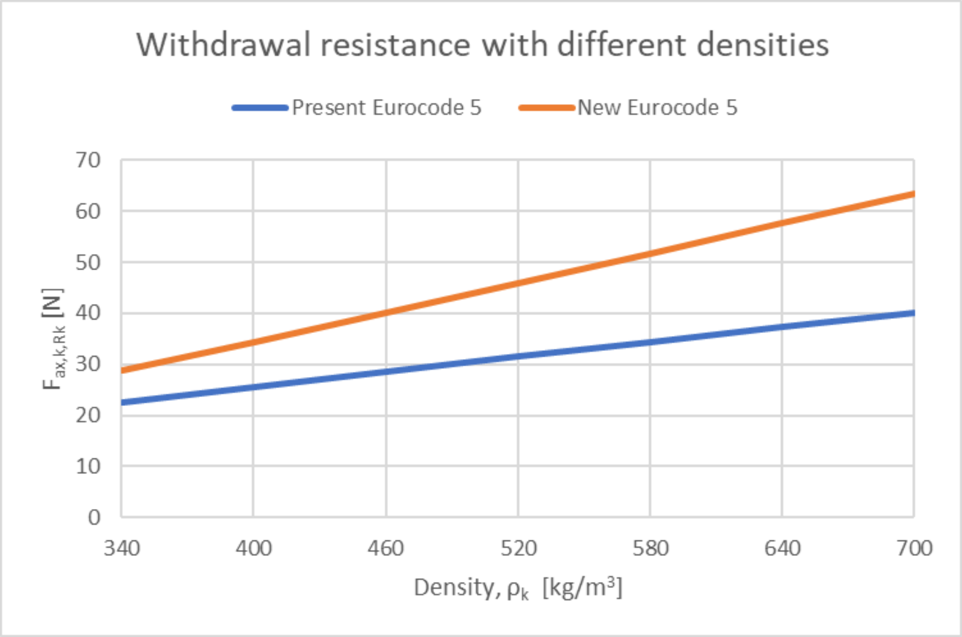


Figure 4: Withdrawal resistance using different characteristic timber densities.

The nomenclature used in the withdrawal resistance of axially loaded screws and rods with wood screw thread in the Present Eurocode 5 and the New Eurocode 5 is presented in Table 2.

Table 2: Nomenclature used in the withdrawal resistance of axially loaded screws and rods with wood screw thread.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{ax,\alpha,Rk}$	$F_{w,k}$	characteristic withdrawal capacity of a fastener, in N
$f_{ax,k}$		characteristic withdrawal strength perpendicular to the grain, in N/mm^2
	$f_{w,k}$	characteristic withdrawal strength, in N/mm^2
l_{ef}	l_w	penetration length of the threaded part, in mm
n_{ef}		effective number of screws
n		number of screws acting together in the connection
ρ_k	ρ_k	Characteristic timber density, in kg/m^3
α	ε	angle between the screw axis and the grain direction
d	d	outer thread diameter of the fastener, in mm

d_1	d_1	inner thread diameter of the fastener, in mm
	k_{screw}	prefactor for withdrawal categories for screws and woodscrew threaded rods
	ki	withdrawal category for screws and woodscrew threaded rods (Annex N.7 in New Eurocode 5 [1])
	k_{mat}	material parameter for the number of laminations
	n_p	number of layers penetrated by the fastener

2.1.2 Nails

The characteristic withdrawal capacity of axially loaded nails is given by Equation (*12*) in the Present Eurocode 5 and by Equation (*15*) in the New Eurocode 5. The characteristic withdrawal strength, diameter and withdrawal length are common parameters for both equations. The expression provided by the New Eurocode 5 has additional parameter π (pi). For determining the characteristic withdrawal strength, the expressions provided by the Present Eurocode 5 and the New Eurocode 5 are not the same. According to the Present Eurocode 5, the characteristic withdrawal strength $f_{ax,k}$ is determined by tests in accordance with EN 1382 and EN 14358 if it is not specified, but the New Eurocode 5 provides an expression to determine the characteristic withdrawal strength $f_{w,k}$ for all nails. The multiplication factor for the values of the withdrawal resistance for smooth nails that are installed in timber at or near fiber saturation point, which is most probably to dry out later in service, is 1/3 in the New Eurocode 5 and it is 2/3 for all nails in the Present Eurocode 5. The nomenclature used in the withdrawal resistance of axially loaded nails in the Present Eurocode 5 and the New Eurocode 5 is presented in Table 3.

Present Eurocode 5

$$F_{ax,Rk} = f_{ax,k} * d * t_{pen} \tag{12}$$

a) For smooth nails:

with $t_{pen} \geq 12d$,

$$f_{ax,k} = 20 \times 10^{-6} * {\rho_k}^2 \tag{13}$$

with $8d \leq t_{pen} < 12d$,

$$f_{ax,k} = 20 \times 10^{-6} * {\rho_k}^2 * \left(\frac{t_{pen}}{4d} - 2\right) \tag{14}$$

b) For nails other than smooth nails:

For threaded (other than smooth) nails with $6d \leq t_{pen} < 8d$, the characteristic withdrawal strength must be multiplied by $\left(\frac{t_{pen}}{2d} - 3\right)$, i.e., $f_{ax,k} * \left(\frac{t_{pen}}{2d} - 3\right)$

New Eurocode 5

$$F_{w,k} = \pi * d * l_w * f_{w,k} \tag{15}$$

- Ring shank nails (threaded nails) with 1.9 mm ≤ d ≤ 8 mm

For $l_{w,2} \geq 8d$:

$$\mathrm{f_{w,k}} = 2 * \left(\frac{\rho_k}{350}\right)^{1.25} \tag{16}$$

For $6d \leq l_{w,2} < 8d$:

$$\mathrm{f_{w,k}} = 2 * \left(\frac{\rho_k}{350}\right)^{1.25} * \left(\frac{l_{w,2}}{2d} - 3\right) \tag{17}$$

For not predrilled members:

$$\mathrm{f_{w,k}} = 0.117 * d^{0.6} * l_w * {\rho_k}^{0.8} \tag{18}$$

- Smooth nails with 1.9 mm ≤ d ≤ 8 mm and not predrilled timber members

For $l_{w,2} \geq 12d$:

$$\mathrm{f_{w,k}} = k_w * \left(\frac{\rho_k}{350}\right) \tag{19}$$

$$k_w = 0.78$$

For 8$d \leq l_{w,2} < 12d$:

$$k_{\mathrm{w}} = 0.78 * \left(\frac{l_{w,2}}{4d} - 2\right) \tag{20}$$

Table 3: Nomenclature used in the withdrawal resistance of axially loaded nails.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{ax,Rk}$	$F_{w,k}$	characteristic withdrawal capacity of nails, in N
$f_{ax,k}$	$f_{w,k}$	characteristic point side withdrawal strength of nails, in N/mm^2
d	d	diameter of the nail, in mm
t_{pen}	$l_{w,2}$	withdrawal length of the profiled part of the nail, in mm
	l_w	withdrawal length of the nail, in mm
ρ_k	ρ_k	characteristic timber density, in kg/m^3

2.1.3 Bolts

The withdrawal capacity of axially loaded bolts is not included in the New Eurocode 5. In the Present Eurocode 5, the withdrawal capacity and axial load-bearing capacity of axially loaded bolts is given by:

$$F_{ax,Rk} = \min \begin{cases} F_{ax,bolt,k} \\ 3 * f_{c,90,k} * A_{washer} \end{cases} \tag{21}$$

$$A_{washer} = \min \begin{cases} 12 * t_{plate} \\ 4 * d_{bolt} \end{cases} \tag{22}$$

where

$F_{ax,Rk}$	is the withdrawal capacity and axial load-bearing capacity of an axially loaded bolt, in N;
$F_{ax,bolt,k}$	is the tensile capacity of the bolt, in N;
$f_{c,90,k}$	is the characteristic compressive strength perpendicular to grain, N/mm^2;
A_{washer}	is the area of the washer, in mm^2;
t_{plate}	is the thickness of the steel plate, in mm;
d_{bolt}	is the diameter of the bolt, in mm.

2.1.4 Example case for withdrawal resistance

In this example case, withdrawal capacity of threaded rods is predicted by the formulas given in the Present Eurocode 5 and the New Eurocode 5. The correlation between experimental results and predicted values is evaluated and used for comparison between the Present Eurocode 5 and the New Eurocode 5. A collection of experimental results, which is used in an article by Stamatopoulos and Malo [10], is used in this example case. It is clearly stated in the article that the collection of experimental results consists of results by Blaß and Krüger [11] and Stamatopoulos and Malo [9, 12, 13]. The collection of experimental results is used for determining the withdrawal capacities of single threaded rods [10]. The experimental results are presented in Table 4 [10].

The article says that the results include both the withdrawal capacity and the withdrawal stiffness at reference climatic conditions (MC ≈ 12%). There are 31 sets (denoted as $S_{d\text{-}\alpha\text{-}l}$) of the total 221 test results and are arranged according to the varied parameters: diameter, angle of fastener axis to grain direction and penetration length respectively. The values for the mean and characteristic 5%-fractile withdrawal capacity and the corresponding coefficient of variation (CoV) are given in Table 4 for each set of having at least five number of test results (n_{tests}). The obtained values are also double checked with the values provided in the article by Stamatopoulos and Malo [10].

Table 4: Collection of experimental results from withdrawal tests of single threaded rods [10].

Set name	**Ref.**	n_{tests}	d [mm]	α [deg]	l [mm]	ρ_m [kg/m^3]	ρ_k [a] [kg/m^3]	$F_{ax,\alpha,Rm,test}$ [kN]	$F_{ax,\alpha,Rk,test}$ [b] [kN]	**CoV** [%]
S16-45-200	[11]	10	16	45	200	430	359	45.6	36.3	10.9
S16-45-400		10	16	45	400	433	361	92.4	80.8	6.5
S20-45-200		10	20	45	200	431	359	56.6	44.9	10.9
S20-45-400		10	20	45	400	433	361	117.3	101.0	7.1
S16-90-200		10	16	90	200	422	352	37.4	31.1	8.5
S16-90-400		10	16	90	400	441	368	94.1	83.0	6.1
S20-90-200		10	20	90	200	425	354	47.9	40.9	7.5
S20-90-400		10	20	90	400	441	368	115.1	103.6	3.9
S20-90-100	[9, 12, 13]	10	20	90	100	472	394	28.0	21.7	11.7
S20-90-250		5	20	90	250	472	394	73.2	64.7	2.8
S20-90-300		5	20	90	300	487	406	96.5	80.8	7.2
S20-90-450		5	20	90	450	486	405	139.2	121.9	5.3
S20-60-100		6	20	60	100	476	396	28.7	18.3	17.3
S20-60-300		5	20	60	300	488	407	93.6	66.9	12.3
S20-60-450		5	20	60	450	476	397	141.7	125.3	3.1
S20-30-100		10	20	30	100	478	399	27.9	20.9	13.0
S20-30-300		5	20	30	300	477	397	99.9	77.4	10.7
S20-30-450		5	20	30	450	475	396	144.6	115.5	9.2
S20-20-100		10	20	20	100	477	398	30.2	19.5	18.9
S20-20-300		5	20	20	300	478	398	98.7	74.3	10.8
S20-20-450		5	20	20	450	473	394	145.8	124.7	6.3
S20-10-100		10	20	10	100	468	390	25.8	17.9	17.7
S20-10-300		5	20	10	300	479	399	99.8	76.9	9.8
S20-10-450		5	20	10	450	446	372	127.5	88.7	13.8
S20-0-100		10	20	0	100	456	380	26.2	19.6	13.9
S20-0-300		5	20	0	300	474	395	89.7	66.8	11.7
S20-0-450		5	20	0	450	458	382	130.2	66.7	23.9

S20-0-600		5	20	0	600	443	369	161.6	141.8	5.2
S20-10-600[c]		5	20	10	600	462	385	_	_	_
S20-20-600[c]		5	20	20	600	481	401	_	_	_
S20-30-600[c]		5	20	30	600	486	405	_	_	_

[a] *the characteristic density was determined by* $\rho_k = \rho_m/1.2$ [14].

[b] *the characteristic withdrawal capacity was determined according to EN14358* [15].

[c] *in these sets, steel failure was observed so withdrawal capacity was undetermined* [10].

The characteristic density is an approximated value in this case and is determined by dividing the mean density by a factor of 1.2 (i.e., $\rho_k = \rho_m/1.2$) which is formulated by rearranging the expression $\rho_m = 1.2 * \rho_k$ provided in EN 384 [14]. The strength parameters are assumed as logarithmically normally distributed [15]. The characteristic 5%-fractile withdrawal capacity is determined according to EN 14358 [15] by:

$$F_{ax,\alpha,Rk,test} = \exp\left(\tilde{y} - k_s(n) * s_y\right) \qquad (23)$$

The expressions for determining the mean value $\tilde{y}$ and the standard deviation s_y are provided in EN 14358 [15], but Excel is used in this example case. For logarithmically normally distributed test values, the standard deviation s_y cannot be less than 0.05 (5%) [15], therefore the minimum value of the standard deviation s_y used in the calculation is 0.05 (5%). The value of the factor $k_s(n)$, which depends on the number of test specimens (n_{tests}), is given in Table 1 of EN 14358 [15]. The values used in the calculation are $k_s(n) = 2.46$ for $n_{tests} = 5$, $k_s(n) = 2.388$ for $n_{tests} = 6$ and $k_s(n) = 2.10$ for $n_{tests} = 10$. The experimental characteristic withdrawal capacity by EN 14358 [15] and the predicted characteristic withdrawal capacities by the Present Eurocode 5 and the New Eurocode 5 are given in Table 5 for each set which is having at least five number of test results (n_{tests}).

Table 5: Characteristic withdrawal capacities of single threaded rods.

Set name	n_{tests}	$F_{ax,\alpha,Rk,test}$ [kN]	$F_{ax,\alpha,Rk,Present\ Eurocode\ 5}$ [kN]	$F_{w,k,New\ Eurocode\ 5}$ [kN]
S16-45-200	10	36.3	31.8	36.9
S16-45-400	10	80.8	63.9	76.7
S20-45-200	10	44.9	39.7	42.9
S20-45-400	10	101.0	79.9	89.1
S16-90-200	10	31.1	34.4	36.1
S16-90-400	10	83.0	71.3	78.3

S20-90-200	10	40.9	43.3	42.3
S20-90-400	10	103.6	89.2	90.9
S20-90-100	10	21.7	23.5	22.5
S20-90-250	5	64.7	58.8	60.4
S20-90-300	5	80.8	72.4	75.9
S20-90-450	5	121.9	108.3	113.6
S20-60-100	6	18.3	22.5	22.7
S20-60-300	5	66.9	69.0	76.0
S20-60-450	5	125.3	101.5	111.2
S20-30-100	10	20.9	20.7	22.8
S20-30-300	5	77.4	61.9	74.2
S20-30-450	5	115.5	92.6	110.9
S20-20-100	10	19.5	20.2	20.5
S20-20-300	5	74.3	60.6	66.9
S20-20-450	5	124.7	90.0	99.2
S20-10-100	10	17.9	19.5	16.3
S20-10-300	5	76.9	59.8	53.3
S20-10-450	5	88.7	84.8	78.6
S20-0-100	10	19.6	19.1	14.1
S20-0-300	5	66.8	59.0	46.5
S20-0-450	5	66.7	86.1	69.2
S20-0-600	5	141.8	111.7	91.5
S20-10-600 [a]	5	–	–	–
S20-20-600 [a]	5	–	–	–
S20-30-600 [a]	5	–	–	–

[a] *in these sets, steel failure was observed so withdrawal capacity was undetermined* [10].

In the Present Eurocode 5, the withdrawal capacity for screws and rods with wood screw thread with diameters greater than 12 mm is given by Equation (*5*). The withdrawal strength parameter ($f_{ax,k}$) in Equation (*5*) for screws and rods with wood screw thread with diameters greater than 12 mm is not provided in the Present Eurocode 5 and must be obtained by testing according to EN 14592 [2]. The value of the withdrawal strength parameter $f_{ax,k}$, which is used in this case, is 11.92 MPa. This value is from the article by Stamatopoulos and Malo [9] and it is the value of the withdrawal strength parameter of rods with wood screw thread with diameters d = 20 mm embedded in a GL30c timber member with associated characteristic density ρ_a = 400 kg/m^3. Two withdrawal capacities have been calculated for the individual tests, first by using the actual density and second by using the characteristic density of the sets they belong to. The values of the withdrawal capacities for individual tests are included in Figure 5. The withdrawal capacities for the sets, as shown in Figure 5, have been calculated by using the characteristic density of the sets they belong to.

In the New Eurocode 5, Equation (*6*) and Equation (*7*) are provided for screws and rods with wood screw thread with diameters up to 22 mm. Equation (*6*) is used for determination of the withdrawal capacity and Equation (*7*) is used for determining the withdrawal strength parameter. The number of penetrated layers (n_p) exists in the expression for the withdrawal strength parameter, and it is obtained by dividing the withdrawal length (l_w) by the thickness (t) of one layer of the timber member (i.e., $n_p = l_w/t$). The thickness (t) of one layer of the timber member, which is used in the calculation, is 45 mm [9, 11]. The prefactor k_{screw} = 8 from Table N.5 in Annex N of the New Eurocode 5 for the middle screw category k8 is used for calculating the withdrawal strength parameter. Two withdrawal capacities have been calculated for the individual tests, first by using the actual density and second by using the characteristic density of the sets they belong to. The values of the withdrawal capacities for individual tests are included in Figure 6. The withdrawal capacities for the sets, as depicted in Figure 6, have been calculated by using the characteristic density of the sets they belong to.

The correlation between the experimental characteristic withdrawal capacities and the predictions by the Present Eurocode 5 is depicted in Figure 5. The correlation between the experimental characteristic withdrawal capacities and the predictions by the New Eurocode 5 is shown in Figure 6. The predictions provided by the Present Eurocode 5 and the New Eurocode 5 are on the safe side as shown in Figure 5 and Figure 6 respectively.

When actual density is used for determining the withdrawal capacity for individual tests, the predictions provided by the Present Eurocode 5 are on the safe side in a greater number, especially for the tests with higher withdrawal capacities, than the predictions provided by the New Eurocode 5. When a withdrawal capacity of more than 60 kN is considered only two individual tests are overestimated by the Present Eurocode 5, but several tests are overestimated by the New Eurocode 5.

For individual tests where characteristic density is used for determining the withdrawal capacity, the predictions provided by the Present Eurocode 5 and the New Eurocode 5 are almost the same and on the safe side as shown in Figure 5 and Figure 6 respectively.

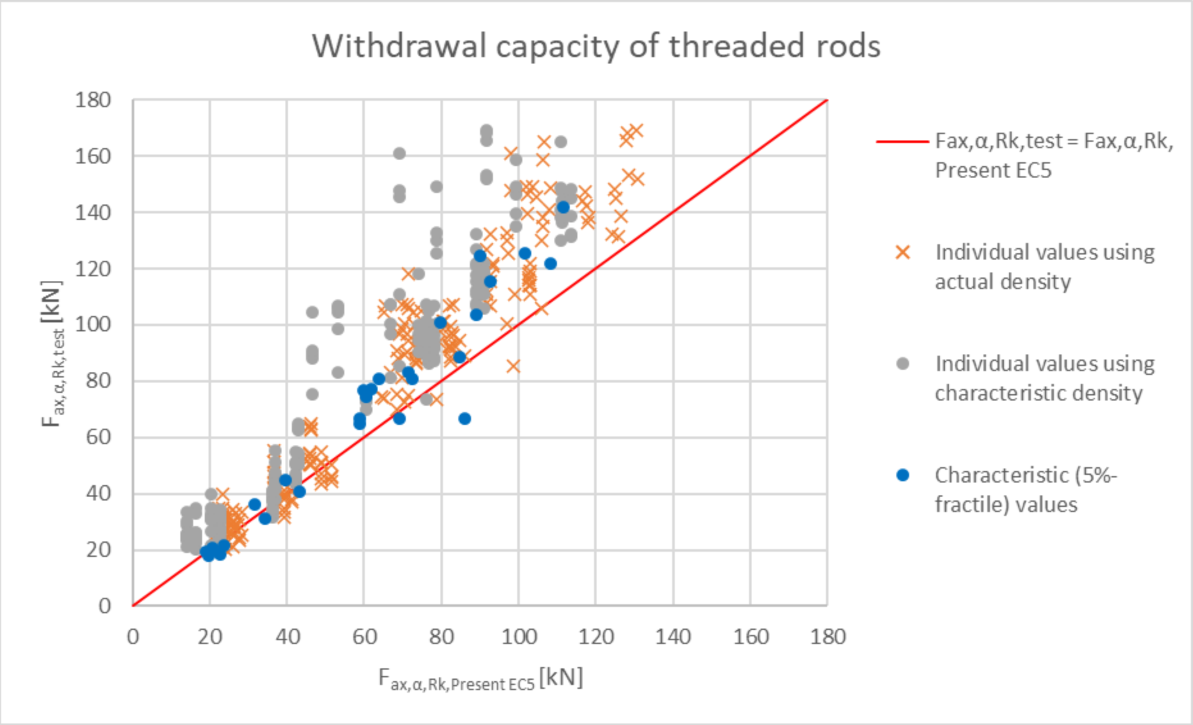


Figure 5: Correlation between experimental characteristic withdrawal capacity and the prediction by the Present Eurocode 5.

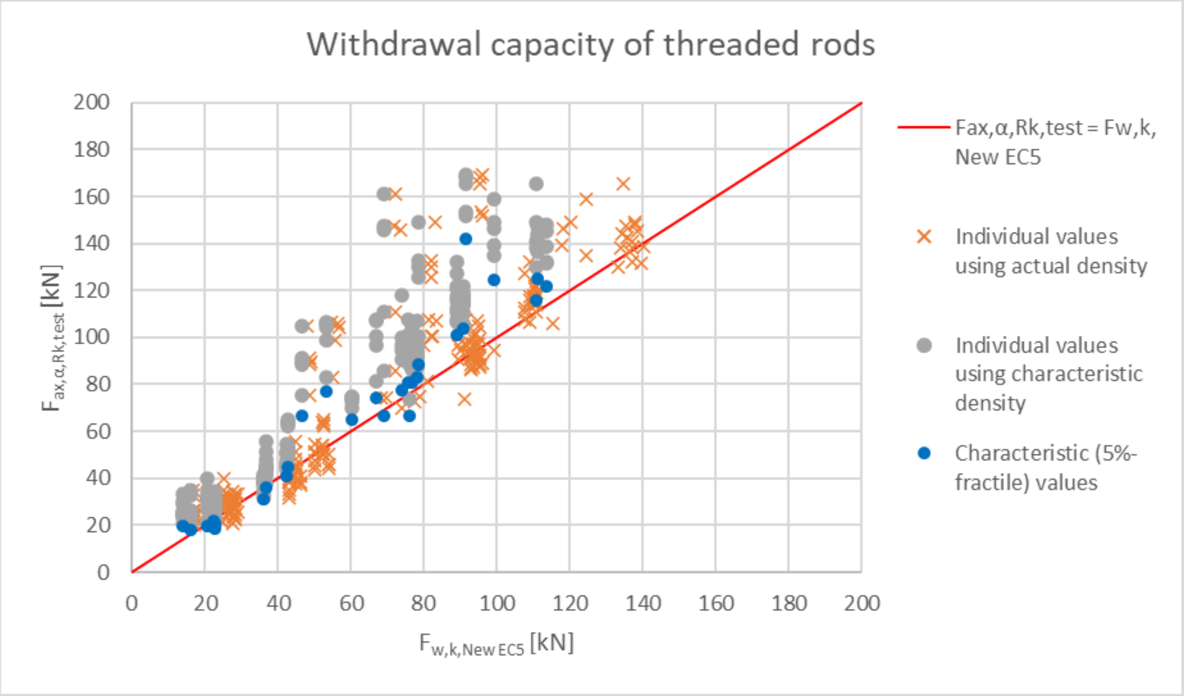


Figure 6: Correlation between experimental characteristic withdrawal capacity and the prediction by the New Eurocode 5.

The predictions by the Present Eurocode 5 and the New Eurocode 5 for the characteristic withdrawal capacity of the sets are generally on the safe side as depicted in Figure 5 and Figure 6 respectively. However, they have predicted one point (one set) each with overestimated characteristic withdrawal capacity. For the set S20-0-450, the difference between the predicted value by the Present Eurocode 5 and the value of the experimental result is 19.4 kN (86.1 kN – 66.7 kN = 19.4 kN). For the set S20-60-300, the difference between the predicted value (76.0 kN) by the New Eurocode 5 and the value of the experimental result (66.9 kN) is 9.1 kN. The New Eurocode 5 overestimates less than the Present Eurocode 5 and this means that the New Eurocode 5 predicts better than the Present Eurocode 5 in a such situation. For the sets, the Pearson correlation coefficient (PCC) is used to evaluate the degree of correlation between the experimental results and the predicted values by the Present Eurocode 5, and between the experimental results and the predicted values by the New Eurocode 5. The PCC = 0.9684 between the predictions by the Present Eurocode 5 and the experimental results is nearly equal to the PCC = 0.9585 between the predictions by the New Eurocode 5 and the experimental results. The PCC indicates that these correlations are very strong correlations.

It can be concluded that both the Present Eurocode 5 and the New Eurocode 5 have generally provided safe side predictions to the experimental results. The correlation between the predictions by the Present Eurocode 5 and the experimental results, and the correlation between the predictions by the New Eurocode 5 and the experimental results are very strong.

2.2 Head pull-through resistance

2.2.1 Screws and rods with wood screw thread

The formulas provided by the New Eurocode 5 and the Present Eurocode 5 for the determination of the characteristic head pull-through capacity of connections with axially loaded screws and rods with wood screw thread are different. The expression for the determination of the characteristic head pull-through capacity of a connection in the Present Eurocode 5 includes the parameter n_{ef} as given in Equation (*24*). Hence, the characteristic head pull-through capacity of a connection is based on the effective number of fasteners in the connection. The characteristic head pull-through parameter $f_{head,k}$ is determined in accordance with EN 14592 for the associated density ρ_a. The angle between the fastener axis and the grain direction α cannot be lower than 30 degrees ($\alpha \geq 30°$) to eliminate the risk of splitting failure.

The expression in the New Eurocode 5, as given in Equation (*25*), is for determining the characteristic head pull-through capacity of a fastener. The characteristic head pull-through capacity of a connection is based on the actual number of fasteners acting together in the connection. The characteristic head pull-through parameter f_{head} is determined directly by Equation (*26*) or Equation (*27*). The thickness of the first timber member must be greater than 4d ($t_1 \geq d$) to avoid the risk of failure modes according to the New Eurocode 5. The nomenclature used in the head pull-through resistance of axially loaded screws and rods with wood screw thread in the Present Eurocode 5 and the New Eurocode 5 is given in Table 6.

Present Eurocode 5

The characteristic head pull-through resistance of connections with axially loaded screws and rods with wood screw thread is determined by:

$$F_{ax,\alpha,Rk} = n_{ef} * f_{head,k} * {d_h}^2 * \left(\frac{\rho_k}{\rho_a}\right)^{0.8} \tag{24}$$

The effective number of screws, *n_{ef}*, for a connection with a group of axially loaded screws is given by Equation (*4*).

New Eurocode 5

The characteristic head pull-through resistance $F_{pull,k}$ of axially loaded screw or rod with wood screw thread having head diameter, $d_{head} \geq 1.8d$, is given by:

$$F_{pull,k} = \begin{cases} f_{head} * A_{head} & \text{for } A_{head} \leq 4072 \text{ mm}^2 \\ 3f_{c,90,k} * A_{head} & \text{for } A_{head} > 4072 \text{ mm}^2 \end{cases} \tag{25}$$

$$f_{head} = 19 * \exp\left(-\frac{d_{head}}{50}\right) * \left(\frac{\rho_k}{350}\right)^{0.8} \tag{26}$$

$d_{head} = 72$ mm gives the value $A_{head} = 4072$ mm^2

- For screw-press bonding in the connection,

$$f_{head} = 14 * {d_{head}}^{-0.14} * \left(\frac{\rho_k}{350}\right)^{0.8} \tag{27}$$

Table 6: Nomenclature used in the head pull-through resistance of axially loaded screws and rods with wood screw thread.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{ax,\alpha,Rk}$		characteristic head pull-through resistance of the connection, in N, at an angle α to the grain, $\alpha \geq 30°$
	$F_{pull,k}$	characteristic head pull-through resistance of the fastener, in N
$f_{head,k}$		characteristic head pull-through parameter of the screw in compliance with EN 14592 for the associated density ρ_a, in N/mm^2

	$f_{head,k}$	characteristic head pull-through parameter, in N/mm^2
n_{ef}		effective number of screws
n		number of screws acting together in a connection
ρ_k	ρ_k	characteristic density of the member, in kg/m^3
ρ_a		associated density for $f_{head,k}$, in kg/m^3
α		angle between the screw axis and the grain direction with $\alpha \geq 30°$
d_h	d_{head}	diameter of the head of the fastener, in mm
	A_{head}	area of the fastener head or the area inside the perimeter of the fastener head, in mm^2
	$f_{c,90,k}$	characteristic compressive strength perpendicular to grain, in N/mm^2

2.2.2 Nails

For determining the characteristic head pull-through capacity of nails, the expressions provided by the Present Eurocode 5 and the New Eurocode 5 are different. In the Present Eurocode 5, the characteristic head pull-through strength $f_{head,k}$ of the nail is determined by tests in accordance with EN 1383 and EN 14358 if it is not specified. The value of $f_{head,k}$ is multiplied by a factor of 2/3 for nails installed in timber at or near fiber saturation point, which is most probably to dry out later in service. In the New Eurocode 5, the $f_{head,k}$ does not exist in the expression for the determination of the characteristic head pull-through resistance of nails. The thickness of the first timber member must be greater than 4*d* ($t_1 \geq d$) to avoid the risk of failure modes according to the New Eurocode 5. The nomenclature used in the head pull-through resistance of axially loaded nails in the Present Eurocode 5 and in the New Eurocode 5 is presented in Table 7.

Present Eurocode 5

The characteristic head pull-through capacity of nails with head diameter $d_h \geq 1.8d$, for both nailing perpendicular and nailing inclined to the grain is given by:

a) For nails other than smooth nails, as defined in EN 14592:

$$F_{ax,Rk} = f_{head,k} * {d_h}^2 \tag{28}$$

b) For smooth nails:

$$F_{ax,Rk} = f_{ax,k} * d * t + f_{head,k} * {d_h}^2 \tag{29}$$

- for smooth nails with $t_{pen} \geq 12d$,

$$f_{head,k} = 70 \times 10^{-6} * {\rho_k}^2 \tag{30}$$

New Eurocode 5

The characteristic head pull-through capacity of a nail with head diameter, $d_{head} \geq 1.8d$, is given by:

$$F_{pull,k} = 15 * {d_{head}}^2 * \left(\frac{\rho_k}{350}\right)^{0.8} \tag{31}$$

Table 7: Nomenclature used in the head pull-through resistance of axially loaded nails.

Present Eurocode 5	New Eurocode 5	Meaning
$F_{ax,\alpha,Rk}$	$F_{pull,k}$	characteristic head pull-through resistance, in N
$f_{ax,k}$		characteristic point side withdrawal strength of nails, in N/mm^2
$f_{head,k}$		characteristic head pull-through strength parameter of the nail, in N/mm^2
d		diameter of the nail, $d \geq 8$ mm
d_h	d_{head}	diameter of the nail head, in mm
t		thickness of the head side timber member, in mm
t_{pen}		length of the point side penetration or the length of the threaded portion of the nail, excluding the point length, in the point side timber member, in mm
ρ_k	ρ_k	characteristic density of the timber member, in kg/m^3

2.3 Tensile resistance

2.3.1 Screws and rods with wood screw thread

The expressions provided by the New Eurocode 5 and the Present Eurocode 5 for the determination of the characteristic tensile resistance of connections with axially loaded screws and rods with wood screw thread are not the same. In the Present Eurocode 5, the characteristic tensile resistance of a connection is based on the effective number of fasteners in the connection. The characteristic tensile resistance of the fastener $f_{tens,k}$ is determined in compliance with EN 14592. In the New Eurocode 5, an expression is given for the determination of the characteristic tensile resistance of a fastener from EN 1993-1-8:2005. The characteristic tensile resistance of a connection is based on the actual number of fasteners acting together in the connection. The nomenclature used in the tensile resistance of axially loaded screws and rods with wood screw thread in the Present Eurocode 5 and in the New Eurocode 5 is given in Table 8.

Present Eurocode 5

The characteristic tensile resistance of a connection with axially loaded screws and rods with wood screw thread is determined by:

$$F_{t,Rk} = n_{ef} * f_{tens,k} \tag{32}$$

The effective number of screws, n_{ef}, for a connection with a group of axially loaded screws is given by Equation (*4*).

New Eurocode 5

The characteristic tensile resistance of axially loaded screws and rods with wood screw thread can be taken from the respective European technical product specification or the New Eurocode 5 provides an expression from EN 1993-1-8:2005 which is given by:

$$F_{t,k} = 0.9 * A_s * f_{u,k} \tag{33}$$

Table 8: Nomenclature used in the tensile resistance of axially loaded screws and rods with wood screw thread.

Present Eurocode 5	New Eurocode 5	Meaning
$F_{t,Rk}$	$F_{t,k}$	characteristic tensile resistance of a connection with axially loaded fasteners, in N
$f_{tens,k}$		characteristic tensile strength of the screw in compliance with EN14592, in N/mm^2
n_{ef}		effective number of fasteners in the connection
n		number of fasteners acting together in the connection
	$f_{u,k}$	characteristic steel strength for the type of fastener used in the connection, in N/mm^2
	A_s	nominal stress area of the fastener based on the inner thread diameter d_1 for screws and rods with wood screw thread, in mm^2

2.3.2 Nails and bolts

The characteristic tensile capacity of axially loaded nails is not covered by the Present Eurocode 5 and tensile capacity of bolts is only mentioned without additional information. The New Eurocode 5 provides an expression from EN 1993-1-8:2005 for determining the characteristic tensile resistance of axially loaded nails and bolts and it is given by:

$$F_{t,k} = 0.9 * A_s * f_{u,k} \tag{34}$$

where

$f_{u,k}$ is characteristic steel strength for nails, in N/mm^2;

A_s is the nominal stress area of the fastener based on the relevant diameter, in mm^2.

- d for nails and d_{sp} (approximately 0.86*d*) for bolts

2.4 Compression resistance

2.4.1 Screws and rods with wood screw thread

The compression (buckling) capacity of a connection with axially loaded screws and rods with wood screw thread is not covered by the Present Eurocode 5. In the New Eurocode 5, the compression capacity of axially loaded screws and rods with wood screw thread with 6 mm ≤ d ≤ 22 mm and with 0.55 ≤ d_1/d ≤ 0.76 is determined by:

$$F_{c,k} = \frac{\gamma_R}{\gamma_{M1}} * k_c * N_{pl,k} \tag{35}$$

$$k_c = \begin{cases} 1 & \text{for } \bar{\lambda}_k \le 0.2 \\ \dfrac{1}{k + \sqrt{k^2 - \bar{\lambda}_k{}^2}} & \text{for } \bar{\lambda}_k > 0.2 \end{cases} \tag{36}$$

$$k = 0.5\left[1 + 0.49 * \left(\bar{\lambda}_k - 0.2\right) + \bar{\lambda}_k{}^2\right] \tag{37}$$

$$\bar{\lambda}_k = \sqrt{\frac{N_{pl,k}}{N_{ki,k}}} \tag{38}$$

$$N_{pl,k} = \pi * \frac{{d_1}^2}{4} * f_{y,k} \tag{39}$$

$$N_{ki,k} = \sqrt{c_h * E_s * I_s} \tag{40}$$

$$c_h = (0.19 + 0.012 * d) * \rho_k * \left(\frac{90° + \varepsilon}{180°}\right) \tag{41}$$

$$E_s * I_s = 210000 * \pi * \frac{{d_1}^4}{64} \tag{42}$$

where

γ_R	is the partial factor for a material property;
γ_{M1}	is the partial factor for a design resistance based on an (semi) empirical analysis with a ductile failure mode, see section 4.3.2 (2) in prEN 1993-1-8:2020 [1];
k_c	is the factor for the buckling of the fastener;
$N_{pl,k}$	is the characteristic axial yield capacity of the fastener, in N;
$N_{ki,k}$	is the ideal elastic buckling load, in N;
$f_{y,k}$	is the characteristic yield strength of the fastener in N/mm^2;
d_1	is the inner thread diameter of the fastener, in mm;
d	is the outer thread diameter of the fastener, in mm;
c_h	is the characteristic value of the foundation modulus, in N/mm^2;
ρ_k	is the characteristic density of the member, in kg/m^3;
ε	is the angle between screw axis and grain direction;
$E_s I_s$	is the bending stiffness of the steel dowel-type fastener, in Nmm^2.

3 Laterally loaded fasteners

In the New Eurocode 5, the characteristic lateral resistance of a single fastener per shear plane $F_{v,k}$ is given by:

$$F_{v,k} = F_{D,k} + F_{rp,k} \tag{43}$$

where

$F_{D,k}$ is the characteristic dowel-effect contribution per shear plane, in N;

$F_{rp,k}$ is the characteristic rope-effect contribution, in N.

The New Eurocode 5 treats the characteristic dowel-effect contribution and the rope-effect contribution in two separate sections. The contributions of the yield moment and the embedment strength are considered in the New Eurocode 5 and the Present Eurocode 5 for the determination of the characteristic lateral resistance of a metal dowel-type fastener per shear plane. The characteristic embedment strength and the characteristic yield moment are included under each section of the type of metal dowel-type fasteners in the Present Eurocode 5. In the New Eurocode 5, the characteristic yield moment and the characteristic embedment strength have their own sections. Based on the structure and organization of the topics of yield moment and the embedment strength, the New Eurocode 5 is more user-friendly than the Present Eurocode 5.

3.1 Dowel-effect contribution of a single fastener in a single and double shear planes

For both timber-to-timber and steel-to-timber connections with fasteners loaded in a single shear plane and in double shear planes, the New Eurocode 5 provides the dowel-effect contribution of a single fastener per shear plane. The New Eurocode 5 gives the same set of failure modes for both timber-to-timber connections and steel-to-timber connections when determining the characteristic value of the dowel-effect contribution of a fastener. The Present Eurocode 5 gives different sets of failure modes for timber-to-timber connections and steel-to-timber connections.

In the New Eurocode 5 and the Present Eurocode 5, six failure modes (a) to (f) are given for a connection with a fastener loaded in a single shear plane as shown in Figure 7. The expressions provided by the New Eurocode 5 and the Present Eurocode 5 for the six failure modes (a) to (f) are the same. The only difference is that the embedment depth of an inner member in the expression for the failure mode (b) must be taken as half of the thickness of the inner member ($t_{h,2} = t_2/2$) in the New Eurocode 5, but a reduction factor 0.5 is directly included in the expression for the corresponding failure mode (b) in the Present Eurocode 5. The New Eurocode 5 gives the names of the failure modes (a), (b), (d) and (f) for a symmetric connection with a fastener loaded in double shear planes as depicted in Figure 9 according to the failure modes (a), (b), (d) and (f) respectively for a single shear plane in the connection. For a symmetric timber-to-timber connection with a fastener loaded in double shear planes, the Present Eurocode 5 gives the names of the failure modes (g), (h), (j) and (k) as shown in Figure 8 according to the failure modes (g), (h), (j) and (k) respectively for a single shear plane in the connection. For a single shear plane in a symmetric connection with a fastener loaded in double shear planes, the expressions provided by the New Eurocode 5 for the failure modes (a), (b), (d) and (f) are the same with the corresponding expressions provided by the Present Eurocode 5 for the failure modes (g), (h), (j) and (k) respectively. The only difference is that the embedment depth of an inner member in the expression for the failure mode (b) must be taken as half of the thickness of the inner member ($t_{h,2}$ = t_2/2) in the New Eurocode 5, but a reduction factor 0.5 is directly included in the expression for the corresponding failure mode (h) in the Present Eurocode 5.

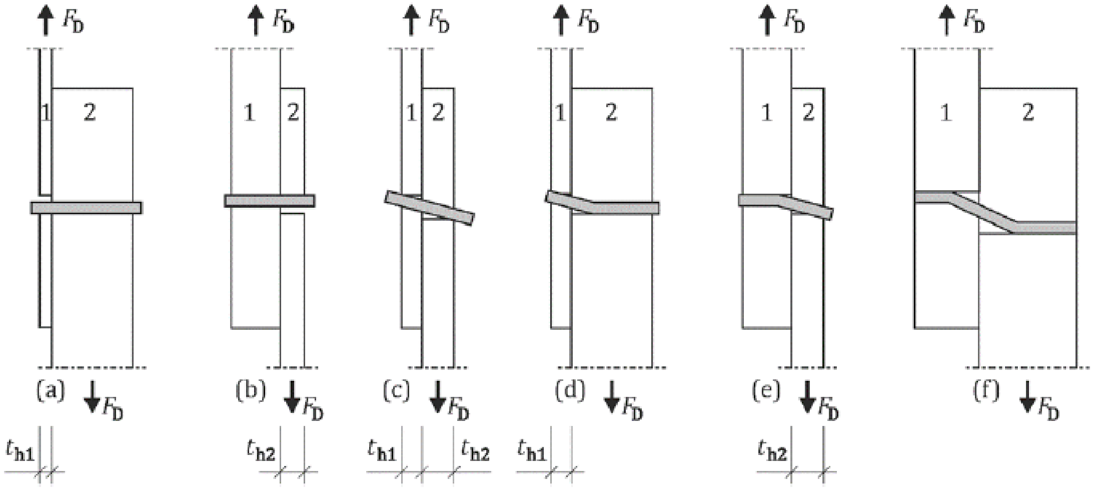


Figure 7: Failure modes (a) to (f) for a fastener loaded in single shear plane [1].

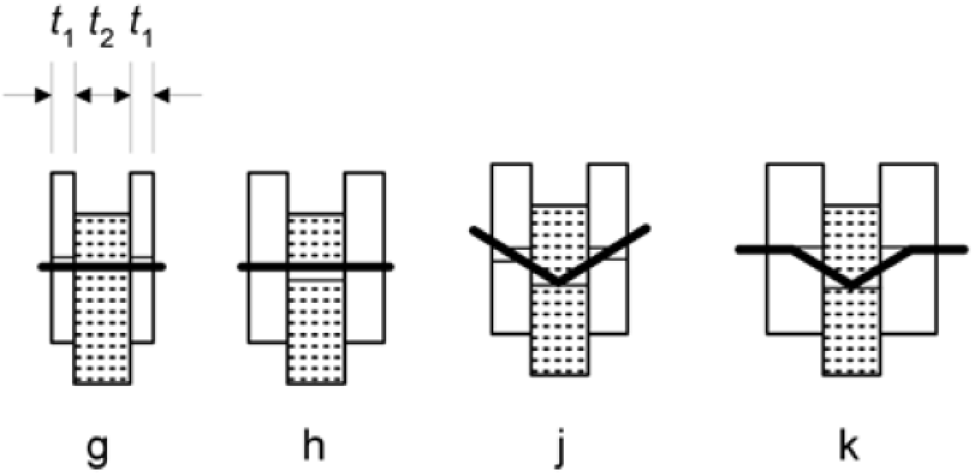


Figure 8: Failure modes (g), (h), (j) and (k) of a symmetric connection with a fastener loaded in double shear planes [2].

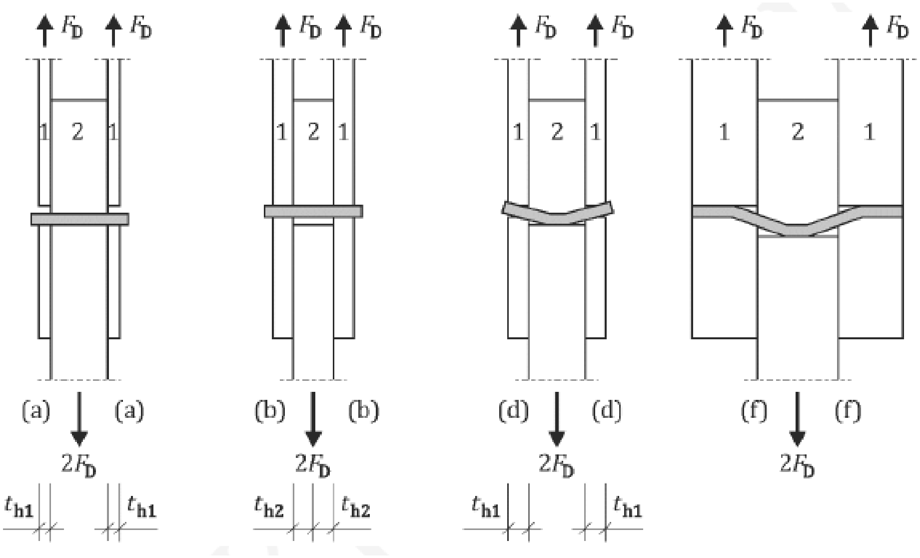


Figure 9: Failure modes (a), (b), (d) and (f) of a single shear plane for a fastener loaded in double shear planes [1].

The expressions provided to determine the characteristic value of the dowel-effect contribution of a fastener per shear plane $F_{D,k}$ for the six failure modes (a) to (f) are for timber-to-timber and steel-to-timber connections in the New Eurocode 5, but for only timber-to-timber connections in the Present Eurocode 5. The characteristic value of the dowel-effect contribution of a fastener per shear plane ($F_{D,k}$) is the minimum value of the expressions for the six failure modes (a) to (f):

$$F_{D,k} = \min\{(\mathrm{a}); (\mathrm{b}); (\mathrm{c}); (\mathrm{d}); (\mathrm{e}); (\mathrm{f})\} \tag{44}$$

where

$(a), (b), (c), (d), (e)$ and (f) are the expressions (Johansen's equations) for the six failure modes (a) to (f) and are given below by Equations (*45*) to (*50*) respectively.

The expressions (Johansen's equations) for the six failure modes (a) to (f) are given by:

Failure mode	**Expression (Johansen's equation)**	
(a)	$f_{h,1,k} t_{h1} d$	(45)
(b)	$f_{h,2,k} t_{h2} d$	(46)
(c)	$\frac{f_{h,1,k} t_{h1} d}{1+\beta}\left[\sqrt{\beta + 2\beta^2\left[1 + \frac{t_{h2}}{t_{h1}} + \left(\frac{t_{h2}}{t_{h1}}\right)^2\right] + \beta^3\left(\frac{t_{h2}}{t_{h1}}\right)^2} - \beta\left(1 + \frac{t_{h2}}{t_{h1}}\right)\right]$	(47)
(d)	$1.05\frac{f_{h,1,k} t_{h1} d}{2+\beta}\left[\sqrt{2\beta(1+\beta) + \frac{4\beta(2+\beta)M_{y,Rk}}{f_{h,1,k} d {t_{h1}}^2}} - \beta\right]$	(48)

(e) $$1.05\frac{f_{h,1,k}t_{h2}d}{1+2\beta}\left[\sqrt{2\beta^2(1+\beta)+\frac{4\beta(1+2\beta)M_{y,Rk}}{f_{h,1,k}d{t_{h2}}^2}}-\beta\right] \tag{49}$$

(f) $$1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,Rk}f_{h,1,k}d} \tag{50}$$

with

$\beta = \frac{f_{h,2,k}}{f_{h,1,k}}$ in all the expressions above (51)

For a timber-to-timber connection, the Present Eurocode 5 provides expressions for the six failure modes (a) to (f) to determine the Johansen's part of the characteristic load-carrying capacity (dowel-effect contribution) of a fastener per shear plane. For a steel-to-timber connection, the Present Eurocode 5 provides different expressions to determine the characteristic dowel-effect contribution (Johansen's part) of a fastener per shear plane. The characteristic lateral resistance of a steel-to-timber connection depends on the thickness of the steel plates. According to the Present Eurocode 5, steel plates having thickness less than or equal to 0.5*d* are thin plates and steel plates having thickness greater than or equal to 1*d* with the tolerance on hole diameters being less than 0.1*d* are thick plates. The characteristic load-carrying capacity of a connection with steel plate having thickness between a thin and a thick plate is to be determined by linear interpolation between the values for thin and thick plate.

In the Present Eurocode 5, the characteristic dowel-effect contribution (Johansen's part) of metal dowel-type fastener in steel-to-timber connection is taken as the minimum value found from the expressions of the failure modes given below:

- Single shear with a thin steel plate ($t_p \leq 0.5d$)

$$F_{v,Rk} = \min\begin{cases} 0.4f_{h,k}t_1d & \text{(a)} \\ 1.15\sqrt{2M_{y,Rk}f_{h,k}d} & \text{(b)} \end{cases} \tag{52}$$

- Single shear with a thick steel plate ($t_p \geq d$)

$$F_{v,Rk} = \min\begin{cases} f_{h,k}t_1d & \text{(c)} \\ f_{h,k}t_1d\left[\sqrt{2+\frac{4M_{y,Rk}}{f_{h,k}d{t_1}^2}}-1\right] & \text{(d)} \\ 2.3\sqrt{M_{y,Rk}f_{h,k}d} & \text{(e)} \end{cases} \tag{53}$$

- Double shear with any thickness of a steel plate as an inner member

$$F_{v,Rk} = \min \begin{cases} f_{h,1,k} t_1 d & \text{(f)} \\ f_{h,1,k} t_1 d \left[\sqrt{2 + \frac{4M_{y,Rk}}{f_{h,1,k} d t_1{}^2}} - 1 \right] & \text{(g)} \\ 2.3 \sqrt{M_{y,Rk} f_{h,1,k} d} & \text{(h)} \end{cases} \tag{54}$$

- Double shear with thin steel plates ($t_p \leq 0.5d$) as the outer members

$$F_{v,Rk} = \min \begin{cases} 0.5 f_{h,2,k} t_2 d & \text{(j)} \\ 1.15 \sqrt{2M_{y,Rk} f_{h,2,k} d} & \text{(k)} \end{cases} \tag{55}$$

- Double shear with thick steel plates ($t_p \geq d$) as the outer members

$$F_{v,Rk} = \min \begin{cases} 0.5 f_{h,2,k} t_2 d & \text{(l)} \\ 2.3 \sqrt{M_{y,Rk} f_{h,2,k} d} & \text{(m)} \end{cases} \tag{56}$$

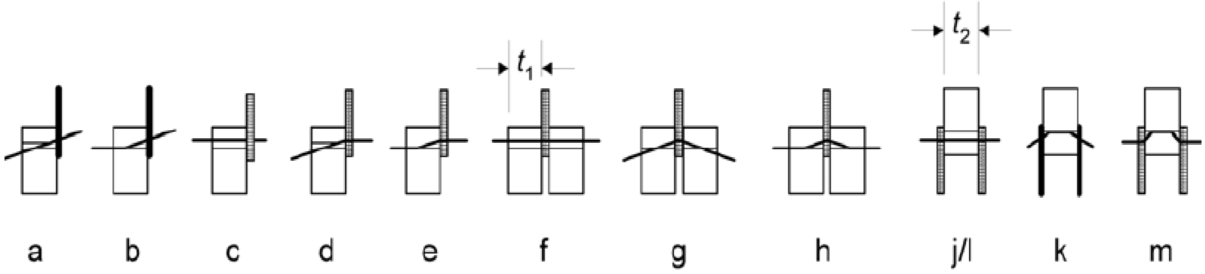


Figure 10: Failure modes (a) to (m) for a fastener in a steel-to-timber connection [2].

The New Eurocode 5 considers the thickness of the steel plate in a steel-to-timber connection by introducing a factor k_{pl} when determining the characteristic embedment strength of the steel plate $f_{h,k}$. The factor k_{pl} depends on the ratio d/t where d is the fastener diameter and t is the thickness of steel plate.

$$f_{h,k} = k_{pl} * 600 \text{ N/mm}^2 \tag{57}$$

where

$k_{pl} = 1.0$ for inner steel plates

$k_{pl} = 0.5$ for $d/t \leq 0.5$ for outer steel plates

$k_{pl} = 1.0$ for $d/t > 1.0$ for outer steel plates and for intermediate ratios *d/t* interpolation is allowed.

In addition to the expressions for the six failure modes (a) to (f) discussed above, the New Eurocode 5 provides the following expressions as a simplification to determine the characteristic value of the dowel-effect contribution of a fastener per shear plane $F_{D,k}$. These simplified formulas are some of the additions made to the New Eurocode 5. In a timber-to-timber connection of members with embedment depths t_{h1} and t_{h2} the simplified formula is given as:

$$F_{D,k} = 1.15\sqrt{\frac{2\beta}{1+\beta}}\sqrt{2M_{y,k}f_{h,1,k}d} * \min\begin{cases} t_{h1}/t_{h1,req} \\ t_{h2}/t_{h2,req} \\ 1 \end{cases} \tag{58}$$

with

$$\beta = \frac{f_{h,2,k}}{f_{h,1,k}} \tag{59}$$

In steel-to-timber connections having timber members with embedment depth t_h the simplified formula is given as:

$$F_{D,k} = 1.15 * 2 * \sqrt{M_{y,k}f_{h,k}d} * \min\begin{cases} t_h/t_{h,req} \\ 1 \end{cases} \tag{60}$$

with

$$t_{h,req} = 1.15 * 4 * \sqrt{\frac{M_{y,k}}{f_{h,k}d}} \tag{61}$$

The expressions for determining the values of the required minimum embedment depths which ensure failure mode (d) or (e) are given in Table 9 and for those which ensure failure mode (f) are given in Table 10.

Table 9: Required minimum embedment depths which ensure failure mode (d) or (e) [1].

Failure mode	**Member 1**	(62)	**Member 2**	(63)
Fasteners in a single shear plane				
(d)	$t_{h1,req} = 1.05\sqrt{2}\sqrt{\frac{M_{y,k}}{f_{h,1,k}d}}\left(\frac{\sqrt{\beta}}{\sqrt{1+\beta}}\right)$		$t_{h2,req} = 1.05\sqrt{2}\sqrt{\frac{M_{y,k}}{f_{h,2,k}d}}\left(\frac{1}{\sqrt{1+\beta}}+\sqrt{2}\right)$	
(e)	$t_{h1,req} = 1.05\sqrt{2}\sqrt{\frac{M_{y,k}}{f_{h,1,k}d}}\left(\frac{\sqrt{\beta}}{\sqrt{1+\beta}}+\sqrt{2\beta}\right)$		$t_{h2,req} = 1.05\sqrt{2}\sqrt{\frac{M_{y,k}}{f_{h,2,k}d}}\left(\frac{1}{\sqrt{1+\beta}}\right)$	

Fasteners in two or more shear planes		
(d)	$t_{h1,req} = 1.05\sqrt{2}\sqrt{\frac{M_{y,k}}{f_{h,1,k}d}}\left(\frac{\sqrt{\beta}}{\sqrt{1+\beta}}\right)$	$t_{h2,req} = \frac{t_{h1}}{\beta}$
(e)	Does not apply	Does not apply

Table 10: Required minimum embedment depths which ensure failure mode (f) [1].

Failure mode	**Member 1**	(64)	**Member 2**	(65)
Fasteners in a single shear plane				
(f)	$t_{h1,req} = 1.15 * 2\sqrt{\frac{M_{y,k}}{f_{h,1,k}d}}\left(\frac{\sqrt{\beta}}{\sqrt{1+\beta}}+1\right)$		$t_{h2,req} = 1.15 * 2\sqrt{\frac{M_{y,k}}{f_{h,2,k}d}}\left(\frac{1}{\sqrt{1+\beta}}+1\right)$	
Fasteners in double shear planes				
(f)	$t_{h1,req} = 1.15 * 2\sqrt{\frac{M_{y,k}}{f_{h,1,k}d}}\left(\frac{\sqrt{\beta}}{\sqrt{1+\beta}}+1\right)$		$t_{h2,req} = 1.15 * 2\sqrt{\frac{M_{y,k}}{f_{h,2,k}d}}\left(\frac{1}{\sqrt{1+\beta}}\right)$	

The nomenclature used in the dowel-effect contribution of a single fastener in a single and double shear planes in the Present Eurocode 5 and the New Eurocode 5 are given in Table 11.

Table 11: Nomenclature used in the dowel-effect contribution of a single fastener in a single shear plane and double shear planes.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{v,Rk}$	$F_{v,k}$	characteristic lateral resistance of a connection in N
$f_{h,1,k}$	$f_{h,1,k}$	characteristic embedment strength of member 1, in N/mm^2
$f_{h,2,k}$	$f_{h,2,k}$	characteristic embedment strength of member 2, in N/mm^2
t_1	t_{h1}	embedment depth of member 1, in mm
t_2	t_{h2}	embedment depth of member 2, in mm

t_p	t	thickness of the steel plate, in mm
$M_{y,Rk}$	$M_{y,k}$	characteristic yield moment, Nmm
d	d	diameter of the fastener, in mm
β	β	ratio between embedment strengths of the members
	$t_{h1,req}$	required minimum embedment depth of the timber member 1 in timber-to-timber connection, in mm
	$t_{h2,req}$	required minimum embedment depth of the timber member 2 in timber-to-timber connection, in mm
$f_{h,k}$	$f_{h,k}$	characteristic embedment strength of timber member in steel-to-timber connection, in N/mm^2
	t_h	embedment depth of the timber member in steel-to-timber connection, in mm
	$t_{h,req}$	required minimum embedment depth of the timber member in steel-to-timber connection, in mm

3.2 Dowel-effect contribution of multiple shear planes

In the New Eurocode 5 and the Present Eurocode 5, the dowel effect contribution per fastener for connections with more than two shear planes is determined by summing the dowel effect contribution of each individual shear plane. In the Present Eurocode 5, a connection with more than two shear planes is decomposed into a series of three -member connections and the dowel effect contribution of each individual shear plane is determined by considering each individual shear plane as part of the three-member connection. The governing failure mode of the fasteners in the respective shear planes must be compatible with each other and must not comprise of a combination of failure modes (a) and (b) from Figure 7 or failure modes (g) and (h) from Figure 8 or failure modes (e), (f) and (j/l) from Figure 10 with other failure modes in order to combine the dowel effect contribution of each individual shear plane. Checking the compatibility of failure modes is not always easy and it is a tedious work for some configurations of connections.

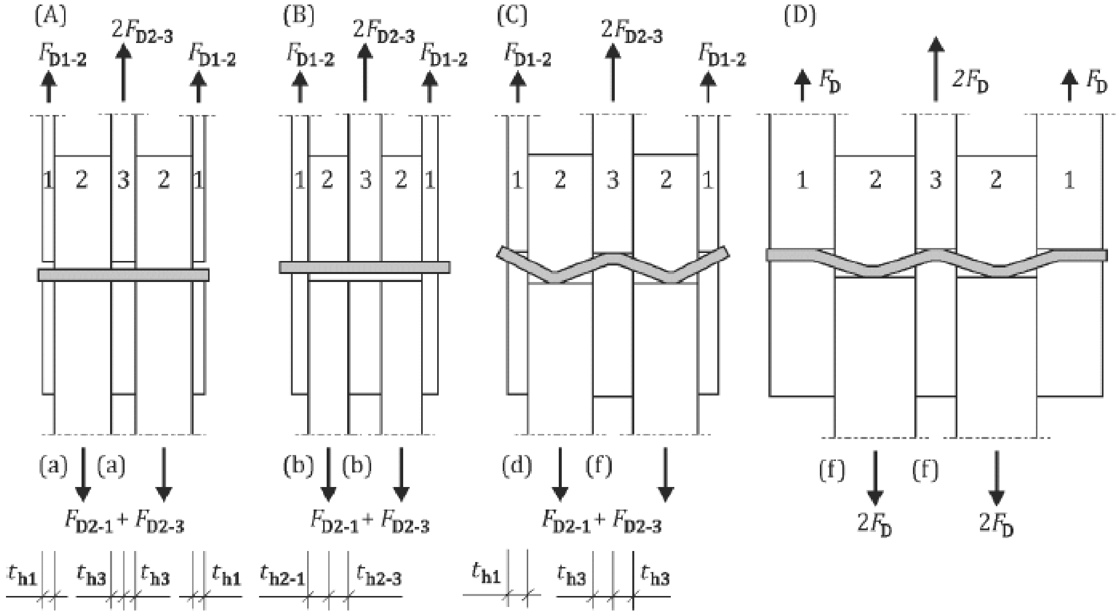
In the New Eurocode 5, the inner members in connections with more than two shear planes, as shown in Figure 11, are considered as inner members in connections with fasteners in double shear planes as depicted in Figure 9. Compatibility between the members is achieved for fasteners that fail in mode (a) only or in mode (b) only or in modes (d) and (f) only or in mode (f) only. In connections with more than two shear planes, the failure modes (a), (b), (d) and (f) can occur for the side members and the failure modes (a), (b) and (f) can occur for the middle members. From these failure modes, the New Eurocode 5 provides four compatible failure mode combinations (A), (B),

(C) and (D) for connections with more than two shear planes. For instance, failure mode combination (A) is the combination of only failure mode (a) for all outer and inner single shear planes as shown in Figure 11. The governing combination of these four compatible failure mode combinations (A), (B), (C) and (D) gives the dowel effect contribution per fastener for connection with more than two shear planes. Combinations of other failure modes, such as failure mode combinations (E), (F) and (G) in Figure 11, are avoided according to the New Eurocode 5. For connections with four or more shear planes, compatibility between the members is ensured for fasteners that fail only in modes (d) and (f) as in combination (C) in Figure 11 and only in mode (f) as in combination (D) in Figure 11, if:

- the inner members have required thickness value in Table 10

- the outer members have more than 64 % of the required thickness value in Table 10

The New Eurocode 5 provides four failure mode combinations (A), (B), (C) and (D) to ensure compatibility between the members in a connection with more than two shear planes, but the compatibility between the failure modes must be checked by the designer according to the Present Eurocode 5.



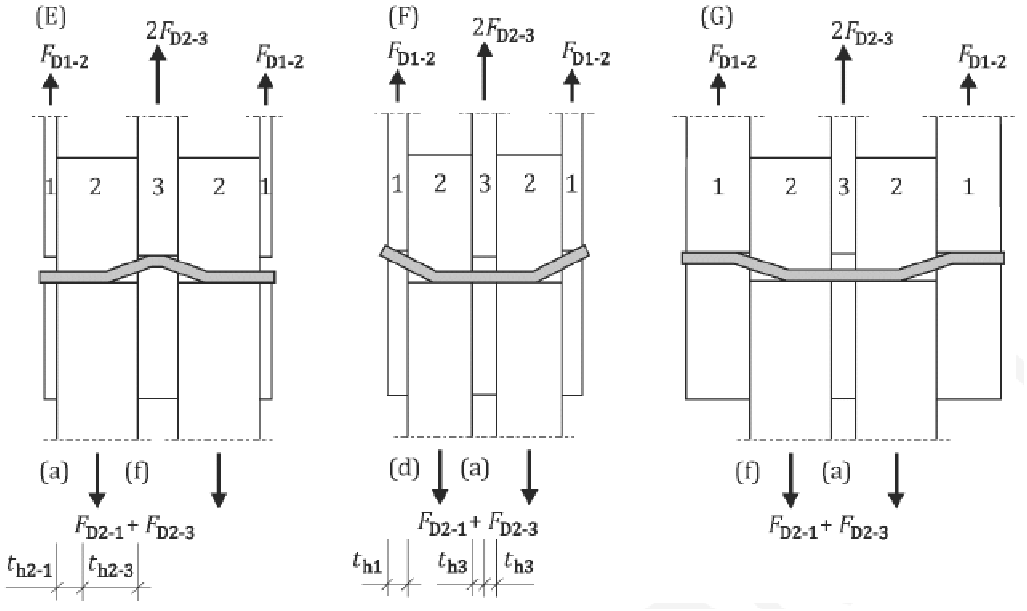


Figure 11: Combinations of failure modes for fasteners in a connection with four shear planes [1].

3.3 Characteristic embedment strength

3.3.1 Nails

The expression provided by the New Eurocode 5 for the determination of the characteristic embedment strength of nails has one more parameter, which is k_{mat}, than by the Present Eurocode 5. k_{mat} is a material factor which depends on the type of the material. For the types of timber that are considered in this thesis, $k_{mat} = 1.0$ as shown in Table 12. In the New Eurocode 5, the characteristic embedment strength, which is given in Table 12, is for all nails. In the Present Eurocode 5, the characteristic embedment strength, which is given in Table 12, is for nails with diameters up to 8 mm ($d \leq 8$ mm). For nails with diameters greater than 8 mm ($d > 8$ mm), the characteristic embedment strength values for bolts are applied according to the Present Eurocode 5.

Table 12: Characteristic embedment strength of nails.

	Present Eurocode 5		**New Eurocode 5**	
Not predrilled	$f_{h,k} = 0.082\rho_k d^{-0.3}$	(66)	$f_{h,\alpha,\beta,k} = \frac{0.082\rho_k d^{-0.3}}{k_{mat}}$ $k_{mat} = 1.0$ for ST and PL	(67)
Predrilled	$f_{h,k} = 0.082(1 - 0.01d)\rho_k$	(68)	$f_{h,\alpha,\beta,k} = \frac{0.082(1 - 0.01d)\rho_k}{k_{mat}}$ $k_{mat} = 1.0$ for SL and PL	(69)

3.3.2 Bolts and Dowels

As given in Table 13, the expressions for the determination of the characteristic embedment strength of bolts and dowels provided by the New Eurocode 5 and the Present Eurocode 5 are the same. In the New Eurocode 5, the characteristic embedment strength value for nails is applied for dowels with diameters less than or equal to 8 mm ($d \leq 8$ mm), and the characteristic embedment strength values for bolts is applied for dowels with diameters up to 30 mm ($d \leq 30$ mm). The expressions for k_{mat} and k_{90} in Table 13 are in accordance with the types of the timber members considered in this thesis, which are SL and PL. In the Present Eurocode 5, the characteristic embedment strength value for nails is applied for dowels with diameters up to 8 mm (6 mm < $d \leq 8$ mm), and the characteristic embedment strength value for bolts is applied for dowels with diameters up to 30 mm (8 mm < $d \leq 30$ mm).

Table 13: Characteristic embedment strength of bolts and dowels.

Present Eurocode 5		**New Eurocode 5**	
$f_{h,\alpha,k} = \dfrac{f_{h,0,k}}{k_{90}\sin^2\alpha + \cos^2\alpha}$	(70)	$f_{h,\alpha,k} = \dfrac{0.082(1-0.01d)\rho_k}{k_{mat}}$	(71)
$f_{h,0,k} = 0.082(1-0.01d)\rho_k$	(72)	$k_{mat} = k_{90}\sin^2\alpha + \cos^2\alpha$	(73)
$k_{90} = 1.35 + 0.015d$	(74)	$k_{90} = 1.35 + 0.015d$	(75)

3.3.3 Screws and rods with wood screw thread

For the determination of the characteristic embedment strength for screws and rods with wood screw thread, the New Eurocode 5 provides an expression as given in Equation (*76*) and the Present Eurocode 5 gives a provision as presented below.

Present Eurocode 5

The characteristic embedment strength values for nails are applied for screws with effective diameters less than or equal to 6 mm ($d_{ef} \leq 6$ mm) and the characteristic embedment strength values for bolts are applied for screws with effective diameters greater than 6 mm ($d_{ef} > 6$ mm).

New Eurocode 5

The characteristic embedment strength for screws and rods with wood screw thread is given by:

$$f_{h,\varepsilon,k} = \frac{0.019 * {\rho_k}^{1.24} * d^{-0.3}}{2.5 * \cos^2\varepsilon + \sin^2\varepsilon} \tag{76}$$

The nomenclature used in the characteristic embedment strength for metal dowel-type fasteners in the Present Eurocode 5 and the New Eurocode 5 are presented in Table 14.

Table 14: Nomenclature used in the characteristic embedment strength for metal dowel-type fasteners.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$f_{h,k}$	$f_{h,\alpha,\beta,k}$	characteristic embedment strength for nails, in N/mm^2
$f_{h,\alpha,k}$	$f_{h,\alpha,k}$	characteristic embedment strength for bolts and dowels, in N/mm^2
	$f_{h,\varepsilon,k}$	characteristic embedment strength for screws and rods with wood screw thread, in N/mm^2
$f_{h,0,k}$		characteristic embedment strength parallel to grain, in N/mm^2
ρ_k	ρ_k	characteristic timber density, in kg/m^3
d	d	diameter of the fastener, in mm
α	α or ε	angle between the fastener axis and the grain direction
	β	angle between the fastener axis and the surface of the wide face

3.4 Characteristic yield moment

3.4.1 Nails

The expressions provided for determining the characteristic yield moment of nails by the Present Eurocode 5 and the New Eurocode 5 are the same as given in Table 15. The only distinguishing parameter is the value of the coefficient in the expressions. The value of the coefficient in the expression by the New Eurocode 5 is 0.3 for all nails, but $M_{y,k}$ is increased by 50 % for square nails where the nail diameter d is taken as the side dimension. The value of the coefficient in the expressions by the Present Eurocode 5 is based on shape of nails, namely 0.3 for round nails and 0.45 for square and grooved nails. For square and grooved nails, the side dimension is taken as the nail diameter d.

Table 15: Characteristic yield moment of nails.

Present Eurocode 5				New Eurocode 5	
Round nails		Square and grooved nails		All nails	
$M_{y,Rk} = 0.3 f_u d^{2.6}$	(77)	$M_{y,Rk} = 0.45 f_u d^{2.6}$	(78)	$M_{y,k} = 0.3 f_{u,k} d^{2.6}$	(79)

3.4.2 Bolts and Dowels

The expressions for determining the characteristic yield moment of nails provided by the Present Eurocode 5 and the New Eurocode 5 are the same and are given in Table 16.

Table 16: Characteristic yield moment for bolts and dowels.

Present Eurocode 5		New Eurocode 5	
$M_{y,Rk} = 0.3 f_{u,k} d^{2.6}$	(80)	$M_{y,k} = 0.3 f_{u,k} d^{2.6}$	(81)

3.4.3 Screws and rods with wood screw thread

For the determination of the characteristic yield moment for screws and rods with wood screw thread, the New Eurocode 5 provides an expression as given in Equation (*82*) and the Present Eurocode 5 gives a provision as presented below.

Present Eurocode 5

For screws with effective diameters less than or equal to 6 mm ($d_{ef} \leq 6$ mm), the characteristic yield moment values for nails are applied and for screws with effective diameters greater than 6 mm ($d_{ef} > 6$ mm), the characteristic yield moment values for bolts are applied.

New Eurocode 5

The characteristic yield moment for screws and rods with wood screw thread is given by:

$$M_{y,k} = 0.3 f_{u,k} d^{2.6} \qquad (82)$$

For screws and rods with wood screw thread with 3.5 mm ≤ d ≤ 22 mm, the outer diameter d is equal to the inner thread diameter d_1 for the following ratios in Table 17:

Table 17: d_1/d values for screws and rods with wood screw thread [1].

d	$3.5 \leq d \leq 10$	$10 \leq d \leq 14$	$14 \leq d \leq 22$
d_1/d	0.65	0.60	0.75

The nomenclature used in the characteristic yield moment for metal dowel-type fasteners in the Present Eurocode 5 and the New Eurocode 5 is given in Table 18.

Table 18: Nomenclature used in the characteristic yield moment for metal dowel-type fasteners.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$M_{y,Rk}$	$M_{y,k}$	characteristic value for the yield moment, in Nmm
f_u or $f_{u,k}$	$f_{u,k}$	characteristic tensile strength of the wire, in N/mm^2
d	d	diameter of the fastener, in mm
	d_1	inner thread diameter of the fastener, in mm

3.5 Rope-effect contribution

For connections with single shear plane, the rope-effect contribution is only accounted for failure modes (c) to (f) in Figure 7 in the New Eurocode 5 and the Present Eurocode 5. For connections with double shear planes, the rope-effect contribution is only accounted for failure modes (j) and (k) in Figure 8 in the Present Eurocode 5 and for failure modes (d) and (f) in Figure 9 in the New Eurocode 5. No rope effect contribution is accounted for failure modes (a) or (b) in Figure 7 and Figure 9 in the New Eurocode 5. No rope effect contribution is accounted for failure modes (a) or (b) in Figure 7 and (g) and (h) in Figure 8 in the Present Eurocode 5. The approach for the determination of the rope effect contribution by the Present Eurocode 5 and the New Eurocode 5 are the same. The Present Eurocode 5 provides no explicit formula for the determination of the rope effect. The New Eurocode 5 provides an expression for the determination of the rope effect contribution. The value of the factor for the rope effect contribution $k_{rp,1}$ is 0.25 in general and 0.40 for ring shank nails in the New Eurocode 5 and they are given in Table 19. The New Eurocode 5 considers the head pull-through, withdrawal and axial capacities and takes the minimum value of these capacities. The value of the factor for the rope effect contribution $k_{rp,1}$ is 1/4 % (0.25) in general and it exists directly in the expression for determining the load-carrying capacity in the Present Eurocode 5. The Present Eurocode 5 considers only the withdrawal resistance. The limitation factor for the rope effect contribution $k_{rp,2}$ in the New Eurocode 5 and the specific percentages in the Present Eurocode 5 are the same and are given in Table 20.

Present Eurocode 5

The characteristic rope effect contribution is the minimum of one fourth of the characteristic withdrawal capacity $F_{ax,Rk}$ of the fastener and a specific percentage ($k_{rp,2}$) of the Johansen part (dowel-effect contribution $F_{D,k}$) and it is given by Equation (*83*). If $F_{ax,Rk}$ is unknown, the rope effect contribution is zero.

$$Rope - effect = \min \begin{cases} \dfrac{F_{ax,Rk}}{4} \\ k_{rp,2} * F_{D,k} \end{cases} \tag{83}$$

New Eurocode 5

The characteristic rope-effect contribution per shear plane per fastener $F_{rp,k}$ is given by:

$$F_{rp,k} = \min \begin{cases} k_{rp,1} * F_{ax,t,k} \\ k_{rp,2} * F_{D,k} \end{cases} \tag{84}$$

$$F_{ax,t,k} = \min \begin{cases} F_{pull,k} \\ F_{w,k} \\ F_{t,k} \end{cases} \tag{85}$$

where

$k_{rp,1}$	is the factor for the rope effect, see Table 19;
$k_{rp,2}$	is the limitation factor for the rope effect, see Table 20;
$F_{D,k}$	is the dowel effect contribution, in N;
$F_{ax,t,k}$	is the characteristic axial capacity of the fasteners, in N;
$F_{pull,k}$	is the characteristic head pull-through resistance, in N;
$F_{w,k}$	is the characteristic withdrawal resistance, in N;
$F_{t,k}$	is the characteristic tensile resistance, in N.

Table 19: Factors $k_{rp,1}$ for the rope effect contribution [1].

Fastener and connection type	$\boldsymbol{k_{rp,1}}$
General	0.25
Ring shank nails	0.40

Table 20: Limitation factors $k_{rp,2}$ for the rope effect contribution [1].

Fastener type	$\boldsymbol{k_{rp,2}}$
Dowels	0
Smooth round nails and uncoated staples	0.15
Smooth square nails and bolts	0.25
Ring shank nails and coated staples	0.50
Screws, rods with wood screw thread and laterally loaded bonded-in rods	1.00

3.6 Example cases for dowel-effect contribution

3.6.1 Fastener in a single shear plane

As shown in Figure 12, a connection with two timber members subjected to tension and fasteners in a single shear plane is used in this example case. The connection is a timber-to-timber connection. The timber members are of solid timber C24 with a characteristic density ρ_k = 350 kg/m^3. Dowels of diameter d = 12 mm with a characteristic tensile strength $f_{u,k}$ = 600 N/mm^2 are used as fasteners in the connection. The angle of the load to the grain direction is 0° (α = 0°) in both timber members. For timber-to-timber connections with fasteners in a single shear plane, the Present Eurocode 5 and the New Eurocode 5 provides the same expressions and follows the same procedure to determine the characteristic value of the dowel-effect contribution of a fastener per shear plane ($F_{D,k}$). The values achieved in this example by using expressions provided by these two versions of Eurocode 5 are therefore the same. Equations (*70*) and (*71*) are applied to determine the value of the characteristic embedment strength and Equations (*80*) and (*81*) to determine the characteristic yield moment in the Present Eurocode 5 and the New Eurocode 5 respectively. Different values of the six failure modes (a) to (f), the minimum value ($F_{D,k,min}$) and the characteristic values ($F_{D,k}$) of the dowel-effect contribution of a fastener for the connection are obtained by changing the thickness of one timber member at a time while keeping the thickness of the other member constant. The values of the six failure modes, the minimum and the characteristic values of the dowel-effect contribution per fastener for the connection by changing the thickness of member one and member two are presented in Table 21 and Table 22 and plotted in Figure 13 and Figure 14 respectively.

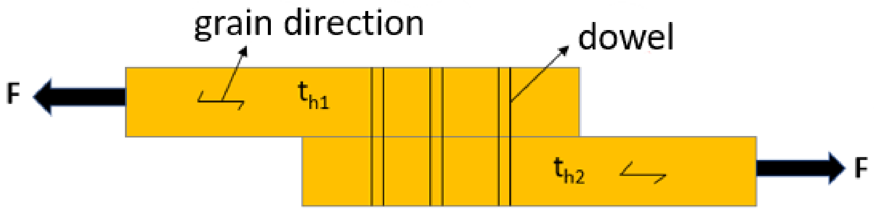


Figure 12: Connection with fasteners in single shear.

Table 21: Values for failure modes and minimum and characteristic dowel-effect contribution of a fastener in a single shear plane by using different thicknesses of member 1.

t_{h1} [mm]	**a** [kN]	**b** [kN]	**c** [kN]	**d** [kN]	**e** [kN]	**f** [kN]	$F_{D,k}$ [kN]	$F_{D,k,\min}$ [kN]
0	0	10.91	3.99	7.16	6.65	9.61	0	0
1d	3.64	10.91	3.64	6.33	6.65	9.61	3.64	3.64
2d	7.27	10.91	3.89	6.24	6.65	9.61	3.89	3.89
3d	10.91	10.91	4.52	6.65	6.65	9.61	4.52	4.52
4d	14.55	10.91	5.36	7.36	6.65	9.61	5.36	5.36
5d	18.18	10.91	6.34	8.24	6.65	9.61	6.35	6.34
6d	21.82	10.91	7.41	9.23	6.65	9.61	6.65	6.65
7d	25.46	10.91	8.54	10.30	6.65	9.61	6.65	6.65

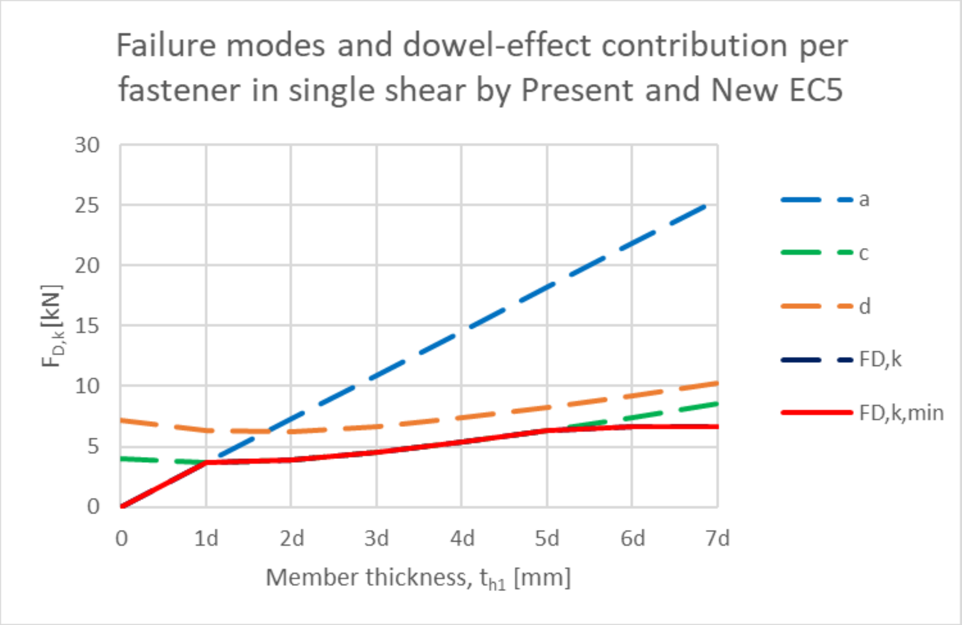


Figure 13: Failure modes and minimum and characteristic values of dowel-effect contribution of a fastener in a single shear plane by using different thicknesses of member 1.

The values presented in Table 21 and plotted in Figure 13 are obtained by holding the thickness of member 2 constant, t_{h2} = 36 mm. Figure 13 shows that the failure mode (a) increases significantly with the thickness of member 1 as it is the embedment failure of only member 1. The failure modes (c) and (d) change slightly with the thickness of the member 1 as they include respectively embedment failure of member 2 and yielding failure of the fastener in addition to embedment failure of member 1. The failure modes (b), (e) and (f) are not drawn in Figure 13 because they are constants as they are independent of the change of the thickness of member 1 (t_{h1}). By referring to the plot of $F_{D,k,min}$, the thicknesses of transition are 1d mm (t_{trans} = 12 mm) and 5d mm (t_{trans} = 60 mm). They are the thicknesses of member 1 where the plot of $F_{D,k,min}$ changes from the failure mode (a) to the failure mode (c) at 1d mm and it changes again at 5d mm from the failure mode (c) to the failure mode (e) which is constant and independent of the thickness change of member 1.

Table 22: Values of failure modes and minimum and characteristic dowel-effect contribution of a fastener in a single shear plane by using different thicknesses of member 2.

t_{h2} [mm]	**a** [kN]	**b** [kN]	**c** [kN]	**d** [kN]	**e** [kN]	**f** [kN]	$F_{D,k}$ [kN]	$F_{D,k,\min}$ [kN]
0	10.91	0	3.99	6.65	7.16	9.61	0	0
1d	10.91	3.64	3.64	6.65	6.33	9.61	3.64	3.64
2d	10.91	7.27	3.89	6.65	6.24	9.61	3.89	3.89
3d	10.91	10.91	4.52	6.65	6.65	9.61	4.52	4.52
4d	10.91	14.55	5.36	6.65	7.36	9.61	5.36	5.36

5d	10.91	18.18	6.34	6.65	8.24	9.61	6.35	6.34
6d	10.91	21.82	7.41	6.65	9.23	9.61	6.65	6.65
7d	10.91	25.46	8.54	6.65	10.30	9.61	6.65	6.65

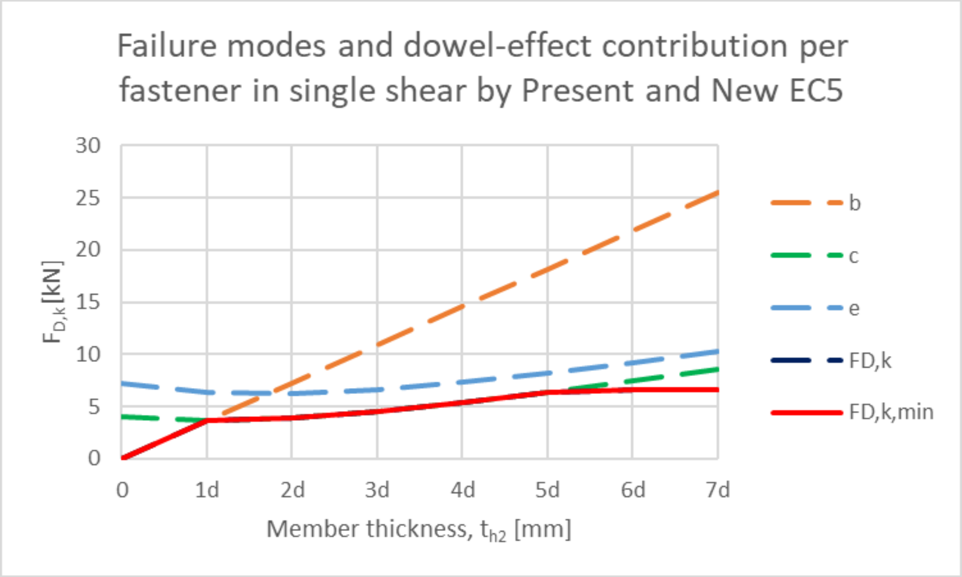


Figure 14: Failure modes and minimum and characteristic values of dowel-effect contribution of a fastener in a single shear plane by using different thicknesses of member 2.

The values presented in Table 22 and plotted in Figure 14 are achieved by keeping the thickness of member 1 constant, t_{h1} = 36 mm. As shown in Figure 14, the failure mode (b), which is the embedment failure of only member 2, increases significantly with the thickness of member 2. The failure modes (a), (d) and (f) are not included in Figure 14. Since they do not depend on the thickness change of member 2, they are constants. The failure modes (c) and (e) decrease slightly at the beginning and keep slightly increasing as the thickness of the member 2 increases. In addition to the embedment failure of member 2, the failure mode (c) includes embedment failure of member 1 and the failure mode (e) includes yielding failure of the fastener. By referring to the plot of $F_{D,k,min}$, the transition thicknesses are 1*d* mm (t_{trans} = 12 mm) and 5*d* mm (t_{trans} = 60 mm). They are the thicknesses where the plot of $F_{D,k,min}$ changes its course from the failure mode (b) to the failure mode (c) at 1*d* mm and it changes its course again from the failure mode (c) to the failure mode (d) which is constant and do not depend on the change of thickness of member 2 beyond the transition thickness 5*d* mm.

3.6.2 Fastener in double shear planes

The connection in this example case, which is also a timber-to-timber connection, consists of two side members (member 1) and one middle member (member 2) subjected to tension and fasteners in double shear planes as depicted in Figure 15. The timber members are of solid timber C24 with a characteristic density ρ_k = 350 kg/m^3. Dowels of diameter d = 12 mm with a characteristic tensile strength $f_{u,k}$ = 600 N/mm^2 are used as fasteners in the connection. The angle of the load to the grain direction is 0° (α = 0°) in all timber members. The Present Eurocode 5 and the New Eurocode 5 provides the same expressions and follows the same procedure to determine the characteristic value of the dowel-effect contribution of a fastener per shear plane ($F_{D,k}$) in timber-to-timber connections with fasteners in double shear planes, however they use different names for the failure modes.

In the New Eurocode 5, the names of the connections with fasteners in double shear planes are (a), (b), (d) and (f) which correspond to the failure modes (a), (b), (d) and (f) for each single shear plane in the connection respectively. In the Present Eurocode 5 the names of the connections with double shear planes are (g), (h), (j) and (k) according to the failure modes (g), (h), (j) and (k) for each single shear plane in the connection respectively. For a single shear plane in a connection with a fastener loaded in double shear planes, the expressions provided by the New Eurocode 5 for the failure modes (a), (b), (d) and (f) are the same with the corresponding expressions provided by the Present Eurocode 5 for the failure modes (g), (h), (j) and (k) respectively. The embedment depth of an inner member in the expression for the failure mode (b) must be taken as half of the thickness of the inner member ($t_{h,2}$ = t_2/2) in the New Eurocode 5, but a reduction factor 0.5 is already existed in the expression for the corresponding failure mode (h) in the Present Eurocode 5. The values achieved in this example case by using expressions provided by the New Eurocode 5 and the Present Eurocode 5 are therefore the same.

Equations (*70*) and (*71*) are applied to determine the value of the characteristic embedment strength and Equations (*80*) and (*81*) to determine the characteristic yield moment. Different values of the four failure modes (a), (b), (d) and (f), the minimum value ($F_{D,k,min}$) and the characteristic value ($F_{D,k}$) of the dowel-effect contribution of a fastener for the connection are obtained by changing either the thickness of the side member (member 1) or the thickness of the middle member (member 2) at a time while holding the thickness of the other member constant. The values of the four failure modes, the minimum and the characteristic values of the dowel-effect contribution for the connection by changing the thickness of side members and middle member are presented in Table 23 and Table 24 and plotted in Figure 16 and Figure 17 respectively.

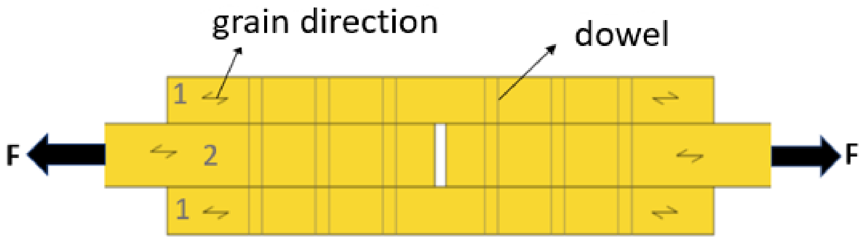


Figure 15: Connection with fasteners in double shear planes [16].

Table 23: Values for failure modes and minimum and characteristic dowel-effect contribution of a fastener in double shear planes by using different thicknesses of side members.

t_{h1} [mm]	**a** [kN]	**b** [kN]	**d** [kN]	**f** [kN]	$F_{D,k}$ [kN]	$F_{D,k,\min}$ [kN]
0	0	7.27	7.16	9.61	0	0
1d	3.64	7.27	6.33	9.61	7.27	3.64
2d	7.27	7.27	6.24	9.61	12.48	6.24
3d	10.91	7.27	6.65	9.61	13.30	6.65
4d	14.55	7.27	7.36	9.61	14.55	7.27
5d	18.18	7.27	8.24	9.61	14.55	7.27
6d	21.82	7.27	9.23	9.61	14.55	7.27

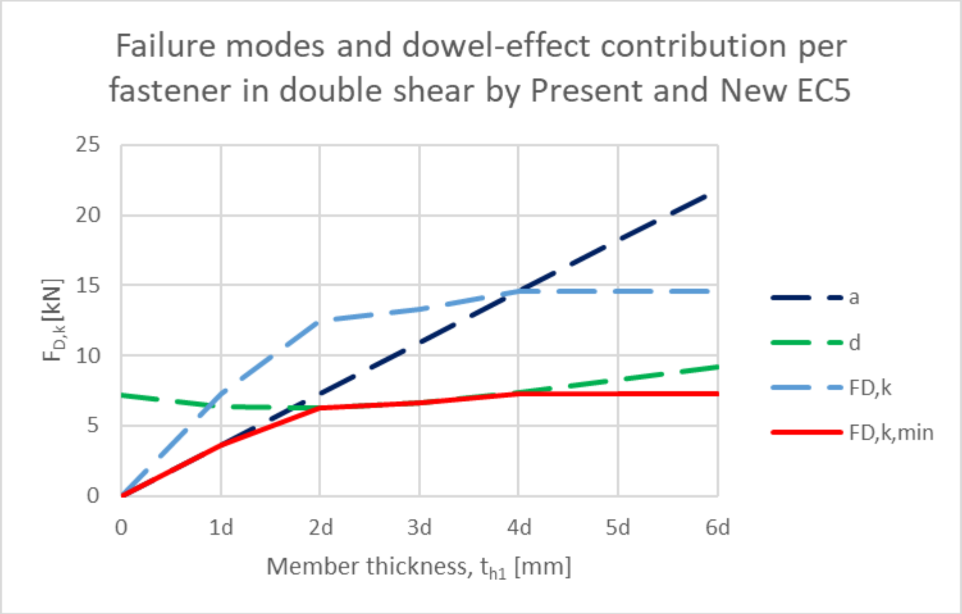


Figure 16: Failure modes and minimum and characteristic values of dowel-effect contribution of a fastener in double shear planes by using different thicknesses of side members.

The values presented in Table 23 and plotted in Figure 16 are achieved by keeping the thickness of middle member (member 2) constant, t_{h2} = 48 mm. As shown in Figure 16, the failure mode (a), which is the embedment failure of only member 1, is increasing significantly with the increasing thickness of member 1. The failure modes (b) and (f) are independent of the change in thickness of member 1. Since they are constant, they are not drawn in Figure 16. The failure mode (d) slightly decreases and then increasing slowly with the thickness of the member 1 as it also depends on yielding failure of the fastener. By referring to the plot of $F_{D,k,min}$, the transition thicknesses are 24 mm (2*d*) and 48 mm (4*d*) conservatively. They are the thicknesses where the plot of $F_{D,k,min}$

changes from the failure mode (a) to the failure mode (d) at 2*d* mm and from the failure mode (d) to the failure mode (b) at 4*d* mm.

Table 24: Values for failure modes and minimum and characteristic dowel-effect contribution of a fastener in double shear planes by using different thicknesses of middle member.

t_{h2} [mm]	**a** [kN]	**b** [kN]	**d** [kN]	**f** [kN]	$F_{D,k}$ [kN]	$F_{D,k,\min}$ [kN]
0	10.91	0	6.65	9.61	0	0
1d	10.91	1.82	6.65	9.61	3.64	1.82
2d	10.91	3.64	6.65	9.61	7.27	3.64
3d	10.91	5.46	6.65	9.61	10.91	5.46
4d	10.91	7.27	6.65	9.61	13.30	6.65
5d	10.91	9.09	6.65	9.61	13.30	6.65
6d	10.91	10.91	6.65	9.61	13.30	6.65

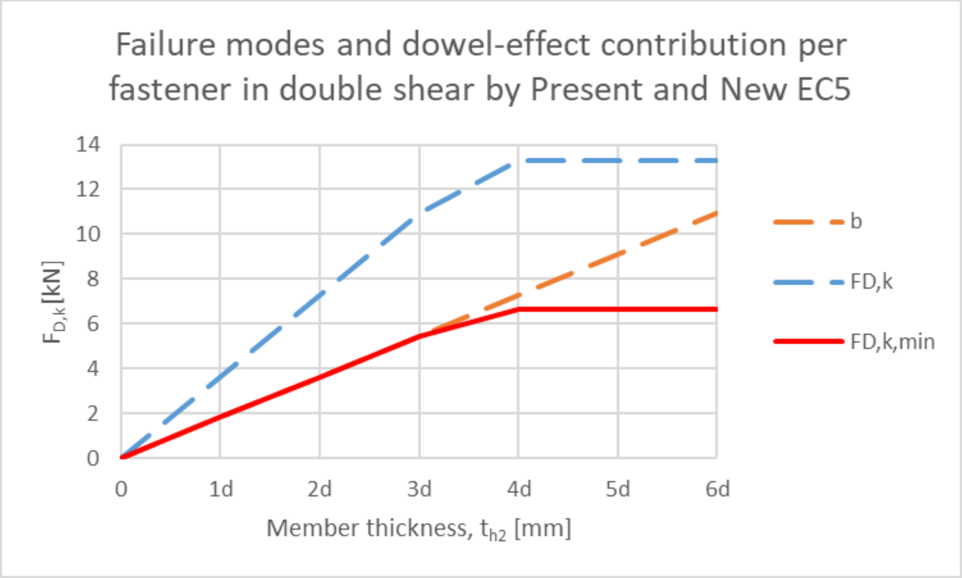


Figure 17: Failure modes and minimum and characteristic values of dowel-effect contribution of a fastener in double shear planes by using different thicknesses of middle member.

The values presented in Table 24 and plotted in Figure 17 are obtained by holding the thickness of side members (member 1) constant, t_{h1} = 36 mm. Figure 17 shows that the failure mode (b) is increasing significantly with the increasing thickness of middle member (member 2) owing to the embedment failure of member 2 only. The failure modes (a), (d) and (f) are independent of the change in thickness of middle member and they are therefore constants. By referring to the plot of $F_{D,k,min}$, the thickness of transition is 4*d* mm conservatively. It is the thickness of the middle member where the plot of $F_{D,k,min}$ changes its course from the failure mode (b) to the failure mode (d) which is independent of the thickness change of member 2 beyond the transition thickness 4*d* mm.

3.6.3 Fastener in multiple shear planes

A connection is used in this example case which consists of a timber member with multiple slotted-in steel plates subjected to tension and fasteners in multiple shear planes as shown in Figure 18. The connection is a steel-to-timber connection. The timber member is a glued laminated timber GL32c with a characteristic density ρ_k = 400 Kg/m^3. Dowels of diameter d = 12 mm with a characteristic tensile strength $f_{u,k}$ = 400 N/mm^2 are used as fasteners in the connection. The thickness of the steel plate is 8 mm and it is assumed as a thick steel plate in this example case. The angle of the load to the grain direction is 0° (α = 0°). The side member (member 1) is the outer most part of the timber member on the side of the connection. The inner member (member 2) is the part of the timber member between two steel plates. Equations (*70*) and (*71*) are applied to determine the value of the characteristic embedment strength of the timber members and Equations (*80*) and (*81*) to determine the characteristic yield moment of the dowels. For connections with more than two shear planes, the dowel effect contribution per fastener is the sum of the dowel effect contributions of each individual shear plane and the inner members are treated as inner members in connections with fasteners in double shear.

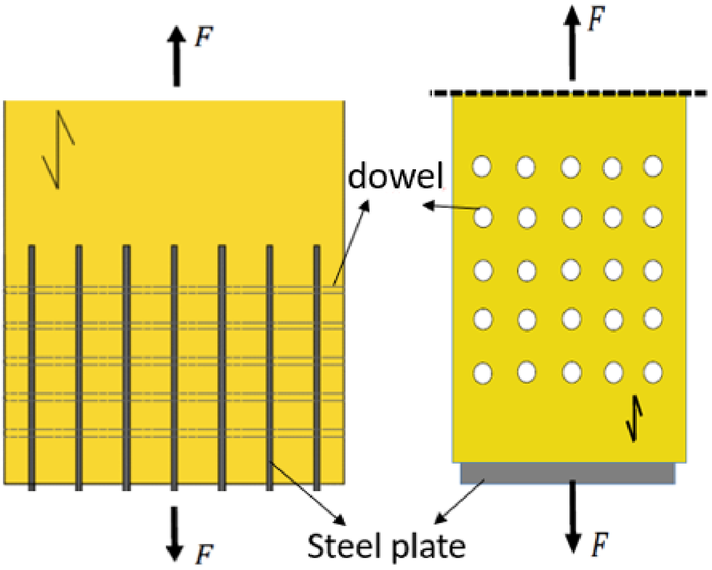


Figure 18: Connections with fasteners in multiple shear planes [16].

The New Eurocode 5 treats the steel plate as a member in a steel-to-timber connection and Equation (*57*) is used to determine the characteristic embedment strength of the steel plate $f_{h,k}$. In the New Eurocode 5 for connections with more than two shear planes, the inner members are considered as inner members in connections with fasteners in double shear planes and compatibility between the members is achieved for fasteners that fail in mode (a) only or in mode (b) only or in modes (d) and (f) only or in mode (f) only. The failure modes (a), (b), (d) and (f) are for the side members and the failure modes (a), (b) and (f) are for the middle members. From these failure modes, the New Eurocode 5 provides four compatible failure mode combinations (A), (B), (C) and (D) for connections with more than two shear planes. For instance, failure mode (A) is the combination of only failure mode (a) for all outer and inner single shear planes as shown in Figure 11. The governing combination of these four compatible failure mode combinations (A), (B), (C) and (D) gives the dowel effect contribution per fastener in connections with more than two shear planes. For the side members, the failure modes (a), (d) and (f) in the New Eurocode 5 give almost the same results with the failure modes (c), (d) and (e) respectively in the Present Eurocode 5. For the middle members, the failure modes (b) and (f) in the New Eurocode 5 give almost the same results with the failure modes (l) and (m) respectively in the Present Eurocode 5.

The Present Eurocode 5 has different failure modes (a) to (m) for a steel-to-timber connection depending on the thickness and location of the steel plates and number of shear planes in the connection. The expressions for failure modes (a) to (m) in a steel-to-timber connection are given in Equations (*52*) to (*56*). The connection is decomposed into a series of three-member connections and the dowel effect contribution of each individual shear plane is determined by considering each individual shear plane as part of the three-member connection. For the side members having single shear plane with a thick steel plate, Equation (*53*) with failure modes (c), (d) and (e) is applied. For the middle members having double shear planes with thick steel plates as the outer members in a three-member connection, Equation (*56*) with failure modes (l) and (m) is used. To get the dowel effect contribution of a fastener in a steel-to-timber connection with more than two shear planes, the failure mode of each individual shear plane must be compatible with each other. If failure mode (l) is the governing failure mode in Equation (*56*), then it is combined with the failure mode (c) in Equation (*53*) to fulfill the compatibility. If failure mode (m) is the governing failure mode in Equation (*56*), then it is combined with either failure mode (d) or failure mode (e) depending on which one is the governing failure mode in Equation (*53*). The Present Eurocode 5 says the strength of the steel plate must be checked but, in this example, it is assumed that the steel plate has enough strength.

Different values of the characteristic dowel-effect contribution per fastener ($F_{D,k}$) in the connection are obtained by using different number of steel plates and by changing either the thickness of the timber side member (member 1) or the thickness of the timber middle member (member 2) at a time for each number of steel plates used while holding the thickness of the other member constant. The characteristic values of the dowel-effect contribution of a fastener in the connection by changing the thicknesses of side members and middle members at a time for each number of steel plate used in the connection are plotted in Figure 19 and Figure 20 respectively.

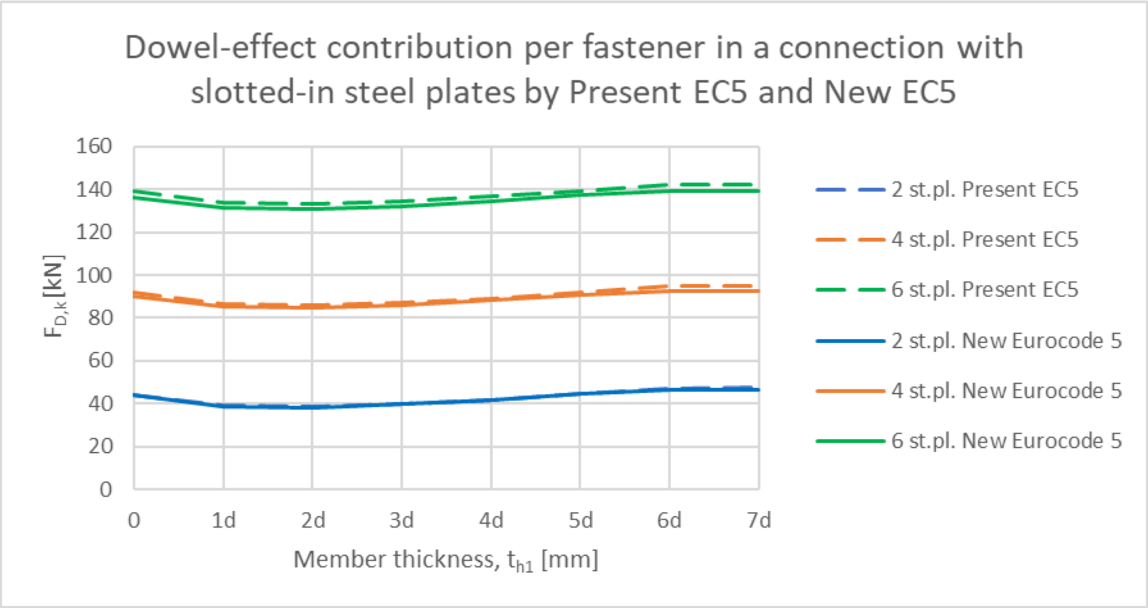


Figure 19: Characteristic dowel-effect contribution of a fastener in a connection with multiple shear planes by using different number of steel plates and different thicknesses of the side members.

Figure 19 shows that the Present Eurocode 5 and the New Eurocode 5 give the same values of the characteristic dowel-effect contribution of a fastener in a connection with multiple shear planes by using different thicknesses of the side members at a time, for the different number of steel plates. In Figure 19, the thickness of the middle member (member 2) is kept constant, t_{h2} = 6d = 72 mm, but the thickness of the side member is varied from very small thickness almost 0 mm (1d * 10^{-12} mm) to 7d mm at a time, for every number of steel plates which are 2, 4 and 6 steel plates. The characteristic dowel-effect contribution of a fastener increases when the number of steel plates increases, but it decreases and then increases slightly with increasing the thickness of the outer members up to 6d mm for all number of steel plates. The characteristic dowel-effect contribution of a fastener depends only on the fastener yielding failure which is constant beyond the 6d mm thickness of the outer member.

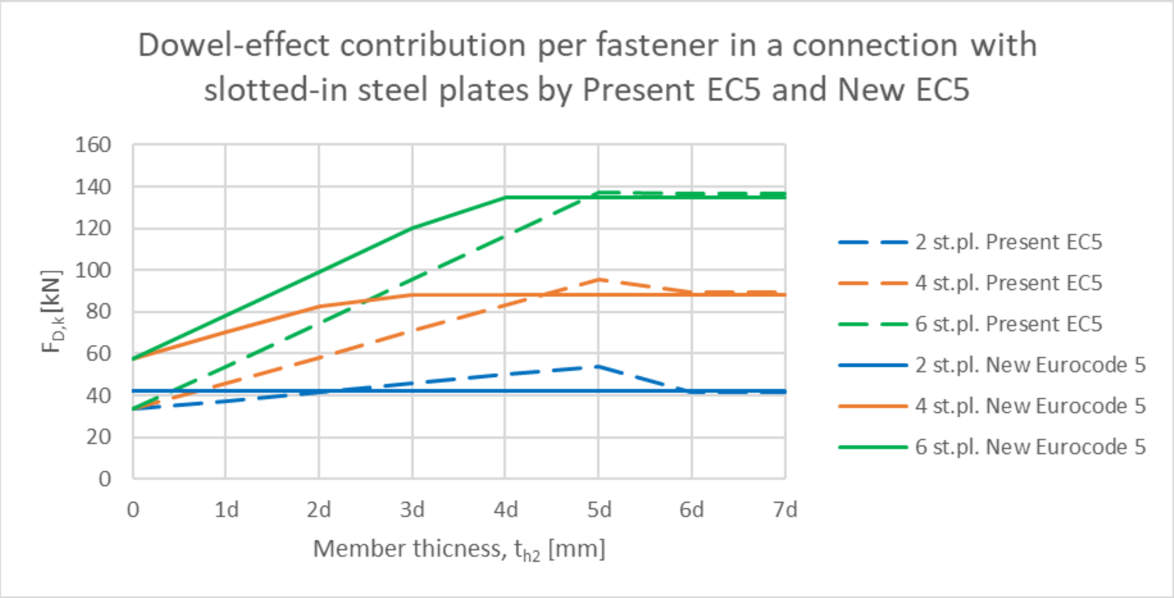


Figure 20: Characteristic dowel-effect contribution of a fastener in a connection with multiple shear planes by using different number of steel plates and different thicknesses of the middle members.

Figure 20 shows that the characteristic dowel-effect contribution of a fastener in a connection with two steel plates is independent of the change in the thickness of the middle timber member in the New Eurocode 5. It depends on the embedment failure of the side members, the embedment strength of the steel plate and the yielding failure of the dowels, but they are all constants in this case. The characteristic dowel-effect contribution of a fastener in the connection with 4 and 6 steel plates, increases with the thickness of the middle members up to a certain thickness of 3*d* mm and 5*d* mm respectively. It is constant beyond these thickness values because it depends on the embedment failure of the side members, the embedment strength of the steel plate and fastener yielding failure, and these are all constant values in this case.

As shown in Figure 20 for each number of steel plates 2, 4 and 6, the characteristic dowel-effect contribution of a fastener in the connection increases with the thickness of the middle members and reaches a maximum value at a thickness of 5*d* mm in the Present Eurocode 5. But it decreases again to a certain value for each number of steel plates as the thickness of middle member increases to 6*d* mm. Beyond the thickness of 6*d* mm, the characteristic dowel-effect contribution of a fastener in the connection for each number of steel plates becomes constant owing to the embedment failure of the side members and yielding failure of the fastener which are both constants.

The Present Eurocode 5 and the New Eurocode 5 give the same and constant values of the characteristic dowel-effect contribution of a fastener in connections with 2, 4 and 6 steel plates beyond the thickness of 6*d* mm. In both the versions of Eurocode 5, when the number of steel plates increases, the number of shear planes also increases and therefore, the characteristic dowel-effect contribution of a fastener in a connection increases.

4 Connection design with metal dowel-type fasteners

4.1 Axial design capacity

Axial design capacity of a connection with fasteners loaded by a design axial tensile force or design axial tensile force component must satisfy the requirement given in Table 25. As presented in Table 25, the requirements for axial design capacity of a connection in the Present Eurocode 5 and the New Eurocode 5 are the same.

Table 25: Requirement for axial design capacity

Present Eurocode 5		**New Eurocode 5**	
$F_{ax,Ed} \leq F_{ax,Rd}$	(86)	$F_{ax,t,Ed} \leq F_{ax,t,Rd}$	(87)
$F_{ax,Rd} = n_{ef} F_{ax,d}$	(88)	$F_{ax,t,Rd} = n_{ef} F_{ax,t,d}$	(89)

4.1.1 Effective number of axially loaded metal dowel-type fasteners

In the Present Eurocode 5, the effective number of fasteners n_{ef} for a connection with multiple fasteners loaded with an axial load component is given by Equation (*90*). In addition to Equation (*90*), the New Eurocode 5 provides expressions in Equation (*91*) based on the number of screws in a group and the angle ε between the fastener axis and the grain direction.

$$n_{ef} = n^{0.9} \qquad \text{in general} \tag{90}$$

$$n_{ef} = \begin{cases} 0.9\,n & \text{for screws } 30° \leq \varepsilon \leq 90° \text{ and controlled insertion moment} \\ 0.9\,n & \text{for a group of more than 10 screws in a timber to timber connection} \\ n & \text{for a group of up to 10 screws in a timber to timber connection} \end{cases} \tag{91}$$

The nomenclature used in the axial design capacity and the effective number of axially loaded metal dowel-type fasteners in the Present Eurocode 5 and the New Eurocode 5 is given in Table 26.

Table 26: Nomenclature used in the axial design capacity and the effective number of axially loaded metal dowel-type fasteners.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{ax,Ed}$	$F_{ax,t,Ed}$	design axial tensile force or design axial tensile force

		component, in N
$F_{ax,Rd}$	$F_{ax,t,Rd}$	design axial tensile resistance of the connection, in N
$F_{ax,d}$	$F_{ax,t,d}$	design axial tensile resistance per fastener, in N
n_{ef}	n_{ef}	effective number of fasteners in a connection
n	n	number of fasteners acting together in the connection
	ε	angle between the fastener axis and the grain direction

4.2 Lateral design capacity

The effective design resistance parallel to a row of fasteners parallel to the grain and the design splitting resistance perpendicular to a row of fasteners parallel to the grain must satisfy the requirements given in Table 27. The requirement for the effective design resistance parallel to a row of fasteners parallel to the grain has the same expression in the New Eurocode 5 and the Present Eurocode 5. The requirements for the design splitting resistance perpendicular to a row of fasteners parallel to the grain in the New Eurocode 5 and the Present Eurocode 5 are discussed in detail in section 7.2.

Table 27: Requirement for lateral design resistance parallel or perpendicular to a row of fasteners parallel to the grain.

Present Eurocode 5				**New Eurocode 5**			
Parallel to grain		Perpendicular to grain		Parallel to grain		Perpendicular to grain	
$F_{v,ef,Rd} \geq F_{row,d}$	(92)	$F_{90,Rd} \geq F_{v,Ed}$	(93)	$F_{v,Rd} \geq F_{v,Ed}$	(94)	$F_{sp,Rd} \geq F_{90,Ed}$	(95)
$F_{v,ef,Rd} = n_{ef} F_{v,Rd}$	(96)	$F_{v,Ed} = \max\begin{cases} F_{v,Ed,1} \\ F_{v,Ed,2} \end{cases}$	(97)	$F_{v,Rd} = n_{ef} F_{v,d}$	(98)	$F_{90,Ed} = F_{Ed} * \sin\alpha$	(99)

The requirement presented in Table 27 is for a force acting parallel or perpendicular to a row of fasteners parallel to the grain. The New Eurocode 5 and the Present Eurocode 5 say that for a force acting at an angle to the direction of a row of fasteners parallel to the grain, as depicted in Figure 21, the force component parallel to the row $F_{v,A,0,Ed}$ in member A and $F_{v,B,0,Ed}$ in member B, must be less than or equal to the effective design resistance component parallel to the row as given in Table 28. The New Eurocode 5 provides a figure, as depicted in Figure 21, which gives a much better illustration and description of the equilibrium of forces of a connection than the figure provided by the Present Eurocode 5.

Table 28: Requirement for lateral design resistance at an angle to a row of fasteners parallel to the grain.

Member	Present Eurocode 5		New Eurocode 5	
Timber member A	$F_{v,A,0,Ed} \leq F_{v,ef,Rd,A}$	(100)	$F_{v,A,0,Ed} \leq F_{v,Rd,A}$	(101)
Timber member B	$F_{v,B,0,Ed} \leq F_{v,ef,Rd,B}$	(102)	$F_{v,B,0,Ed} \leq F_{v,Rd,B}$	(103)

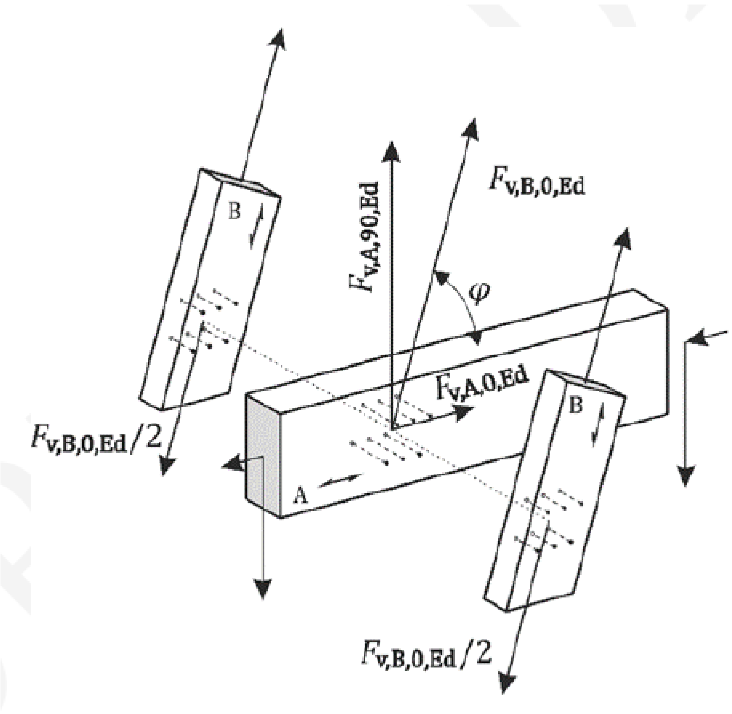


Figure 21: Equilibrium of forces of a connection [1].

4.2.1 Effective number of laterally loaded metal dowel-type fasteners

It is considered that the capacity of a connection with multiple fasteners of the same type and dimension, can be lower than the summation of the individual capacities of each fastener. In the Present Eurocode 5 and the New Eurocode 5, the effective number of fasteners n_{ef} in a row of fasteners perpendicular to the grain is given by:

$$n_{ef} = n_{90} \tag{104}$$

In the Present Eurocode 5 and the New Eurocode 5 for a row of fasteners parallel to the grain, the effective number of fasteners n_{ef} is given in Table 29.

Table 29: Effective number of laterally loaded metal dowel-type fasteners in row parallel to the grain [1].

Fastener	**Effective number of laterally loaded fasteners**	
Nails	$n_{ef} = n^{k_{ef}}$ $k_{ef} = \begin{cases} 1 & \text{for } a_1 \geq 14d \\ 0.85 & \text{for } a_1 = 10d \\ 0.7 & \text{for } a_1 = 7d \end{cases}$ Only predrilled: $k_{ef} = 0.5 \quad \text{for } a_1 = 4d$ For intermediate spacings, linear interpolation of k_{ef} may be applied.	(105) (106) (107)
Screws with $d < 12$ mm	See nails	
Screws and rods with wood screw thread $d \geq 12$ mm, dowels and bolts	$n_{ef} = \min \begin{cases} n \\ n^{0.9} * \sqrt[4]{\frac{a_1}{13d}} \end{cases}$	(108)

The nomenclature used in the lateral design capacity and the effective number of laterally loaded metal dowel-type fasteners in the Present Eurocode 5 and the New Eurocode 5 is given in Table 30.

Table 30: Nomenclature used in the lateral design capacity and the effective number of laterally loaded metal dowel-type fasteners.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{v,ef,Rd}$	$F_{v,Rd}$	effective design resistance per row of fasteners parallel to the grain, in N
$F_{row,d}$	$F_{v,Ed}$	design force per row of fasteners parallel to the grain, in N
$F_{v,Rd}$	$F_{v,d}$	design resistance per fastener, in N
$F_{90,Rd}$	$F_{sp,Rd}$	Design splitting capacity perpendicular to grain, in N
$F_{v,Ed}$	$F_{90,Ed}$	design tensile force component perpendicular to the grain, in N
F_{Ed}	F_{Ed}	design tensile force at an angle α transmitted by the

		connection, in N
$F_{v,Ed,1}$, $F_{v,Ed,2}$		design shear forces on either side of the connection, in N
	$F_{v,A,0,Ed}$	force component parallel to the row of fasteners parallel to the grain in member A, in N
	$F_{v,B,0,Ed}$	force component parallel to the row of fasteners parallel to the grain in member B, in N
$F_{v,ef,Rd,A}$	$F_{v,Rd,A}$	effective design resistance component parallel to the row of fasteners parallel to the grain in member A, in N
$F_{v,ef,Rd,B}$	$F_{v,Rd,B}$	effective design resistance component parallel to the row of fasteners parallel to the grain in member B, in N
n_{ef}	n_{ef}	effective number of fasteners in a row parallel to the grain
	n	number of fasteners in a row parallel to the grain
	n_{90}	number of fasteners in a row perpendicular to the grain
a_1	a_1	spacing between fasteners parallel to the grain, in mm
d	d	diameter of the fastener, in mm

4.3 Interaction of axial and lateral loads

In the Present Eurocode 5 and the New Eurocode 5, the connections subjected to a combination of load in the shear plane (lateral load) and perpendicular to the shear plane (axial load) must satisfy the requirement given by:

$$\left(\frac{F_{ax,Ed}}{F_{ax,Rd}}\right)^p + \left(\frac{F_{v,Ed}}{F_{v,Rd}}\right)^p \leq 1 \tag{109}$$

The values of the exponent *p* in the expression for the interaction of axial and lateral capacities of fasteners in the New Eurocode 5 and the Present Eurocode 5 are given in Table 31. For screws, the New Eurocode 5 gives different values for the exponent *p* depending on the type of failure modes of the screw and thus on the number of hinges on the screw. The exponent *p* has a constant value of 2.0 for screws in the Present Eurocode 5.

Table 31: Exponent p for the interaction of axial and lateral capacities [1].

Fastener	p	**Failure mode**
Smooth nails	1.0	–
Ring shank nails	2.0	–
Screws and rods with wood screw thread	1.0 1.0 1.5 2.0 [a]	Mode unknown Mode (a) and (b) – no plastic hinge Mode (d) and (e) – one plastic hinge Mode (f) two plastic hinges
[a] For screws in the Present Eurocode 5.		

The nomenclature used in the interaction of axial and lateral capacities of metal dowel-type fasteners in the Present Eurocode 5 and the New Eurocode 5 is given in Table 32.

Table 32: Nomenclature used in the interaction of axial and lateral capacities of metal dowel-type fasteners.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{ax,Ed}$	$F_{ax,Ed}$	axial design force of the fastener, in N
$F_{ax,Rd}$	$F_{ax,Rd}$	axial design capacity of the fastener, in N
$F_{v,Ed}$	$F_{v,Ed}$	lateral design force of the fastener, in N
$F_{v,Rd}$	$F_{v,Rd}$	lateral design capacity of the fastener, in N
n_{ef}	n_{ef}	effective number of fasteners in a connection
p	p	exponent taken from Table 31

5 Slip modulus of connections

Generally, the slip modulus is calculated per shear plane per fastener under service load (SLS). Therefore, the slip modulus of a connection is the sum of all slip moduli per shear plane per fastener in the connection according to the New Eurocode 5 and the Present Eurocode 5. The Present Eurocode 5 provides no explicit expression, but the New Eurocode 5 provides an expression for the determination of the slip modulus of a connection K_{SLS} as:

$$K_{SLS} = \sum_{i=1}^{n*m} K_{SLS,i} \tag{110}$$

where

n	is the number of fasteners;
m	is the number of shear planes per fastener;
$K_{SLS,i}$	is the slip modulus of a single fastener per shear plane.

5.1 Lateral slip modulus of metal dowel-type fasteners

a) Serviceability limit state (SLS)

- Timber-to-timber connection

In the New Eurocode 5 and the Present Eurocode 5, the mean lateral slip modulus per shear plane per fastener for two timber members of the same density in timber-to-timber connection for serviceability limit state (SLS) is given in Table 33.

Table 33: Values for the mean lateral slip modulus per shear plane per fastener in timber-to-timber connection for serviceability limit state (SLS).

Type of fastener	**Present Eurocode 5** K_{ser} [N/mm]		**New Eurocode 5** $K_{SLS,v,mean}$ [N/mm]	
Dowels Bolts with or without clearance [a]	${\rho_m}^{1.5}d/23$	(111)	${\rho_{mean}}^{1.5}d/23$	(112)
Nails (with pre-drilling)	${\rho_m}^{1.5}d/23$	(113)	${\rho_{mean}}^{1.5}d^{0.8}/30$	(114)
Screws	${\rho_m}^{1.5}d/23$	(115)	$60(0.7d)^{1.7}$	(116)

Bonded-in rods [b] - Perpendicular to grain ($\varepsilon = 90°$) - Parallel to grain ($\varepsilon = 0°$)	Not included		$\rho_{mean}{}^{1.5}d/25$ $\rho_{mean}{}^{1.5}d/125$	(117) (118)
Nails (without pre-drilling)	$\rho_m{}^{1.5}d^{0.8}/30$	(119)	$\rho_{mean}{}^{1.5}d^{0.8}/30$	(120)
[a] The clearance is added separately to the deformation. [b] For bonded-in rods service class (SC) 1 and 2 apply only.				

The Present Eurocode 5 says that the following expression is applied for ρ_m in Table 33 if the mean densities of the two jointed timber members, as shown in Figure 22, are different, but the New Eurocode 5 does not give provision about two jointed timber members with different densities.

$$\rho_m = \sqrt{\rho_{m,1} * \rho_{m,2}} \tag{121}$$

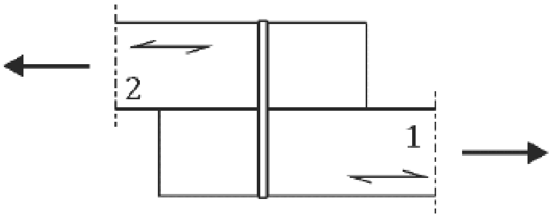


Figure 22: Laterally loaded fastener [1].

The New Eurocode 5 says that the values given in Table 33 for the mean lateral slip modulus are reduced by half (50 %) for connection members loaded perpendicular to the grain (α = 90°) and linear interpolation is applied for intermediate angles (0° < α < 90°), but the Present Eurocode 5 does not give provision for this case.

- Steel-to-timber connection

The mean density ρ_m of the timber member is used for steel-to-timber or concrete-to-timber connections in the Present Eurocode 5, but this is not mentioned in the New Eurocode 5. The value of the mean lateral slip modulus per shear plane per fastener under service load (SLS) is multiplied by 2.0 (doubled) in the New Eurocode 5 and the Present Eurocode 5.

b) Ultimate limit state (ULS)

The value of the mean lateral slip modulus per shear plane per fastener for ultimate limit state (ULS) is the value of the mean lateral slip modulus per shear plane per fastener for serviceability limit state (SLS) multiplied by 2/3 in the New Eurocode 5 and the Present Eurocode 5.

$$K_u = \frac{2}{3} K_{ser} \quad \text{or} \quad K_{ULS,v,mean} = \frac{K_{SLS,v,mean}}{1.5} \tag{122}$$

5.2 Axial slip modulus of metal dowel-type fasteners

The New Eurocode 5 includes the axial slip modulus of connections with fasteners loaded in their axial direction. The axial slip modulus $K_{ax,ser}$ is not covered by the Present Eurocode 5.

a) Serviceability limit state (SLS)

The mean axial slip modulus $K_{SLS,ax,mean}$ per fastener per connected member in a connection for serviceability limit state (SLS) is given in Table 34 provided that the effective withdrawal length l_w is not greater than 20d ($l_w \leq 20d$).

Table 34: Values for the mean axial slip modulus $K_{SLS,ax,mean}$ for axially loaded fasteners in timber-to-timber connections [1].

Type of fastener	$\boldsymbol{K_{SLS,ax,mean}}$ [N/mm]	
Threaded part of screws and rods with wood screw thread	$160\left(\frac{\rho_{mean}}{420}\right)^{0.85} d^{0.9} {l_w}^{0.6}$	(123)
Bonded length of bonded-in rods	$2d^{0.6} {l_w}^{0.6} {\rho_{mean}}^{0.9}$	(124)

b) Ultimate limit state (ULS)

The mean axial slip modulus $K_{LS,ax,mean}$ per fastener per connected member in a connection for ultimate limit state (SLS) is given by:

$$K_{ULS,ax,mean} = \frac{K_{SLS,ax,mean}}{1.5} \tag{125}$$

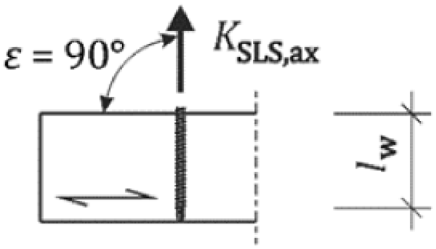


Figure 23: The slip modulus of an axially loaded fastener [1].

5.3 Combinations of axial and lateral slip modulus

The effective slip modulus of a connection with a combined axial and lateral loading of the fasteners is determined from the deformation of the fastener under the applied load.

In a connection where there is no gap between the connected members and the fasteners are loaded in tension and inclined with an inclination angle ε to the grain direction as depicted in Figure 24(a), the mean slip modulus K_{SLS} per shear plane per fastener is determined by:

$$K_{SLS} = K_{SLS,v,mean} \sin\varepsilon\,(\sin\varepsilon - \mu\cos\varepsilon) + \frac{1}{2} K_{SLS,ax,mean} \cos\varepsilon\,(\cos\varepsilon - \mu\sin\varepsilon) \tag{126}$$

In a connection where the fasteners are inclined in crosswise arrangement with an inclination angle ε to the grain direction as shown in Figure 24(b), the mean slip modulus K_{SLS} per shear plane per fastener is determined by:

$$K_{SLS} = K_{SLS,v,mean} \sin^2\varepsilon + \frac{1}{2} K_{SLS,ax,mean} \cos^2\varepsilon \tag{127}$$

a) Inclined fastener

b) Fasteners in crosswise arrangement

Figure 24: Connections with inclined fasteners [1].

The nomenclature used in the slip modulus of connections in the Present Eurocode 5 and the New Eurocode 5 are presented in Table 35.

Table 35: Nomenclature used in the slip modulus of connections.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
K_{ser}	$K_{SLS,v,mean}$	mean lateral slip modulus per shear plane per fastener for serviceability limit state (SLS), in N/mm
ρ_m	ρ_{mean}	mean density of the connection, in kg/m³
d	d	diameter of the fastener, in mm
$\rho_{m,1}$		mean density of the first timber member, in kg/m³

$\rho_{m,2}$		mean density of the second timber member, in kg/m^3
K_u	$K_{ULS,v,mean}$	mean lateral slip modulus of a connection for the ultimate limit state (ULS), in N/mm
	$K_{SLS,ax,mean}$	mean axial slip modulus per shear plane per fastener for serviceability limit state (SLS), in N/mm
	l_w	withdrawal length of the fastener, in mm
	$K_{ULS,ax,mean}$	mean axial slip modulus of a connection for the ultimate limit state (ULS), in N/mm
	α	angle between the direction of acting force and the direction of the grain, in degrees
	ε	angle between the fastener axis and the direction of the grain, in degrees
	μ	friction coefficient between the members, $\mu = 0.25$

5.4 Example case for slip modulus (withdrawal stiffness)

In this example case, the correlation between experimental results and the predicted values by the New Eurocode 5 is evaluated. Withdrawal stiffness (mean axial slip modulus) for screws and rods with wood screw thread is given by Equation (*123*) in the New Eurocode 5. The mean axial slip modulus is not covered by the Present Eurocode 5. The same collection of experimental results is used in this example case for withdrawal stiffness and in the previous example case for withdrawal capacity in section 2.1.4. This collection of experimental results is used to determine the withdrawal properties (capacity and stiffness) of single threaded rods as used in the research article by Stamatopoulos and Malo [10]. It is a collection of experimental results by Blaß and Krüger [11] and Stamatopoulos and Malo [9, 12, 13] as stated in the research article [10].

As stated in section 2.1.4, the research article [10] says that the experimental results include both the withdrawal capacity and the withdrawal stiffness at reference climatic conditions (MC ≈ 12%). There are 31 sets (denoted as $S_{d\text{-}\alpha\text{-}l}$) of the total 221 test results and are arranged according to the varied parameters: diameter, angle of fastener axis to grain direction and penetration length respectively. The values for the experimental withdrawal mean stiffness, and the corresponding coefficient of variation (CoV) are given in Table 36 for each set which is having at least five number of test results (n_{tests}). The obtained values are also double checked with the values provided in the research article by Stamatopoulos and Malo [10]. The predicted withdrawal mean stiffness by the New Eurocode 5 is also presented in Table 36.

Table 36: Collection of experimental results from withdrawal tests of single threaded rods [10] and the prediction by the New Eurocode 5.

Set name	**Ref.**	n_{tests}	d [mm]	α [deg]	l [mm]	ρ_m [kg/m^3]	$k_{ser,ax,m,test}$ [kN/mm]	$k_{SLS,ax,m,New\ Eurocode\ 5}$ [kN/mm]	**CoV** [%]
S16-45-200	[11]	10	16	45	200	430	32.4	47,6	21.5
S16-45-400		10	16	45	400	433	44.3	63,5	8.5
S20-45-200		10	20	45	200	431	37.7	58,2	16.3
S20-45-400		10	20	45	400	433	57.7	88,7	11.7
S16-90-200		10	16	90	200	422	18.2	46,8	11.6
S16-90-400		10	16	90	400	441	29.7	64,5	11.7
S20-90-200		10	20	90	200	425	22.6	57,6	11.6
S20-90-400		10	20	90	400	441	37.8	90,1	5.6
S20-90-100	[9, 12, 13]	10	20	90	100	472	29.0 [a]	41,7	31.1
S20-90-250		5	20	90	250	472	_	_	_
S20-90-300		5	20	90	300	487	61.4	82,5	11.2
S20-90-450		5	20	90	450	486	66.6	97,7	16.4
S20-60-100		6	20	60	100	476	36.6 [a]	41,8	33.2
S20-60-300		5	20	60	300	488	73.5	82,5	17.3
S20-60-450		5	20	60	450	476	90.1	96,1	9.4
S20-30-100		10	20	30	100	478	42.6 [a]	42,0	27.5
S20-30-300		5	20	30	300	477	111.2	81,0	11.2
S20-30-450		5	20	30	450	475	100.3	95,9	10.5
S20-20-100		10	20	20	100	477	53.8 [a]	41,7	23.1
S20-20-300		5	20	20	300	478	116.1	81,1	11.4
S20-20-450		5	20	20	450	473	121.7	95,5	16.0
S20-10-100		10	20	10	100	468	56.0 [a]	40,4	27.4
S20-10-300		5	20	10	300	479	126.9	81,3	9.8
S20-10-450		5	20	10	450	446	132.8	91,0	21.9
S20-0-100		10	20	0	100	456	54.6 [a]	39,6	15.9
S20-0-300		5	20	0	300	474	121.0	80,5	30.1

S20-0-450		5	20	0	450	458	121.8	93,0	13.0
S20-0-600		5	20	0	600	443	128.6	90,3	17.4
S20-10-600		5	20	10	600	462	131.1	93,6	5.3
S20-20-600		5	20	20	600	481	128.0	97,0	14.3
S20-30-600		5	20	30	600	486	114.8	97,7	11.2

[a] *in these sets, mean stiffness values were calculated based on five tests (no stiffness data for the rest of the tests in the set)* [10].

The New Eurocode 5 says that the effective withdrawal length l_w cannot be greater than 20*d*, i.e., l_w =min (l_w; 20*d*), therefore the maximum effective withdrawal length l_w used is 20*d*. For example, for the set S16-90-400 the effective withdrawal length used is l_w = 20*16 = 320 mm instead of the actual withdrawal length 400 mm used in the test. Equation (*123*) is only for axial withdrawal stiffness, which is at angles 90° between the fastener axis and the grain direction (ε = 90°), but the experimental results include angles from 0° up to 90° (0° ≤ ε ≤ 90°). Figure 25 shows the correlation between the mean and individual experimental results and the predictions by the New Eurocode 5. The correlation for angles other than 90° are also included in Figure 25 to examine the outcome of the New Eurocode 5 for the angles other than 90°.

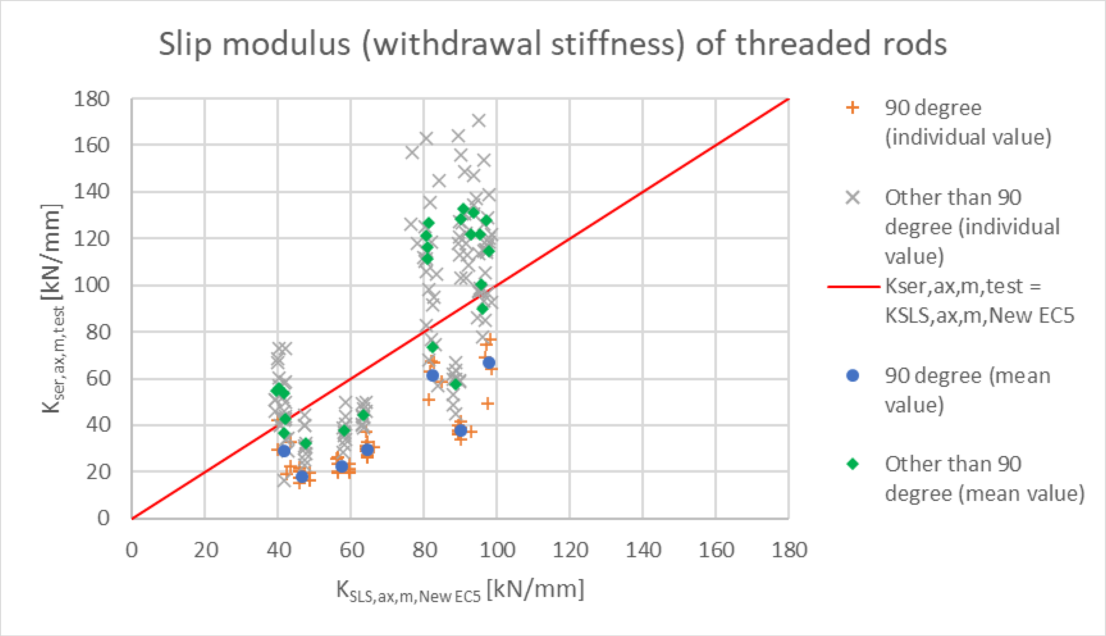


Figure 25: Correlation between experimental mean withdrawal stiffness and the prediction by the New Eurocode 5.

As shown in Figure 25, the predictions by the New Eurocode 5 for the mean (sets) and the individual withdrawal stiffnesses for all angles from 0° up to 90° (0° ≤ ε ≤ 90°) are generally inaccurate. The New Eurocode 5 gives underestimated predictions of the withdrawal stiffness for some individual tests and sets at angles other than 90 degrees which have higher withdrawal stiffness values of greater than or equal to 100 kN/mm (i.e., $K_{SLS,ax,mean} \geq 100$ kN/mm). The New Eurocode 5 predicts overestimated values of withdrawal stiffness for some individual tests and sets at angles other than 90 degrees which have lower withdrawal stiffness values of less than 100 kN/mm (i.e., $K_{SLS,ax,mean} <$ 100 kN/mm). The New Eurocode 5 overestimates the values of the withdrawal stiffness for all individual tests and all sets at angles 90° ($\varepsilon = 90°$) for which it is intended for.

For some individual tests and sets at angles other than 90° which have higher withdrawal stiffness values, the New Eurocode 5 has generally provided underestimated predictions of the withdrawal stiffnesses. For some individual tests and sets at angles other than 90° which have lower withdrawal stiffness values, the New Eurocode 5 has predicted overestimated values of the withdrawal stiffness. The New Eurocode 5 predicts generally overestimated values of the mean axial slip modulus of screws and rods with wood screw thread than the experimental mean withdrawal stiffness values.

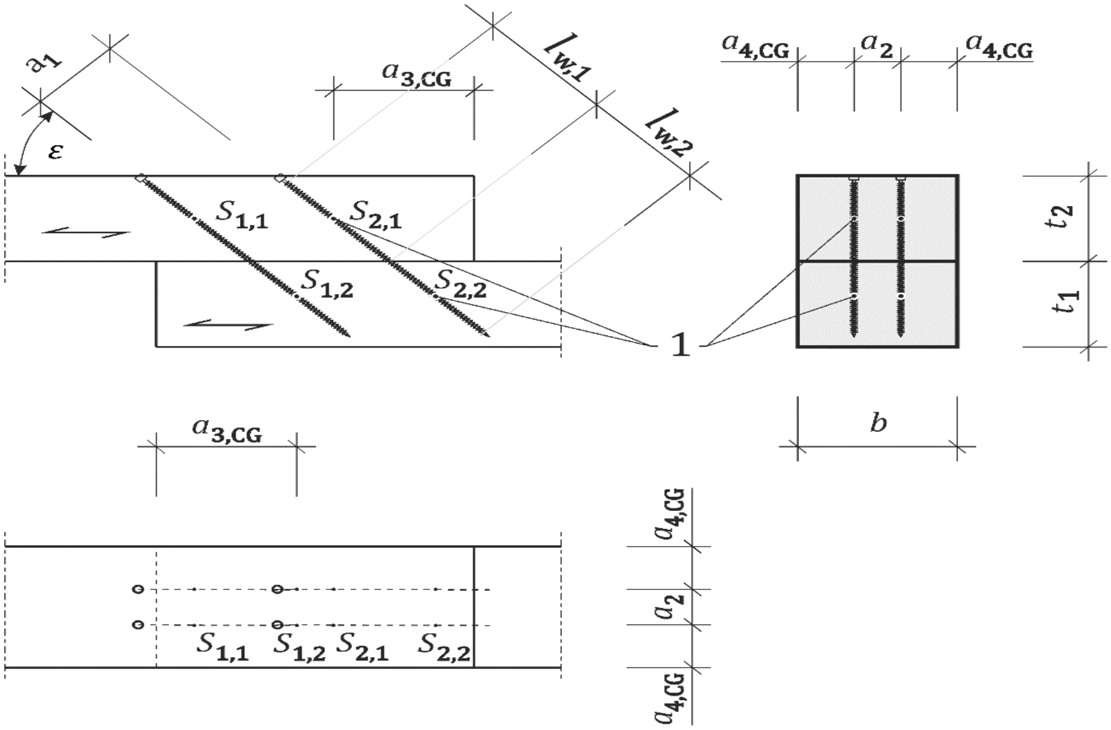
6 Spacing and end and edge distances

6.1 Axially loaded metal dowel-type fasteners

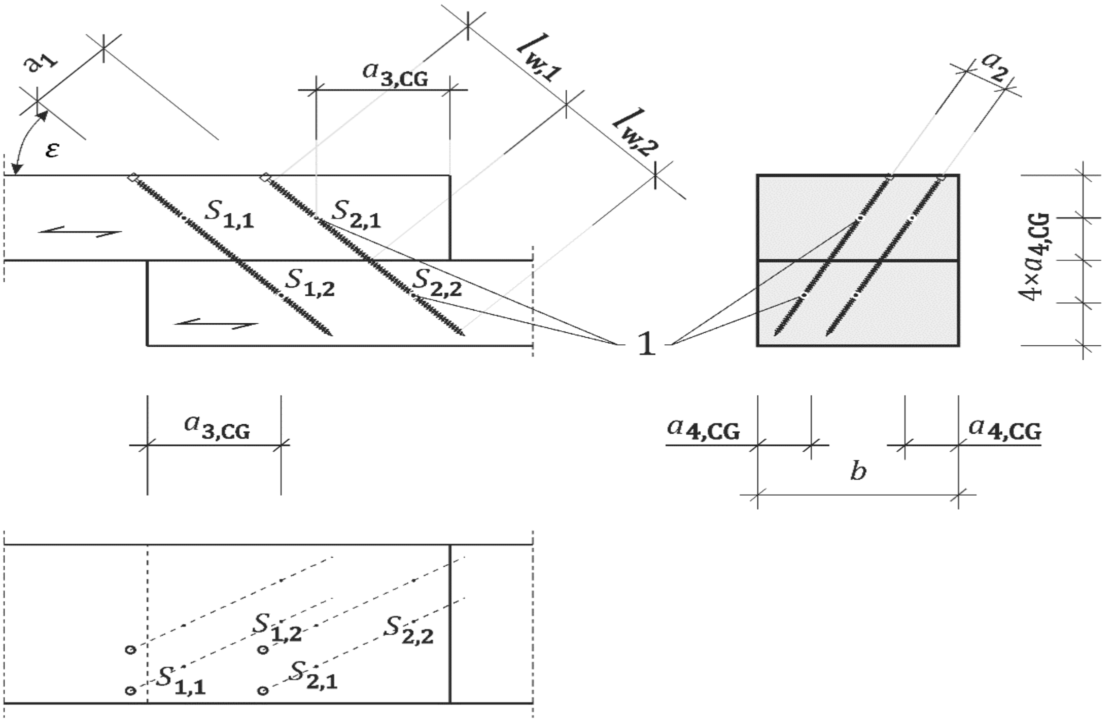
The New Eurocode 5 provides explicitly the minimum values of spacing and end and edge distances for screws with inner diameter d_1 less than or equal to 6 mm ($d_1 \leq 6$ mm) and not predrilled members, and for screws with inner diameter d_1 greater than 6 mm ($d_1 > 6$ mm) and predrilled members. The values for the minimum spacing and end and edge distances for axially loaded screws and rods with wood screw thread provided by the Present Eurocode 5 are the same for all sizes of screws and are not specified whether they are for predrilled or not predrilled timber members. In the New Eurocode 5 and the Present Eurocode 5, the symbols for the names of spacings parallel to the grain and perpendicular to the grain are the same but the symbols for the names of the end and edge distances are changed. The symbol for the name of the distance of the center of gravity of the threaded part of the screw in the structure to the end is changed from $a_{1,CG}$ in the Present Eurocode 5 to $a_{3,CG}$ in the New Eurocode 5 and the symbol for the name of the distance of the center of gravity of the threaded part of the screw in the structure to the edge is changed from $a_{2,CG}$ in the Present Eurocode 5 to $a_{4,CG}$ in the New Eurocode 5. The minimum spacing and end and edge distances for axially loaded screws and rods with wood screw thread having diameter d in the Present Eurocode 5 and New Eurocode 5 are given in Table 37 and in Figure 26.

Table 37: Minimum spacing and end and edge distances of axially loaded screws.

	Minimum spacing between screws in a plane		**Minimum distance of the center of gravity of the threaded part of the screw in the structure to the**	
	Parallel to the grain	**Perpendicular to the grain**	**End**	**Edge**
Present Eurocode 5	a_1	a_2	$a_{1,CG}$	$a_{2,CG}$
All screws	$7d$	$5d$	$10d$	$4d$
New Eurocode 5	a_1	a_2	$a_{3,CG}$	$a_{4,CG}$
Not predrilled $d_1 \leq 6$ mm	$7d$	$5d$	$10d$	$4d$
Predrilled $d_1 > 6$ mm	$5d$	$2.5d$	$10d$	$2d$



a) Screws inclined in one (to grain) direction.



b) Screws inclined in two directions.

Figure 26: Minimum spacing and end and edge distances of axially loaded screws [1].

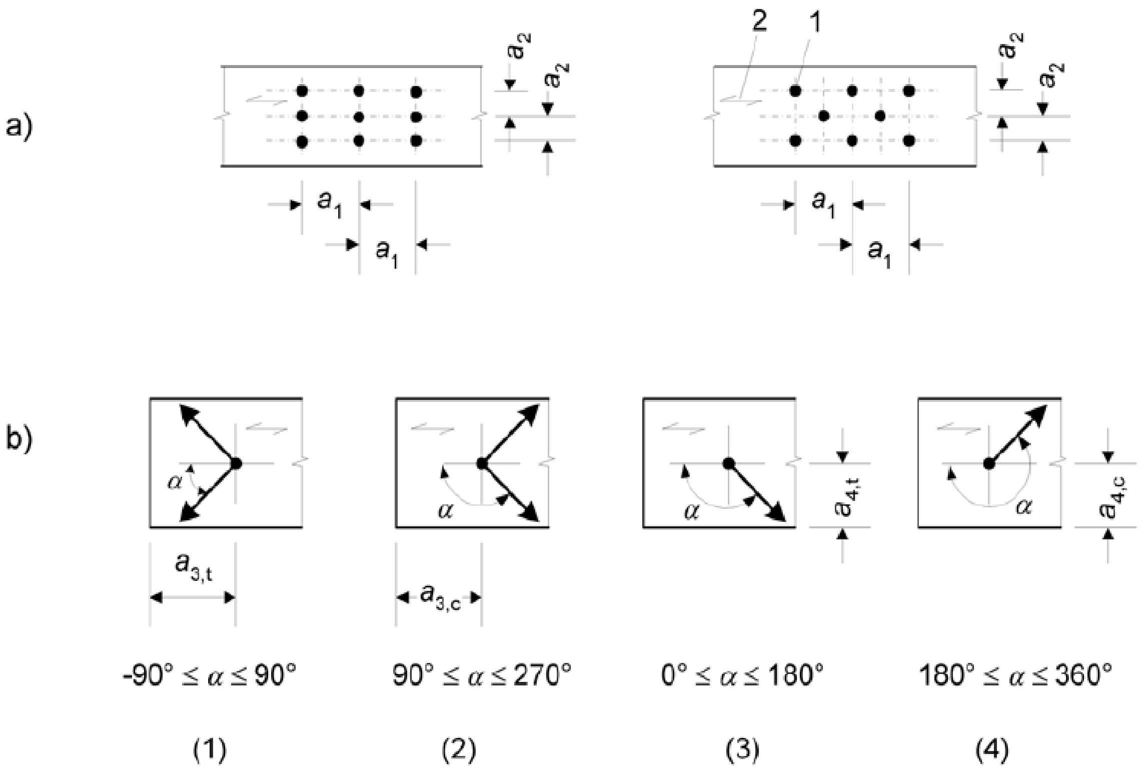
Table 38: Nomenclature of minimum spacings and edge and end distances used in Figure 26 [1].

New Eurocode 5	**Meaning**
a_1	spacing between screws in a plane parallel to grain, in mm
a_2	spacing between screws in a plane perpendicular to grain, in mm
$a_{3,CG}$	distance of the center of gravity of the threaded part of the screw in the structure to the end, in mm
$a_{4,CG}$	distance of the center of gravity of the threaded part of the screw in the structure to the edge, in mm
ε	angle between the axis of the fastener and the grain direction
1	point at the center of gravity of the inclined screw
$S_{i,j}$	center of gravity of the screw i in the timber member j
$l_{w,1}$	withdrawal length in timber member 1, in mm
$l_{w,2}$	withdrawal length in timber member 2, in mm

6.2 Laterally loaded metal dowel-type fasteners

The New Eurocode 5 provides expressions, which do not include sin α or cos α, for the minimum spacing and end and edge distances for laterally loaded metal dowel-type fasteners. The expressions provided by the Present Eurocode 5 include the load to grain angle α as depicted in Figure 27 and as presented in Table 40. The value of the expression which includes either sin α or cos α is maximum when the value of either sin α or cos α in the expression is maximum which is equal to one (1). This means that the expressions for the minimum spacing and end and edge distances provided by the New Eurocode 5 are the maximum evaluated values of the expressions provided by the Present Eurocode 5 by substituting the sin α or cos α with a maximum value of 1 (one). For example, the expression (4+ | cos α |) *d* is given in Table 40 as the expression for the minimum spacing a_1 in the Present Eurocode 5 and the maximum value of this expression is 5*d.* The maximum value of 5*d* is obtained by using the maximum value of cos α, which is 1, in the given expression i.e., (4+ | cos α |) *d* = (4+1) *d* = 5*d*. This maximum value of 5*d* is given in Table 41 as the expression for the minimum spacing a_1 in the New Eurocode 5.

The same principle is used in all the subsequent expressions for the minimum spacing and end and edge distances for each type of laterally loaded metal dowel-type fasteners presented in the following subsections below.



Key:

(1) Loaded end, (2) Unloaded end, (3) Loaded edge and (4) Unloaded edge

1 Fastener and 2 Grain direction

a) Spacing parallel to grain in a row and perpendicular to grain between rows

b) Edge and end distances

Figure 27: Spacings and end and edge distances for fasteners in the Present Eurocode 5 [2].

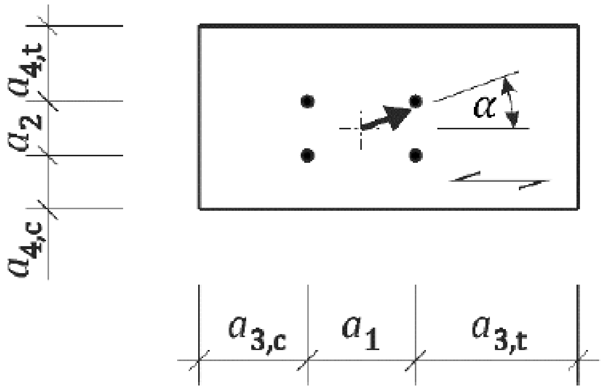


Figure 28: Spacings and edge and end distances for fasteners in the New Eurocode 5 [1].

Table 39: Nomenclature used in the expressions for the minimum spacing and end and edge distances for laterally loaded metal dowel-type fasteners.

Present Eurocode 5 and New Eurocode 5	**Meaning**
a_1	spacing between dowel-type fasteners in a plane parallel to grain, in mm
a_2	spacing between dowel-type fasteners in a plane perpendicular to grain, in mm
$a_{3,c}$	distance between dowel-type fastener and unloaded end, in mm
$a_{3,t}$	distance between dowel-type fastener and loaded end, in mm
$a_{4,c}$	distance between dowel-type fastener and unloaded edge, in mm
$a_{4,t}$	distance between dowel-type fastener and loaded edge, in mm
α	angle between the force and the grain direction (load to grain angle)
ρ_k	characteristic density of the timber member, in kg/m^3

6.2.1 Nails

The expressions for the minimum spacing and end and edge distances for laterally loaded nails provided by the Present Eurocode 5 and the New Eurocode 5 are presented in Table 40 and Table 41 respectively. The timber members are distinguished as without predrilled holes and with predrilled holes based on the timber density value of 430 kg/m^3 in the New Eurocode 5 and 420 kg/m^3 in the Present Eurocode 5.

Present Eurocode 5

Table 40: Minimum spacings and end and edge distances for nails [2].

Spacing or distance (See Figure 27**)**	**Load to grain angle** **α**	**Minimum spacing and end and edge distance**		
		Without predrilled holes		With predrilled holes
		$\rho_k \leq 420$ kg/m^3	$420 < \rho_k \leq 500$ kg/m^3	
Spacing a_1 (parallel to grain)	$0° \leq \alpha \leq 360°$	$d < 5$ mm: $(5+5|\cos\alpha|)\,d$ $d \geq 5$ mm: $(5+7|\cos\alpha|)\,d$	$(7+8|\cos\alpha|)\,d$	$(4+|\cos\alpha|)\,d$
Spacing a_2 (perpendicular to grain)	$0° \leq \alpha \leq 360°$	$5d$	$7d$	$(3+|\cos\alpha|)\,d$
Distance $a_{3,t}$ (loaded end)	$-90° \leq \alpha \leq 90°$	$(10+5\cos\alpha)\,d$	$(15+5\cos\alpha)\,d$	$(7+5\cos\alpha)\,d$
Distance $a_{3,c}$ (unloaded end)	$90° \leq \alpha \leq 270°$	$10d$	$15d$	$7d$
Distance $a_{4,t}$ (loaded edge)	$0° \leq \alpha \leq 180°$	$d < 5$ mm: $(5+2\sin\alpha)\,d$ $d \geq 5$ mm: $(5+5\sin\alpha)\,d$	$d < 5$ mm: $(7+2\sin\alpha)\,d$ $d \geq 5$ mm: $(7+5\sin\alpha)\,d$	$d < 5$ mm: $(3+2\sin\alpha)\,d$ $d \geq 5$ mm: $(3+4\sin\alpha)\,d$
Distance $a_{4,c}$ (unloaded edge)	$180° \leq \alpha \leq 360°$	$5d$	$7d$	$3d$

New Eurocode 5

Table 41: Minimum spacings and end and edge distances for nails [1].

Spacing or distance **(See Figure 28)**	**Minimum spacing and end and edge distances**		
	Not predrilled		Predrilled
	$\rho_k \leq 430$ kg/m^3	$430 < \rho_k \leq 500$ kg/m^3	
Spacing a_1 (parallel to grain)	10d	15d	5d
Spacing a_2 (perpendicular to grain)	5d	7d	4d
Distance $a_{3,t}$ (loaded end)	15d	20d	12d
Distance $a_{3,c}$ (unloaded end)	10d	15d	7d
Distance $a_{4,t}$ (loaded edge)	7d	12d	7d
Distance $a_{4,c}$ (unloaded edge)	5d	7d	3d

6.2.2 Bolts

The minimum spacings and edge and end distances for bolts in the Present Eurocode 5 and the New Eurocode 5 is given in Table 42.

Table 42: Minimum spacings and edge and end distances for bolts.

	Present Eurocode 5		**New Eurocode 5**
Spacings and end/edge distances	**Load to grain angle** **α**	**Minimum spacing or distance**	**Minimum spacing or distance**
a_1 (parallel to grain)	0° ≤ α ≤ 360°	(4+ | cos α |) d	5 d
a_2 (perpendicular to grain)	0° ≤ α ≤ 360°	4 d	4 d
$a_{3,t}$ (loaded end)	-90° ≤ α ≤ 90°	max (7 d; 80 mm)	max (7d; 80 mm)

$a_{3,c}$ (unloaded end)	90° ≤ α < 150° 150° ≤ α < 210° 210° ≤ α ≤ 270°	(1+ 6 sin α) *d* 4 *d* (1+ 6 |sin α|) *d*	4 *d*
$a_{4,t}$ (loaded edge)	0° ≤ α ≤ 180°	max [(2+ 2 sin α) *d*; 3*d*]	4 *d*
$a_{4,c}$ (unloaded edge)	180° ≤ α ≤ 360°	3 *d*	3 *d*

6.2.3 Dowels

The minimum spacings and edge and end distances for dowels in the Present Eurocode 5 and the New Eurocode 5 is given in Table 43.

Table 43: Minimum spacings and edge and end distances for dowels.

	Present Eurocode 5		**New Eurocode 5**
Spacings and end/edge distances	**Load to grain angle α**	**Minimum spacing or distance**	**Minimum spacing or distance**
a_1 (parallel to grain)	0° ≤ α ≤ 360°	(3 + 2 | cos α |) *d*	5 *d*
a_2 (perpendicular to grain)	0° ≤ α ≤ 360°	3 *d*	3 *d*
$a_{3,t}$ (loaded end)	-90° ≤ α ≤ 90°	max (7 *d*; 80 mm)	max (7*d*; 80 mm)
$a_{3,c}$ (unloaded end)	90° ≤ α < 150° 150° ≤ α < 210° 210° ≤ α ≤ 270°	$a_{3,t}$ | sin α| max (3.5 *d*; 40 mm) $a_{3,t}$ | sin α|	4 *d*
$a_{4,t}$ (loaded edge)	0° ≤ α ≤ 180°	max [(2+ 2 sin α) *d*; 3*d*]	4 *d*
$a_{4,c}$ (unloaded edge)	180° ≤ α ≤ 360°	3 *d*	3 *d*

6.2.4 Screws and rods with wood screw thread

In the New Eurocode 5, the values of minimum spacings and edge and end distances for screws and rods with wood screw thread are the same as for nails given in Table 41 in section 6.2.1. In the Present Eurocode 5, the values of minimum spacings and edge and end distances for screws with a diameter less than or equal to 6 mm ($d \leq 6$ mm) are the same as for nails given in Table 40 in section 6.2.1 and for screws with a diameter greater than 6 mm ($d > 6$ mm) are the same as for bolts given in Table 42 in section 6.2.2.

6.3 Staggered laterally loaded metal dowel-type fasteners

In the New Eurocode 5, the minimum combination of the spacings parallel to the grain a_1 and perpendicular to the grain a_2 for staggered laterally loaded metal dowel-type fasteners is given by:

$$\frac{a_{2s}}{a_2} \geq 1 - \left(\frac{a_{1s}}{a_1}\right)^2 \tag{128}$$

with

$$a_{1s}/a_1 \leq 1 \text{ and } a_{2s}/a_2 \leq 1 \tag{129}$$

where

a_{1s}	is the minimum spacing of staggered dowel-type fasteners parallel to grain, see Figure 29;
a_{2s}	is minimum spacing of staggered dowel-type fasteners perpendicular to grain, see Figure 29;
a_1	is the minimum spacing of dowel-type fasteners parallel to grain, taken from section 6.2;
a_2	is the minimum spacing of dowel-type fasteners perpendicular to grain, from section 6.2.

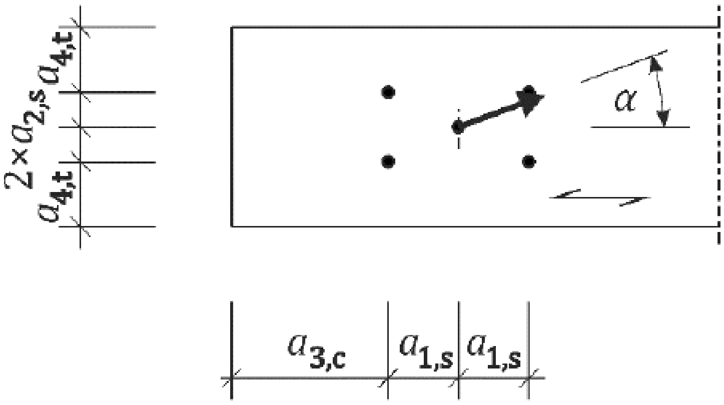


Figure 29: Minimum spacing of staggered fasteners due to a force transmitted by the fasteners in their center of gravity [1].

6.3.1 Laterally loaded metal dowel-type fasteners in moment connections

In the New Eurocode 5, the minimum spacing and end and edge distances for laterally loaded metal dowel-type fasteners in moment connections, as depicted in Figure 15, is given by Equations (*128*) and (*129*).

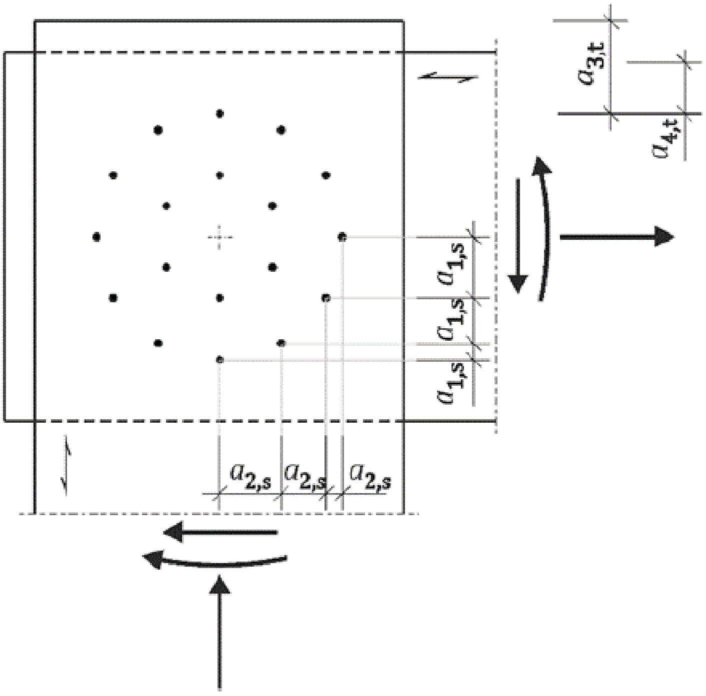


Figure 30: Example of staggered fasteners in a moment connection without necessary reinforcements [1].

7 Brittle failure modes of connections

7.1 Brittle failure modes of connections with fasteners loaded parallel to grain

Brittle failure mode is due to a failure of the wood usually happens before the steel fasteners reach their plastic range. It is usually a sudden collapse of the connection. The New Eurocode 5 includes the brittle failure mode of connections with fasteners loaded parallel to the grain. The Present Eurocode 5 does not include explicitly the brittle failure of connections with fasteners loaded parallel to the grain and it only considers block shear and plug shear failures in its informative Annex A directly. The most common brittle failure modes of connections with metal dowel-type fasteners loaded parallel to grain are splitting, row shear, block shear, net tensile failure and plug shear. The New Eurocode 5 introduces possible situations where the brittle failure modes of connections may be neglected by assessing some conditions given in section 7.1.1. For situations where the brittle failure modes of connections may not be neglected, the New Eurocode 5 divides the connections into two types, symmetrical and unsymmetrical connections. Symmetrical connections are connections where the thicknesses of the inner and the outer members are symmetrical. Unsymmetrical connections have inner and outer members with different thicknesses.

7.1.1 Simplification of brittle failure modes of connections

The New Eurocode 5 gives provision for situations where the brittle failure modes of connections may be neglected for the following two conditions:

1) failure mode (f) in Equation (*50*) governs the design of the connection. By fulfilling the minimum embedment depth given in Table 10, a connection where failure mode (f) governs may be achieved.

2) the minimum spacings and end and edge distances are achieved. The spacings between the fasteners parallel to the grain a_1 and perpendicular to the grain a_2, and the distance from the loaded end $a_{3,t}$ are increased by the factor k_{br}.

For connections with fully penetrated timber members, the factor k_{br} is determined by:

$$k_{br} = \max\begin{cases}1 \\ \left(1 + k_{rp,2}\right) k_{pos}\, {n_0}^{0.5}\, {n_{90}}^{0.3}\, d^{-0.2}\end{cases} \tag{130}$$

$$k_{pos} = \begin{cases}0.65 & \text{for outer members} \\ 1.10 & \text{for inner members}\end{cases} \tag{131}$$

For connections with partially penetrated timber members, the factor k_{br} is determined by:

$$k_{br} = \max\begin{cases} 1 \\ \left(1 + k_{rp,2}\right) {n_0}^{0.3}\, {n_{90}}^{-0.2}\, d^{-0.4} \end{cases} \tag{132}$$

where

k_{br} is the factor to increase the spacings a_1, a_2 and loaded end distance $a_{3,t}$;

$k_{rp,2}$ is the limitation for the rope effect contribution which is given in Table 20;

k_{pos} is the factor related to the position of the timber member;

n_0 is the number of fasteners in a row parallel to the grain;

n_{90} is the number of fasteners in a row perpendicular to the grain;

d is the diameter of the fastener, in mm.

7.1.2 Design brittle failure resistance of symmetrical connection

According to the New Eurocode 5, symmetrical connections are connections where the thicknesses of the inner and the outer timber members are symmetrical. The design brittle failure resistance of a symmetrical connection with multiple shear planes, $F_{br,Rd}$, is the sum of the individual resistances of the timber members in the connection and is given by:

$$F_{br,Rd} = \min\begin{cases} F_{b,2,d}\left(n_2 + n_1 \dfrac{t_1}{t_2}\right) & \text{failure of outer members} \\ F_{b,1,d}\left(n_2 \dfrac{t_2}{t_1} + n_1\right) & \text{failure of inner members} \end{cases} \tag{133}$$

where

$F_{b,1,d}$ is the design brittle failure resistance of the inner member;

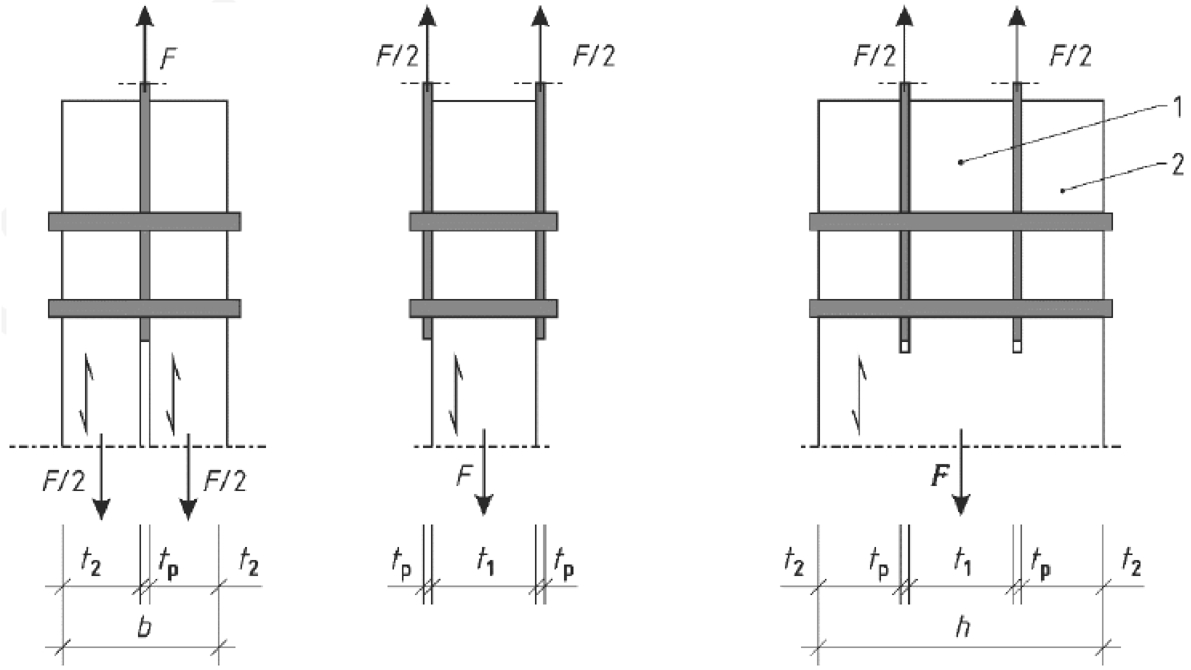
$F_{b,2,d}$ is the design brittle failure resistance of the outer member;

n_1 is the number of inner timber members;

n_2 is the number of outer timber members;

t_1 is the thickness of the inner timber member, as shown in Figure 31;

t_2 is the thickness of the outer timber member, as shown in Figure 31;



a) Outer members b) Inner member c) One inner and two outer members

Key: 1 = inner member 2 = outer member

Figure 31: Generic definition of outer and inner timber members [1].

7.1.3 Design resistance of a timber member in a connection

The design brittle failure resistance of a connection consisting multiple timber members is the sum of the design brittle failure resistance of the individual timber members in the connection. Therefore, the design brittle failure resistance of the individual timber members in the connection must be obtained. According to the New Eurocode 5, the design brittle failure resistance of a timber member in a connection with a single row of fasteners is the minimum of design resistances of splitting failure, row shear failure or net tensile failure. In a connection with more than one row of fasteners, the design brittle failure resistance of a timber member is the minimum of the design resistances of the failure modes of splitting, row shear, net tensile, block shear or plug shear. In the Present Eurocode 5, the design brittle failure resistance of a timber member in a connection is not explicitly provided.

7.1.4 Design capacity of an individual failure plane

There are three types of failure planes in a connection with multiple fasteners according to the New Eurocode 5. These failure planes are side shear plane, bottom shear plane and head tensile plane. In the New Eurocode 5, the capacities of these individual failure planes are used to obtain the resistances of different failure modes of a connection. Finding the capacities of these individual failure planes in advance, make the expressions for the resistances of the different failure modes of a connection easier to understand and use them. According to the New Eurocode 5, a basic geometry of a generic connection with multiple fasteners is given by Figure 32. In the given geometry, as depicted in Figure 32, four fasteners are in a line parallel to the grain (n_0 = 4) and three fasteners are in a line perpendicular to the grain direction (n_{90} = 3).

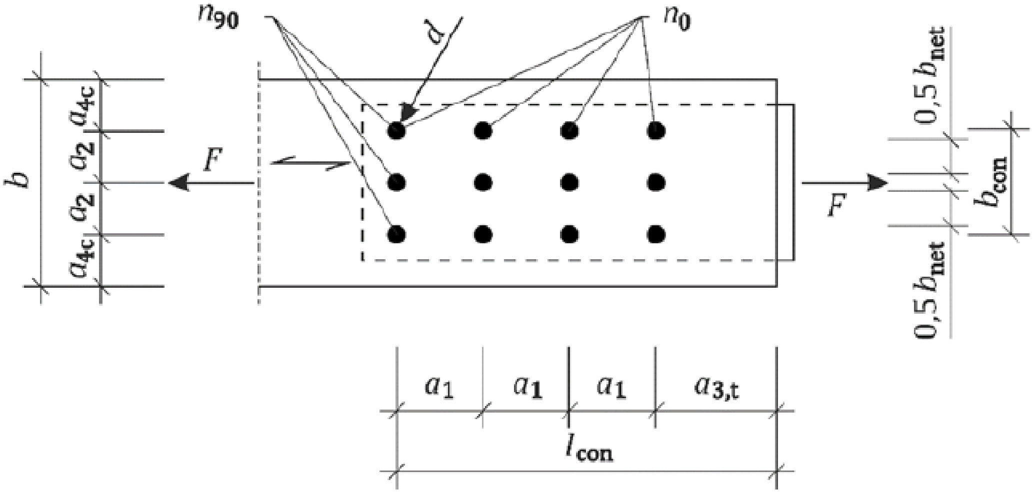


Figure 32: Basic geometry of a generic connection with multiple fasteners [1].

7.1.4.1 Side shear plane

A side shear plane is a plane with lateral shear crack along the exterior row of fasteners in the connection. The expression to determine the design shear resistance per lateral shear plane $F_{v,la,d}$ is given by:

$$F_{v,la,d} = k_v t_{ef} l_{con} f_{v,d} \tag{134}$$

$$k_v = 0.4 + 1.4\sqrt{\frac{G_{mean}}{E_{0,mean}}} \tag{135}$$

$$l_{con} = a_1(n_0 - 1) + a_{3,t} \tag{136}$$

7.1.4.2 Bottom shear plane

A bottom shear plane is a plane with horizontal shear cracks along the entire rows of fasteners, which is parallel to grain, in the connection. The expression to determine the design shear resistance of a bottom shear plane $F_{v,b,Rd}$ is given by:

$$F_{v,b,Rd} = k_v l_{con} b_{net} f_{v,d} \tag{137}$$

$$k_v = 0.4 + 1.4\sqrt{\frac{G_{mean}}{E_{0,mean}}} \tag{138}$$

$$l_{con} = a_1(n_0 - 1) + a_{3,t} \tag{139}$$

$$b_{net} = (a_2 - d_{hole,max})(n_{90} - 1) \tag{140}$$

7.1.4.3 Head tensile plane

Head tensile plane is a plane with a head tensile crack along the first column of fasteners in the connection. Equation (*141*) is used to determine the design tensile failure resistance parallel to the grain of the head tensile plane $F_{t,Rd}$. The thickness of the timber member is the effective thickness of the head tensile plane for connections with fully penetrating fasteners. For connections with partially penetrating fasteners, the effective thickness of the plane is determined in section 7.1.4.4.

$$F_{t,Rd} = b_{net}t_{ef}f_{t,0,d} \tag{141}$$

$$b_{net} = (a_2 - d_{hole,max})(n_{90} - 1) \tag{142}$$

7.1.4.4 Effective thickness

The expressions for determining effective thickness in the Present Eurocode 5 and the New Eurocode 5 are different. In the New Eurocode 5, there are two types of effective thicknesses of the failure planes given depending on the type of deformation in the connection, namely the elastic effective thickness and the plastic effective thickness. The effective thickness is elastic effective thickness when the deformation is elastic due to brittle member failure, and it is plastic effective thickness when the deformation is plastic due to yielding failure of fasteners. In the Present Eurocode 5, the effective thickness, as shown in

Figure 33, of failure planes depends on the thickness of the steel plates and the number of plastic hinges of the fasteners in the connection and do not explicitly mention the type of the effective thickness.

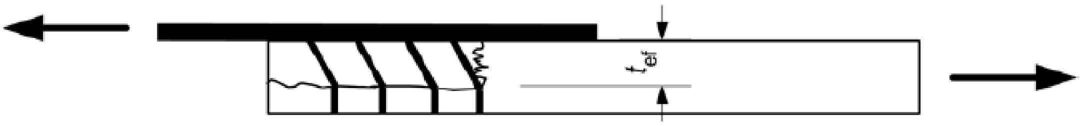


Figure 33: Effective thickness [2].

Present Eurocode 5

- The effective thickness for thin steel plates $t_p \leq 0.5d$, (for failure modes given in brackets) is determined by:

$$t_{ef} = \begin{cases} 0.4\, t_1 & \text{(a)} \\ 1.4\sqrt{\frac{M_{y,Rk}}{f_{h,k}\, d}} & \text{(b)} \end{cases} \tag{143}$$

- The effective thickness for thick steel plates $t_p \geq d$, (for failure modes given in brackets) is determined by:

$$t_{ef} = \begin{cases} 2\sqrt{\frac{M_{y,Rk}}{f_{h,k}\, d}} & \text{(e)(h)} \\ t_1\left[\sqrt{2 + \frac{4M_{y,Rk}}{f_{h,k}\, d{t_1}^2}} - 1\right] & \text{(d)(g)} \end{cases} \tag{144}$$

- For steel plates with intermediate thickness, interpolation is applied.

New Eurocode 5

The elastic effective thickness of the failure planes is applied for connections with fully penetrating fasteners. For partially penetrated timber members, the effective thickness of the failure planes in plug shear can be calculated by:

$$t_{ef,ps} = \min\begin{cases} t_{ef,el} \\ t_{ef,pl} \end{cases} \tag{145}$$

a) Elastic effective thickness

The elastic effective thickness of the failure planes $t_{ef,el}$ can be calculated separately for inner and outer members.

- For one inner member, the elastic effective thickness of the failure planes is given by Equation (*146*). For multiple inner timber members, the elastic effective thickness of the failure planes is given by multiplying Equation (*146*) by a factor of 0.85, i.e., $0.85t_{ef,el}$.

$$t_{ef,el} = \min\begin{cases} t_{h,i} & \text{if } \frac{t_{h,i}}{d} \leq 11\alpha_{cl} \\ \max\begin{cases} \left(2 - \frac{t_{h,1}}{11d}\right)\alpha_{cl} t_{h,i} \\ 0.65\alpha_{cl} t_{h,1} \end{cases} & \text{if } \frac{t_{h,i}}{d} > 11\alpha_{cl} \end{cases} \tag{146}$$

with

$\alpha_{cl} = 1$ when mode (f) governs in steel-to-timber connections;

$\alpha_{cl} = 0.65$ for timber-to-timber connections and for steel-to-timber connections for all failure modes excluding mode (f).

- For outer member, the elastic effective thickness of the failure planes is given by:

$$t_{ef,el} = \min\begin{cases} \alpha_{cl} t_{h,o} & \text{if } \dfrac{t_{h,o}}{d} \leq 3 \\ \max\begin{cases} \left(1.17 - \dfrac{t_{h,2}}{18d}\right) \alpha_{cl} t_{h,o} \\ 0.35 \alpha_{cl} t_{h,2} \end{cases} & \text{if } \dfrac{t_{h,o}}{d} > 3 \end{cases} \tag{147}$$

with

$\alpha_{cl} = 1$ when mode (f) governs in steel-to-timber connections;

$\alpha_{cl} = 0.65$ for timber-to-timber connections and for steel-to-timber connections for all failure modes excluding mode (f).

b) Plastic effective thickness

The plastic effective thickness $t_{ef,pl}$ can be calculated separately for non-predrilled fasteners and predrilled fasteners.

- For non-predrilled fasteners, the plastic effective thickness is given by:

$$t_{ef,pl} = \sqrt{\frac{M_{y,k}}{2 d f_{h,0,k}}} + \frac{t_h}{2} \tag{148}$$

- For predrilled fasteners, the plastic effective thickness is given by:

$$t_{ef,pl} = \sqrt{\frac{M_{y,k}}{d f_{h,0,k}}} + t_{ef,el,2} \tag{149}$$

$$t_{ef,el} = \min\begin{cases} t_{h,pl} & \text{if } \dfrac{t_{h,pl}}{d} \leq 11 \\ \max\begin{cases} \left(2 - \dfrac{t_{h,pl}}{11d}\right) t_{h,pl} \\ 0.65 t_{h,pl} \end{cases} & \text{if } \dfrac{t_{h,pl}}{d} > 11 \end{cases} \tag{150}$$

$$t_{h,pl} = t_h - \sqrt{\frac{M_{y,k}}{d f_{h,0,k}}} \tag{151}$$

7.1.5 Splitting failure

Splitting failure, as depicted in Figure 34(a), is a failure of the timber member in the connection due to tensile stresses perpendicular to the grain that generate a longitudinal crack along a row of fasteners loaded parallel to the grain. Splitting may not be the cause of the global failure of a connection with multiple rows of fasteners since it is a more locally failure in a single row of fasteners. In the New Eurocode 5 and the Present Eurocode 5, splitting along a row of fasteners loaded parallel to the grain is implicitly considered by the effective number of fasteners n_{ef} and by respecting some spacing limitations. The design splitting resistance along a row of fasteners loaded parallel to the grain is also implicitly covered in this thesis in section 4.2. The effective number n_{ef} for a row of fasteners parallel to the grain is discussed in detail in section 4.2.1. The design splitting failure resistance along a row of fasteners loaded parallel to the grain must satisfy the requirements given in Table 44. The requirement for the design splitting failure resistance along a row of fasteners loaded parallel to the grain has the same expression in the New Eurocode 5 and the Present Eurocode 5.

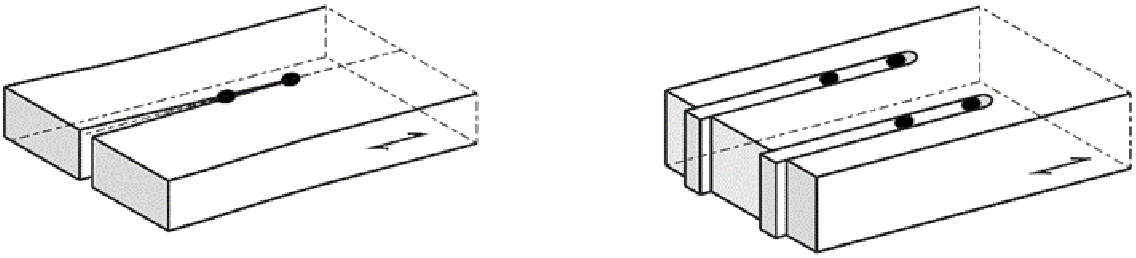
Table 44: Requirements for the design splitting failure resistance along a row of fasteners loaded parallel to the grain.

Present Eurocode 5		**New Eurocode 5**	
$F_{v,ef,Rd} \geq F_{row,d}$	(152)	$F_{v,Rd} \geq F_{v,Ed}$	(153)
$F_{v,ef,Rd} = n_{ef} F_{v,Rd}$	(154)	$F_{v,Rd} = n_{ef} F_{v,d}$	(155)

7.1.6 Row shear failure

Row shear failure, as depicted in Figure 34(b), is a failure of the timber member due to shear stresses that generate parallel cracks along each row of fasteners in the connection. This failure is defined by the failure of two side shear planes for each row of fasteners. For the row shear failure, no explicit provision is given by the Present Eurocode 5. In the New Eurocode 5, the expression for the design row shear failure resistance of a timber member, $F_{rs,d}$, is given by:

$$F_{rs,d} = 2 n_{90} F_{v,la,d} \tag{156}$$



a) Splitting failure b) Row shear failure

Figure 34: Splitting failure and Row shear failure modes [1].

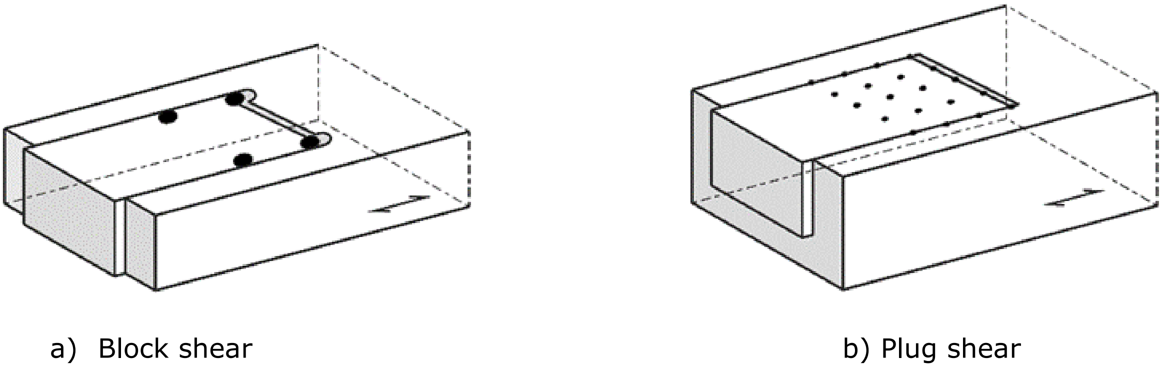
7.1.7 Block shear failure

Block shear failure, as depicted in Figure 35(a), is a failure of the timber member generated by the tear out of the loaded area of the timber along the perimeter of the fastener area where the fastener protrudes the full thickness of the timber member. Block shear failure, as shown in Figure 37, is defined by the failure of two side shear planes along the exterior rows of fasteners and a head tensile plane along the first column of fasteners in the connection. The expressions provided for determining the block shear failure by the Present Eurocode 5 and the New Eurocode 5 are different.

The expression for the design block shear failure resistance provided by the New Eurocode 5, as given in Equation (*162*), is for timber-to-timber and steel-to-timber connections. According to the New Eurocode 5, the block shear failure resistance of the timber member is the maximum of the tensile resistance of the head tensile plane or the sum of the shear resistances of the two side shear planes only. As depicted in Figure 32, the net length of the shear fracture side l_{con} is considered without the reduction of the cross-section of the timber member due to the pre-drilled holes for the fasteners. The provided expression is for the design resistance using design material strength. The design material strength is obtained using the partial factor for strength property of the material γ_M.

The expression provided by the Present Eurocode 5, as given in Equation (*157*), is for both the block shear and plug shear failure resistances of the timber member in steel-to-timber connections only. For timber-to-timber connections, no explicit provision is given by the Present Eurocode 5. According to the Present Eurocode 5, the block shear failure resistance is the maximum of the tensile resistance of the head tensile plane or the sum of the shear resistances of the two side shear planes and the bottom shear plane corresponding to the effective thickness. For connections with fully penetrated timber members, there is no activated bottom shear plane and Equation (*157*) gives the block shear failure resistance of the timber member which is the maximum of the tensile resistance of the head tensile plane and the sum of the shear resistances of only the two side shear planes. This is taken into account by Equation (*159*) which means that the type of failure mode of the shear plane in the connection is decisive for the number of shear planes to be used in Equation (*157*). Equation (*159*) gives two side shear planes for failure modes (c,f,j/l,k,m) and for all other failure modes it gives two side shear planes and a bottom shear plane. As depicted in Figure 36, the total net length of the shear fracture area $L_{net,v}$ is considered with the reduction of the cross-section of the timber member due to the pre-drilled holes for the fasteners. The provided expression is for the characteristic resistance. Partial factor for the resistance property γ_R is used to convert the characteristic resistance to the design resistance.

Therefore, the partial factors used to determine the design block shear failure resistance in the New Eurocode 5 and the Present Eurocode 5 are not the same. The partial factor for strength property of the material γ_M is used in the New Eurocode 5 and the partial factor for the resistance property γ_R is used in the Present Eurocode 5.



a) Block shear b) Plug shear

Figure 35: Block shear and plug shear failure modes [1].

Present Eurocode 5

The block shear failure resistance and the plug shear failure resistance of the timber member, as depicted in Figure 36, is given by:

$$F_{bs,Rk} = \max\begin{cases}1.5A_{net,t}f_{t,0,k}\\ 0.7A_{net,v}f_{v,k}\end{cases} \tag{157}$$

with

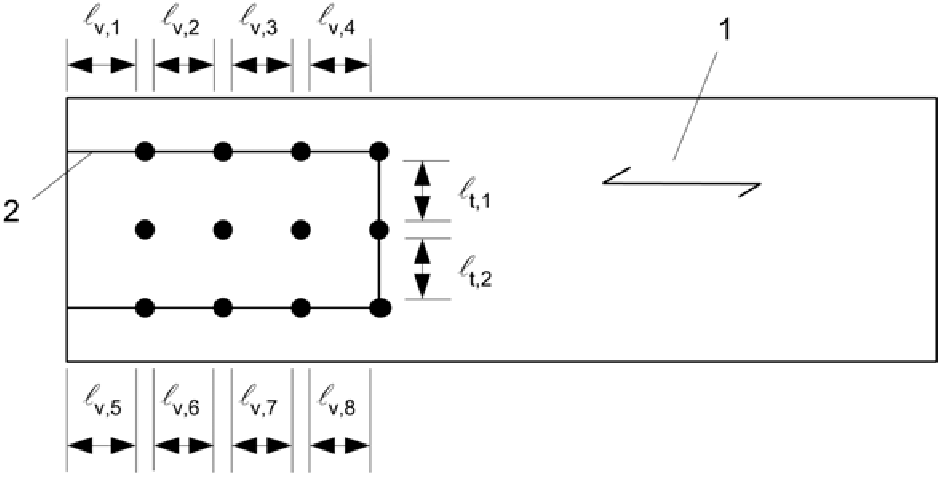
$$A_{net,t} = L_{net,t}\, t_1 \tag{158}$$

$$A_{net,v} = \begin{cases}L_{net,v}\, t_1 & \text{failure modes (c, f, j/l, k, m)}\\ \dfrac{L_{net,v}}{2}\left(L_{net,t} + 2t_{ef}\right) & \text{all other failure modes}\end{cases} \tag{159}$$

and

$$L_{net,v} = \sum_i l_{v,i} \tag{160}$$

$$L_{net,t} = \sum_i l_{t,i} \tag{161}$$



Key: 1 Grain direction and 2 Fracture line

Figure 36: Terms used in the expression for block shear failure [2].

New Eurocode 5

For connections with fully penetrated timber member, the design block shear failure resistance, $F_{bs,d}$, is determined by:

$$F_{bs,d} = \max\left(2\, F_{v,la,d};\ F_{t,Rd}\right) \tag{162}$$

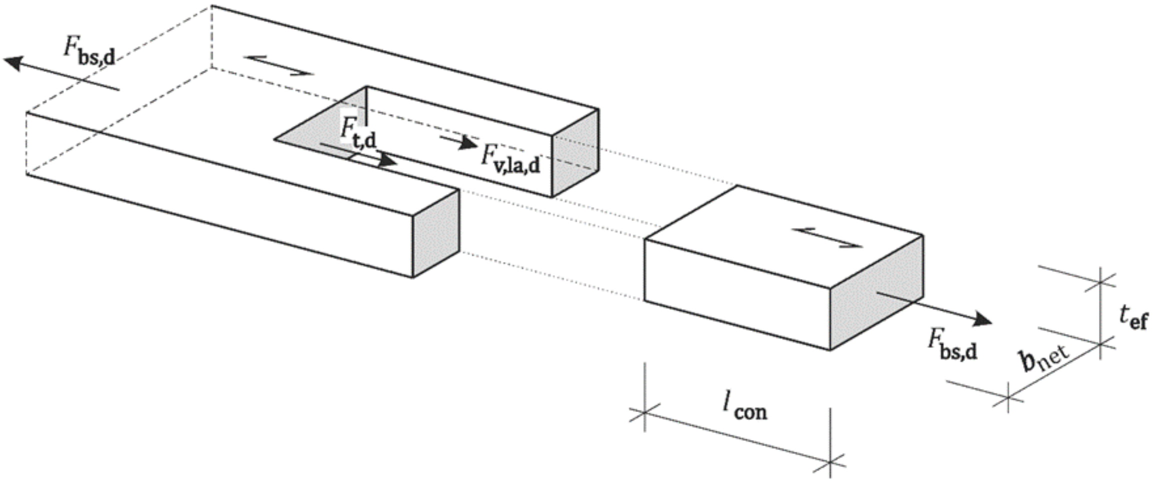


Figure 37: Block shear failure surfaces [1].

7.1.8 Plug shear failure

Plug shear failure, as depicted in Figure 35(b), is a failure of the timber member generated by the tear out of the loaded area of the timber along the perimeter of the fastener area where the fastener protrudes the partial thickness of the timber member.

This failure, as depicted in Figure 38, is defined by the failure of two side shear planes along the exterior rows of fasteners, a head tensile plane along the first column of fasteners and a bottom shear plane parallel to the grain. The expressions provided for determining the plug shear failure by the Present Eurocode 5 and the New Eurocode 5 are different.

The expression provided by the New Eurocode 5, as given in Equation (*163*), is for timber-to-timber and steel-to-timber connections. According to In the New Eurocode 5, the plug shear failure resistance of the timber member is the maximum of the sum of the shear resistances of the two side shear planes or the sum of the tensile resistance of the head tensile plane and the shear resistance of the bottom shear plane. As depicted in Figure 32, the net length of the shear fracture side l_{con} is considered without the reduction of the cross-section of the timber member due to the pre-drilled holes for the fasteners. The provided expression is for the design resistance using design material strength which also uses partial factor γ_M for strength property of the material.

The expression provided by the Present Eurocode 5, as shown in Equation (*157*), is for both the plug shear and block shear failure resistances of the timber member in steel-to-timber connections only. For timber-to-timber connections, no explicit provision is given by the Present Eurocode 5. For connections with partially penetrated timber member, Equation (*157*) gives the plug shear failure resistance of the timber member which is the maximum of the tensile resistance of the head tensile plane or the sum of the shear resistances of the two side shear planes and the bottom shear plane corresponding to the effective thickness. This is taken into account by Equation (*159*) which means that the type of failure mode of the shear plane in the connection is decisive for the number of shear planes to be used in Equation (*157*). Equation (*159*) gives two side shear planes for failure modes (c,f,j/l,k,m) and for all other failure modes it gives two side shear planes and a bottom shear plane. As depicted in Figure 36, the total net length of the shear fracture area $L_{net,v}$ is considered with the reduction of the cross-section of the timber member due to the pre-drilled holes for the fasteners. The provided expression is for the characteristic resistance and partial factor γ_R for the resistance property is to be used to convert it to the design resistance.

Therefore, the partial factors used to determine the design plug shear failure resistance in the New Eurocode 5 and the Present Eurocode 5 are different. The partial factor for strength property of the material γ_M is used in the New Eurocode 5 and the partial factor for the resistance property γ_R is used in the Present Eurocode 5.

$$F_{ps,d} = \max\begin{cases} 2F_{v,la,d} \\ F_{t,Rd} + F_{v,b,Rd} \end{cases} \tag{163}$$

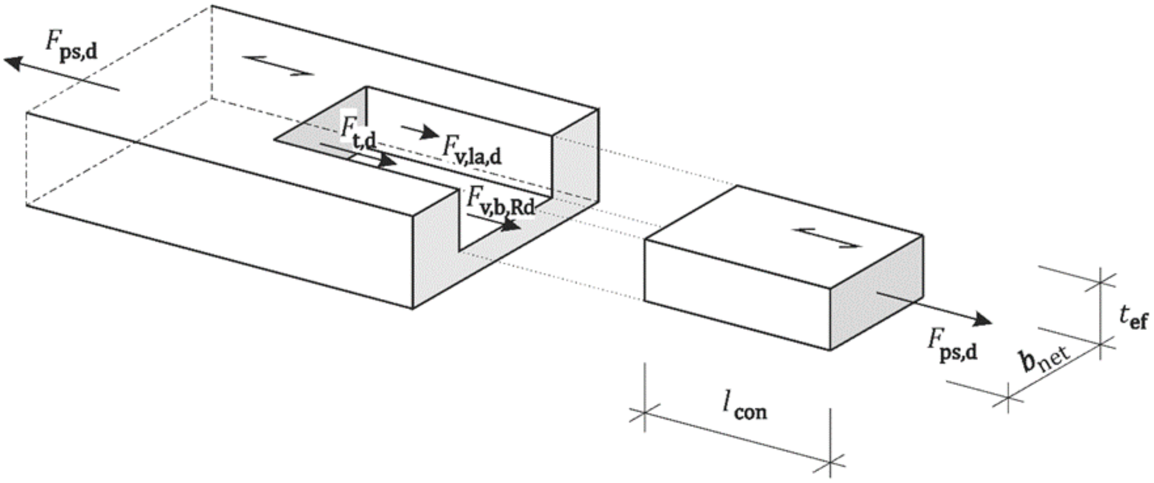


Figure 38: Plug shear failure surfaces [1].

7.1.9 Net tensile failure

In the New Eurocode 5 and the Present Eurocode 5, there is no explicit definition and expression given for net tensile failure depicted in Figure 39. The design net tensile failure resistance is determined according to section 8.1.2 in the New Eurocode 5 [1] and section 6.1.2 in the Present Eurocode 5 [2]. The process of determination of the design net tensile failure resistance by the New Eurocode 5 and the Present Eurocode 5 is the same. In a timber member subjected to tension parallel to the grain, the design tensile stress along the grain $\sigma_{t,0,d}$ must be less than or equal to the design tensile strength along the grain $f_{t,0,d}$. The net section is determined at a critical section which is the section having the largest number of fasteners perpendicular to the load direction. The consideration of the reduction of the cross-section of the timber member due to the pre-drilled holes for the fasteners and slots for metal plates is provided in section 7.2.3 in the New Eurocode 5 [1] and in section 5.2 in the Present Eurocode 5 [2]. The approach used in the Present Eurocode 5 and the New Eurocode 5 for the consideration of the reduction of the cross-section of the timber member is the same. For depths in bending and widths in tension less than 150 mm (h < 150 mm), the effect of member size on material strength by the depth modification factor k_h is considered according to sections 5.3 and 5.4 in the New Eurocode 5 [1] and sections 3.2 and 3.3 in the Present Eurocode 5 [2] for solid timber (ST) and glued laminated timber (GL) respectively. The values of the exponents in Equations (*170*) and (*171*) are not the same and they are 0.1 and 0.08 respectively.

Table 45: Net tensile failure.

Present Eurocode 5		**New Eurocode 5**	
$\sigma_{t,0,d} \leq f_{t,0,d}$	(164)	$\sigma_{t,0,d} \leq f_{t,0,d}$	(165)
$f_{t,0,d} = k_{mod} k_h f_{t,0,k} / \gamma_M$	(166)	$f_{t,0,d} = k_{mod} k_h f_{t,0,k} / \gamma_M$	(167)

$k_h = \min\begin{cases}(\frac{150}{h})^{0.2} \\ 1.3\end{cases}$ for ST	(168)	$k_h = \min\begin{cases}(\frac{150}{h})^{0.2} \\ 1.3\end{cases}$ for ST	(169)
$k_h = \min\begin{cases}(\frac{600}{h})^{0.1} \\ 1.1\end{cases}$ for GL	(170)	$k_h = \min\begin{cases}(\frac{600}{h})^{0.08} \\ 1.1\end{cases}$ for GL	(171)

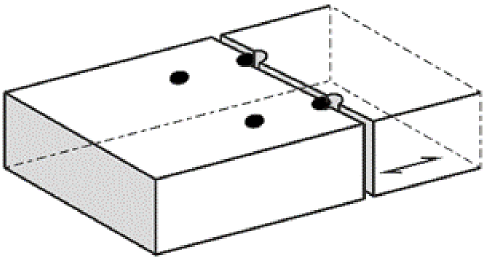


Figure 39: Net tensile failure [1].

The nomenclature used in the brittle failure modes of connections with fasteners loaded parallel to the grain in the Present Eurocode 5 and the New Eurocode 5 is presented in Table 46.

Table 46: Nomenclature used in the brittle failure modes of connections with fasteners loaded parallel to the grain.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
	k_v	a reduction factor for shear
t_{ef}	t_{ef}	the effective thickness of the plane, determined in 7.1.4.4, in mm
	l_{con}	the length of the connection parallel to the grain, see Figure 32, in mm
$f_{v,k}$	$f_{v,d}$	the characteristic/design shear strength of timber, in N/mm^2
	a_1	the spacing of fasteners parallel to grain, in mm
	n_0	the number of fasteners in a row parallel to grain, see Figure 32
	$a_{3,t}$	distance from loaded end parallel to grain, in mm
	G_{mean}	the mean shear modulus of timber, in N/mm^2

	$E_{0,mean}$	the mean modulus of elasticity of the timber parallel to the grain, in N/mm^2
	$F_{v,la,d}$	the design shear resistance per lateral shear plane, in N
	b_{net}	the net width between the fasteners over the whole cross-section, see Figure 19, in mm
	n_{90}	the number of fasteners in a row perpendicular to the grain, see Figure 32
	a_2	the spacing between the fasteners perpendicular to the grain, in mm
	$d_{hole,max}$	the largest diameter of the predrilled hole or diameter of the fastener, in mm
	$F_{v,b,Rd}$	the design shear resistance of bottom shear plane, in N
$f_{t,0,k}$	$f_{t,0,d}$	the characteristic/design tensile strength of the timber parallel to the grain, in N/mm^2
	$F_{t,Rd}$	the design tensile failure resistance parallel to grain of the head tensile plane, in N
	$t_{ef,el}$	the elastic effective thickness, determined in section 7.1.4.4, in mm
	$t_{ef,pl}$	the plastic effective thickness, determined in section 7.1.4.4, in mm
t_1	$t_{h,1}$	the penetration length of the fastener in the inner member, which corresponds to the thickness of the inner timber member $t_{h,i}$, in mm
	α_{cl}	the factor related to the clamping condition of the fastener, defined by the yielding mode
t_1	$t_{h,2}$	the thickness of the outer timber member $t_{h,o}$ for fully penetrated members or the penetration length of the fastener for partially penetrated members, in mm
$M_{y,Rk}$	$M_{y,k}$	characteristic yield moment given in section 3.4, in Nmm
$f_{h,k}$	$f_{h,0,k}$	the characteristic embedment strength of the timber member given in section 3.3, in N/mm^2
	t_h	the embedment depth of the fastener, in mm
	$t_{ef,el,2}$	the remaining elastic effective thickness, in mm

	$t_{h,pl}$	the plastic penetration length, determined by Equation (151), in mm
$A_{net,t}$		the net cross-sectional area perpendicular to the grain, in mm^2
$A_{net,v}$		the net shear area in the parallel to the grain direction, in mm^2
$L_{net,t}$		the net width of the cross-section perpendicular to the grain, in mm
$L_{net,v}$		total net length of the shear fracture area, in mm
$l_{v,i}$, $l_{t,i}$		are distances defined in Figure 36, in mm
$F_{v,ef,Rd}$	$F_{v,Rd}$	effective design resistance per row of fasteners loaded parallel to the grain, in N
$F_{row,d}$	$F_{v,Ed}$	design force per row of fasteners loaded parallel to the grain, in N
$F_{v,Rd}$	$F_{v,d}$	design resistance per fastener, in N
n_{ef}	n_{ef}	effective number of fasteners in a row parallel to the grain, determined in section 4.2.1
	$F_{rs,d}$	the design row shear failure resistance of a timber member, in N
$F_{bs,Rk}$	$F_{bs,d}$	the characteristic/design block shear failure resistance of a timber member, in N
	$F_{ps,d}$	the design plug shear failure resistance of a timber member, in N
$\sigma_{t,0,d}$	$\sigma_{t,0,d}$	the design tensile stress parallel to the grain, in N/mm^2
$f_{t,0,d}$	$f_{t,0,d}$	the design tensile strength parallel to the grain, in N/mm^2
k_{mod}	k_{mod}	the modification factor accounting for the effect of the duration of load and moisture content
γ_M	γ_M	the partial factor for the material property
k_h	k_h	the depth modification factor
h	h	the depth for bending members or width for tensile members, in mm

7.2 Brittle failure modes of connections with fasteners loaded perpendicular to the grain

Brittle failure mode is due to a failure of the wood usually happens before the steel fasteners reach their plastic range. It is usually a sudden collapse of the connection. Splitting failure is a failure of the timber member in a connection loaded to tensile force or tensile force component perpendicular to the grain, as depicted in Figure 40(a), that generate a longitudinal fracture along a row of fasteners parallel to the grain due to tensile stresses perpendicular to the grain. The New Eurocode 5 and the Present Eurocode 5 include the brittle failure mode of connections with fasteners loaded perpendicular to the grain, but with different expressions. The design splitting failure resistance is based on the design shear forces created on the sides of the cross-section of the beam by the tensile force or tensile force component.

In the New Eurocode 5, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain does not depend on the position of the connection along the beam length. The design splitting resistance must be equal to or greater than the tensile force or tensile force component perpendicular to the grain which is equal to the sum the values of the two shear forces on the sides as shown in Figure 42(a). The design splitting resistance of a connection with fasteners loaded perpendicular to the grain depends on the number of fasteners in a row parallel to the grain n_0 and on the distance from the loaded edge to the center of the most distant fastener h_e. This means that the design splitting resistance increases with the increasing number of fasteners in a row parallel to the grain n_0 and with increasing the distance from the loaded edge to the center of the most distant fastener h_e. If the distance from the loaded edge to the center of the most distant fastener h_e is kept constant, the design splitting resistance depends on the number of fasteners in a row parallel to the grain n_0 and on the number of fasteners in a row perpendicular to the grain n_{90}. This means that the design splitting resistance increases with the increasing number of fasteners in a row perpendicular to the grain n_{90} and with the increasing number of fasteners in a row parallel to the grain n_0.

In the Present Eurocode 5, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain must be equal to or greater than the maximum of the shear force values $F_{v,Ed,1}$ or $F_{v,Ed,2}$ on the sides as depicted in Figure 40(a) and therefore it depends on the position of the connection along the beam length. When a connection is not at midspan of the beam, the values of the two shear forces $F_{v,Ed,1}$ and $F_{v,Ed,2}$ are not equal and hence, the maximum value of the shear forces $F_{v,Ed,1}$ or $F_{v,Ed,2}$ is decisive for the design splitting resistance of the connection. When a connection is at midspan of the beam, the values of the two shear forces $F_{v,Ed,1}$ and $F_{v,Ed,2}$ are equal and hence, one of the shear forces $F_{v,Ed,1}$ or $F_{v,Ed,2}$ is decisive for the design splitting resistance of the connection. The design splitting resistance of a connection with fasteners loaded perpendicular to the grain does not depend on the number of fasteners in a row parallel to the grain n_0 but depends on the distance from the loaded edge to the center of the most distant fastener h_e. If the distance from the loaded edge to the center of the most distant fastener h_e is kept constant, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain does not depend on the number of fasteners in a row perpendicular to the grain n_{90} and on the number of fasteners in a row parallel to the grain n_0. The design splitting resistance of a connection with fasteners loaded perpendicular to the grain must satisfy the requirement given in Table 47.

Table 47: Requirements for the design splitting resistance of a connection with fasteners loaded perpendicular to the grain.

Present Eurocode 5		**New Eurocode 5**	
$F_{v,Ed} \leq F_{90,Rd}$	(172)	$F_{90,Ed} \leq F_{sp,Rd}$	(173)
$F_{v,Ed} = \max\begin{cases}F_{v,Ed,1}\\F_{v,Ed,2}\end{cases}$	(174)	$F_{90,Ed} = F_{Ed} * \sin\alpha$	(175)

Present Eurocode 5

The characteristic splitting resistance of a connection with fasteners loaded perpendicular to the grain, as the arrangement shown in Figure 40, is given by:

$$F_{90,Rk} = 14\, b\, w \sqrt{\frac{h_e}{(1-\frac{h_e}{h})}} \tag{176}$$

$$w = \begin{cases} \max\begin{cases}(\frac{w_{pl}}{100})^{0.35}\\ 1\end{cases} & \text{for punched metalplate fasteners} \\ 1 & \text{for all other fasteners}\end{cases} \tag{177}$$

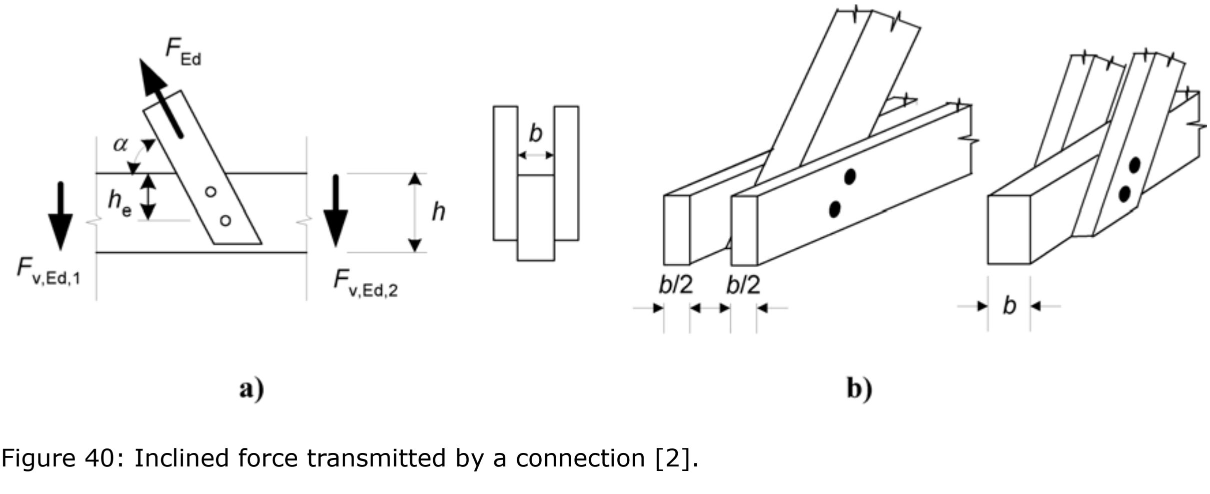


Figure 40: Inclined force transmitted by a connection [2].

New Eurocode 5

The characteristic splitting resistance of one connection with fasteners loaded perpendicular to the grain is given by:

$$F_{sp,Rk} = k_{mat} k_G b_{ef} k_{con,0} k_{con,90} \sqrt{\frac{h_e}{(1 - \frac{h_e}{h})}} \tag{178}$$

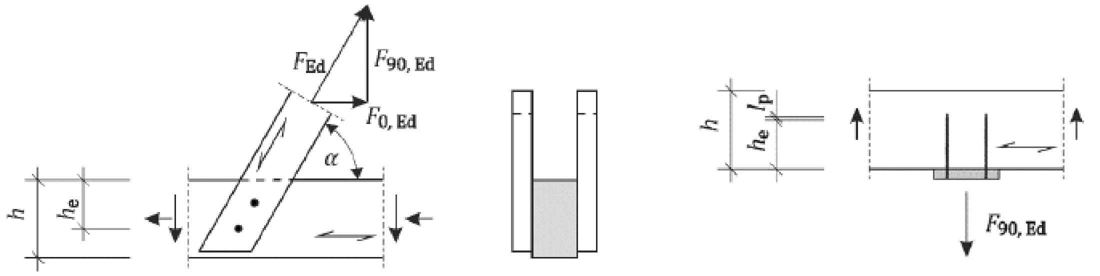
$$k_{mat} = \begin{cases} 0.6 & \text{ST} \\ 0.8 & \text{PL} \end{cases} \tag{179}$$

$$k_G = (0.05\, \rho_k + 2) \tag{180}$$

$$b_{ef} = b \tag{181}$$

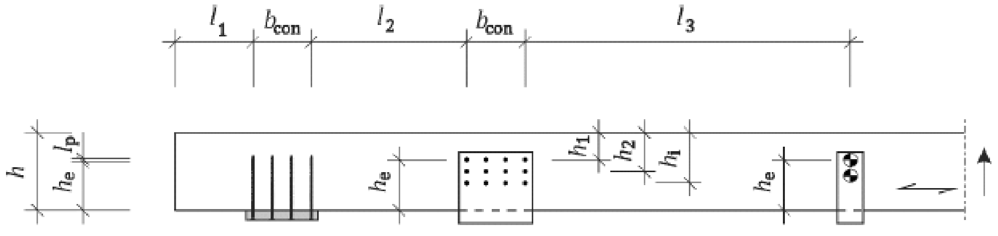
$$k_{con,0} = \max \begin{cases} 1 \\ 0.7 + \dfrac{1.4 b_{con}}{h} \end{cases} \tag{182}$$

$$k_{con,90} = \frac{n_{90}}{\sum_{i=1}^{n_{90}} (\frac{h_1}{h_i})^2} \tag{183}$$



a) Laterally loaded fasteners

b) Axially loaded fasteners



c) Multiple connections

Key:

l_1	is end distance of a group of dowel-type fasteners parallel to the grain, in mm;
l_2	is spacing between a group of dowel-type fasteners parallel to the grain, in mm;

l_3	is spacing between a group of dowel-type fasteners and shear connectors, in mm;
b_{con}	is width of a connection, in mm;
h	is the depth of the beam, in mm;
h_e	is the distance from the loaded edge to the location where the full connection force is transmitted, for screws the penetration length without the point, in mm;
l_p	is point length of screws, in mm;
$F_{90,Ed}$	is the design load perpendicular to the grain, in N.

Figure 41: Loaded edge distance, end face distance and distances between connections [1].

For ratios $h_e/h \geq 0.7$ other cross-section forces or moments are usually governing the design of a connection therefore splitting failure may be neglected. The characteristic splitting failure resistance of multiple connections with the same h_e/h ratio can be determined by multiplying Equation (*178*) with a modification factor $k_{n,1}$ which is given by:

$$k_{n,1} = \begin{cases} \sqrt{\frac{1}{n}} & \text{for } 2h \leq a_1 \leq 6h \\ 1 & \text{for } l_2 < h \text{ or } l_2 \geq 8h \end{cases} \tag{184}$$

The modification factor $k_{n,1}$ is determined by linear interpolation for the distances between connections $h \leq l_2 < 2h$ or $6h < l_2 < 8h$.

Table 48: Nomenclature used in the brittle failure modes of connections with fasteners loaded perpendicular to the grain.

Present Eurocode 5	**New Eurocode 5**	**Meaning**
$F_{90,Rd}$	$F_{sp,Rd}$	the design splitting failure resistance
$F_{v,Ed}$	$F_{90,Ed}$	the design tensile force component perpendicular to the grain
$F_{v,Ed,1}$, $F_{v,Ed,2}$		the design shear forces on either side of the connection, in N
F_{Ed}	F_{Ed}	the design tensile force transmitted by the connection
$F_{90,Rk}$	$F_{sp,Rk}$	the characteristic splitting resistance

b	b	the member thickness, in mm
w		a modification factor
h_e	h_e	The distance from the loaded edge to the location where the full connection force is transmitted, for screws the penetration length without the point, in mm
h	h	the member depth, in mm
	k_{mat}	a reduction factor
	k_G	a fracture parameter, in N/mm$^{1.5}$
	b_{con}	the distance between the outermost columns within one connection, see Figure 41(c), in mm
	n_{90}	the number of fasteners in a row perpendicular to the grain
	h_i	the distance of the ith row to the unloaded edge of the member, with $h_{i+1} - h_i \leq 0.5h$, see Figure 41(c), in mm
	ρ_k	the density of the timber, in kg/m^3
	n	the number of connections
	a_1	spacing between fasteners along the grain, in mm
	l_2	The distance between fasteners of two consecutive connections, see Figure 41(c), in mm

7.2.1 Example case for splitting resistance of a connection with fasteners loaded perpendicular to the grain

This is an example case for the design splitting resistance of a connection with fasteners loaded perpendicular to the grain. The expressions for design splitting resistance of a connection with fasteners loaded perpendicular to the grain provided by the Present Eurocode 5 and the New Eurocode 5 have many variable parameters. The aim of this example is to examine how the design splitting resistance is affected by the expressions provided by the New Eurocode 5 and the Present Eurocode 5. This example is solved by considering two variable parameters from which only one parameter is varying at a time and one constant parameter. In the first, the distance from the loaded edge to the center of the most distant fastener h_e and the number of dowels parallel to the grain n_0 are the variable parameters and the number of dowels perpendicular to the grain n_{90} is the constant parameter. In the second, the number of dowels parallel to the grain n_0 and perpendicular to the grain n_{90} are the variable parameters and the distance from the loaded edge to the center of the most distant fastener h_e is the constant parameter. The parameters used in all the tables and the figures in this example case are h = 450 mm, b = 80 mm, a_1 = 60 mm, a_2 = 50 mm, $a_{4,c}$ = 150 mm, ρ_k = 400 kg/m^3, dimeter of the dowels d = 12 mm, k_{mod} = 0.9 and γ_M = 1.3. The value of $a_{4,t}$ varies corresponding to the applied number of dowels perpendicular to the grain n_{90}.

By holding the number of dowels perpendicular to the grain n_{90} (n_{90} = 1) constant, the values of the design splitting resistance with different distances from the loaded edge to the center of the most distant fastener h_e and different number of dowels parallel to the grain n_0 are presented in

Table 49 and given in Figure 42 and Figure 43. By keeping the distance from the loaded edge to the center of the most distant fastener h_e (h_e = 300 mm) constant, the values of the design splitting resistance with different number of dowels perpendicular to the grain n_{90} and different number of dowels parallel to the grain n_0 are presented in Table 50 and given in Figure 44 and Figure 45.

In the New Eurocode 5, the design splitting resistance must be equal to or greater than the applied design tensile force or design tensile force component perpendicular to the grain which is equal to the sum the values of the two design shear forces on the sides of the beam ($F_{sp,Rd} \geq F_{90,Ed}$). The design splitting resistance of a connection with fasteners loaded perpendicular to the grain does not depend on the position of the connection along the beam length.

In the Present Eurocode 5, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain must be equal to or greater than the maximum of the design shear force values on the sides of the beam and therefore it depends on the position of the connection along the beam length. $F_{90,Rd}$ is the design splitting resistance when the connection is at the support of the horizontally placed beam and one of the design shear forces on the sides of the beam has a maximum value which is equal to the value of the applied design tensile force perpendicular to the grain and the other shear force has a minimum value which is equal to zero. $F_{90,Rd}^*$ is the design splitting resistance when a connection is at midspan of the beam and each of the design shear forces on the sides of the beam has a maximum value which is equal to half of the value of the applied design tensile force perpendicular to the grain. $F_{90,Rd}$ must be equal to or greater than the value of the applied design tensile force perpendicular to the grain ($F_{90,Rd} \geq F_{v,Ed}$) and $F_{90,Rd}^*$ must be equal to or greater than half of the value of the applied design tensile force perpendicular to the grain ($F_{90,Rd}^* \geq F_{v,Ed}/2$). Therefore, $F_{90,Rd} = 2\ F_{90,Rd}^*$ as presented in Table 49 and depicted in Figure 42.

When the number of dowels in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0 are kept constant, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain increases with increasing distances from the loaded edge to the center of the most distant fastener h_e in the New Eurocode 5 and the Present Eurocode 5 as given in Table 49 and as shown in Figure 42 and Figure 43. when the number of dowels in a row perpendicular to the grain n_{90} and the distance from the loaded edge to the center of the most distant fastener h_e are kept constant, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain increases in the New Eurocode 5 and remains constant in the Present Eurocode 5 with the increasing number of dowels in a row parallel to the grain n_0 as given in Table 49 and as shown in Figure 42 and Figure 43.

Table 49: Design splitting resistance with different distances from the loaded edge to the center of the most distant fastener h_e and different number of dowels in a row parallel to the grain n_0.

	2 dowels parallel to grain ($n_0 = 2$)			4 dowels parallel to grain ($n_0 = 4$)			6 dowels parallel to grain ($n_0 = 6$)		
h_e [mm]	$F_{90,Rd}^*$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]	$F_{90,Rd}^*$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]	$F_{90,Rd}^*$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
50	5.82	11.63	5.48	5.82	11.63	6.91	5.82	11.63	8.96
100	8.79	17.58	9.39	8.79	17.58	11.83	8.79	17.58	15.34
150	11.63	23.26	14.32	11.63	23.26	18.04	11.63	23.26	23.39
200	14.71	29.42	21.38	14.71	29.42	26.94	14.71	29.42	34.92
250	18.39	36.78	32.58	18.39	36.78	41.05	18.39	36.78	53.21
300	23.26	46.52	52.71	23.26	46.52	66.41	23.26	46.52	86.08

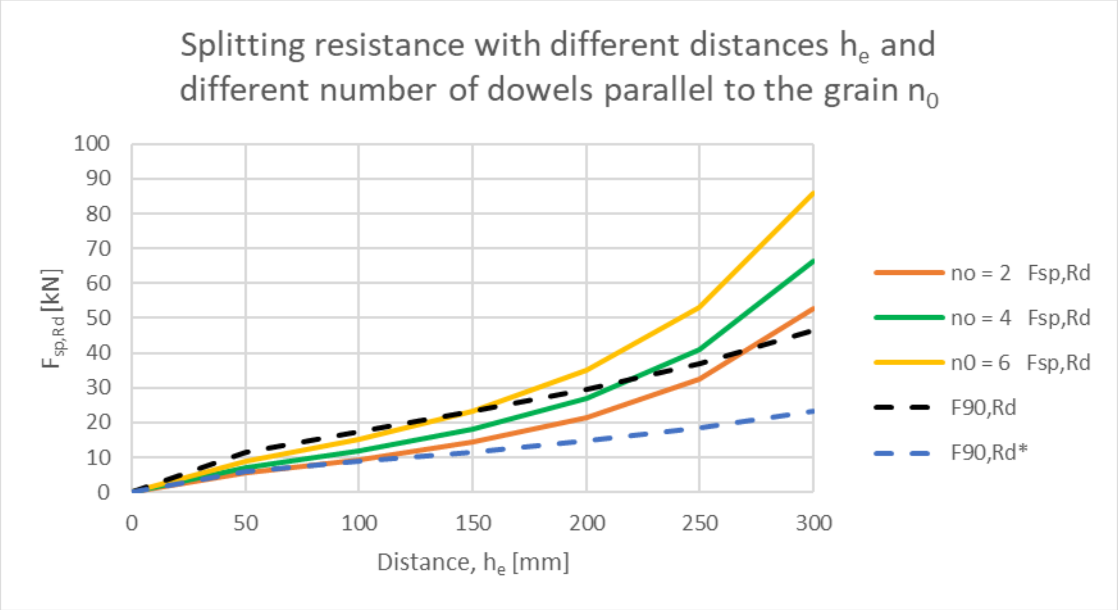
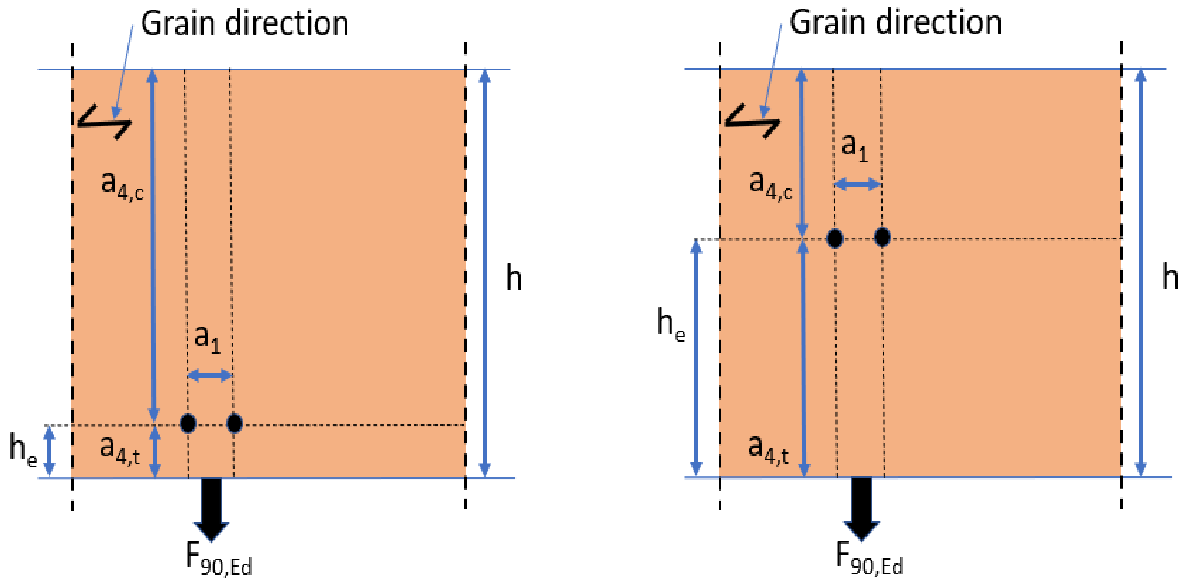
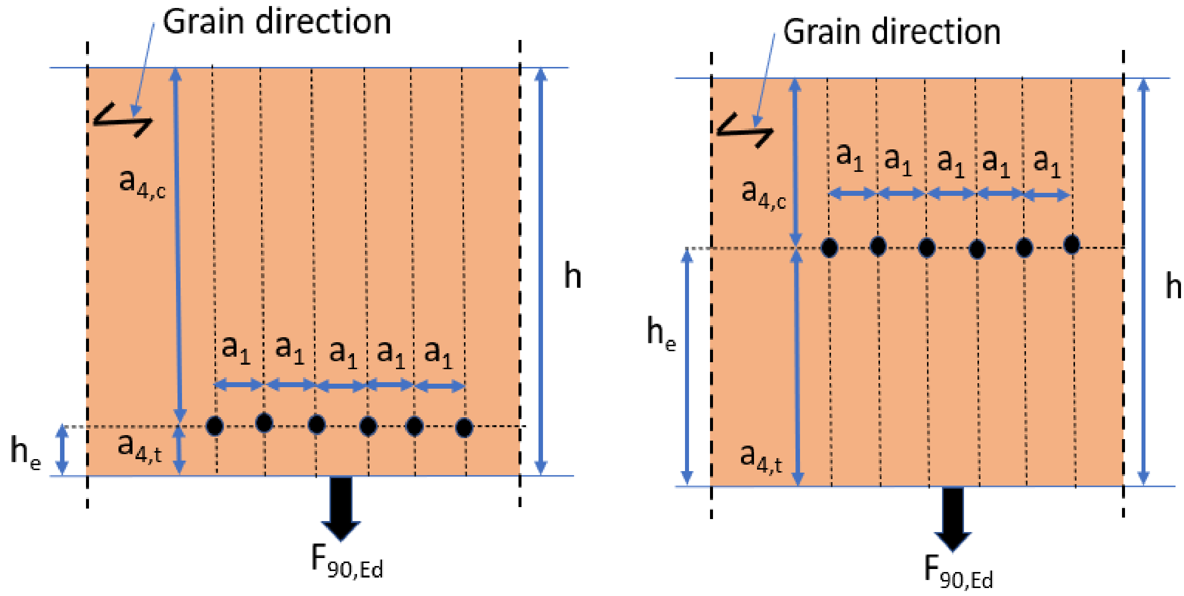


Figure 42: Design splitting resistance with different distances from the loaded edge to the center of the most distant fastener h_e and different number of dowels in a row parallel to the grain n_0.



a) $h_e = 50$ mm, $n_0 = 2$ b) $h_e = 300$ mm, $n_0 = 2$

$F_{sp,Rd} = 5.48$, $F_{90,Ed} = 11.63$ $F_{sp,Rd} = 52.71$, $F_{90,Rd} = 46.52$



a) $h_e = 50$ mm, $n_0 = 6$ b) $h_e = 300$ mm, $n_0 = 6$

$F_{sp,Rd} = 8.96$, $F_{90,Rd} = 11.63$ $F_{sp,Rd} = 86.08$, $F_{90,Rd} = 46.52$

Figure 43: Arrangement of dowels in a row parallel to the grain n_0 at different distances h_e in connections and corresponding values of design splitting resistance in kN.

When the distance from the loaded edge to the center of the most distant fastener h_e is kept constant, the design splitting resistance increases with the increasing number of dowels in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0 in the New Eurocode 5 as shown in Table 50 and in Figure 44 and Figure 45. Hence, the design splitting resistance depends on the number of fasteners in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0 when the distance from the loaded edge to the center of the most distant fastener h_e is kept constant according to the New Eurocode 5. In the Present Eurocode 5 as shown in Table 50 and in Figure 44 and Figure 45, the design splitting resistance remains constant with the increasing number of dowels in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0 when the distance from the loaded edge to the center of the most distant fastener h_e is kept constant. Hence, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain does not depend on the number of fasteners in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0 when the distance from the loaded edge to the center of the most distant fastener h_e is kept constant according to the Present Eurocode 5.

Table 50: Design splitting resistance with different number of dowels in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0.

	2 dowels parallel to grain ($n_0 = 2$)			4 dowels parallel to grain ($n_0 = 4$)			6 dowels parallel to grain ($n_0 = 6$)		
n_{90}	$F_{90,Rd}{}^{*}$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]	$F_{90,Rd}{}^{*}$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]	$F_{90,Rd}{}^{*}$ [kN]	$F_{90,Rd}$ [kN]	$F_{sp,Rd}$ [kN]
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	23.26	46.52	21.93	23.26	46.52	27.63	23.26	46.52	35.82
2	23.26	46.52	28.07	23.26	46.52	35.37	23.26	46.52	45.85
3	23.26	46.52	34.22	23.26	46.52	43.12	23.26	46.52	55.90
4	23.26	46.52	40.38	23.26	46.52	50.88	23.26	46.52	65.96
5	23.26	46.52	46.54	23.26	46.52	58.64	23.26	46.52	76.02
6	23.26	46.52	52.71	23.26	46.52	66.41	23.26	46.52	86.08

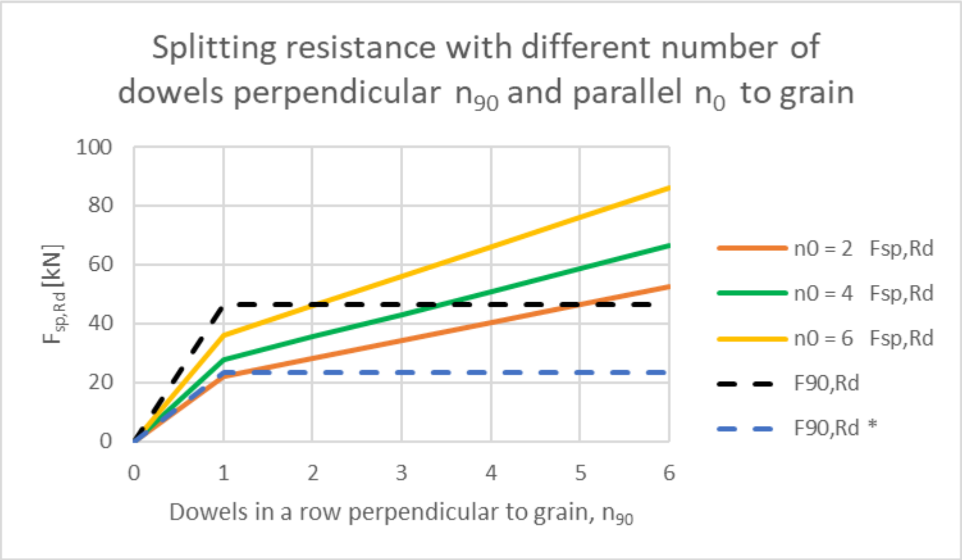
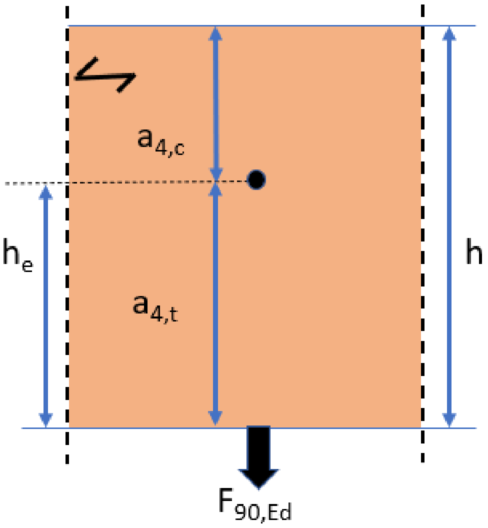
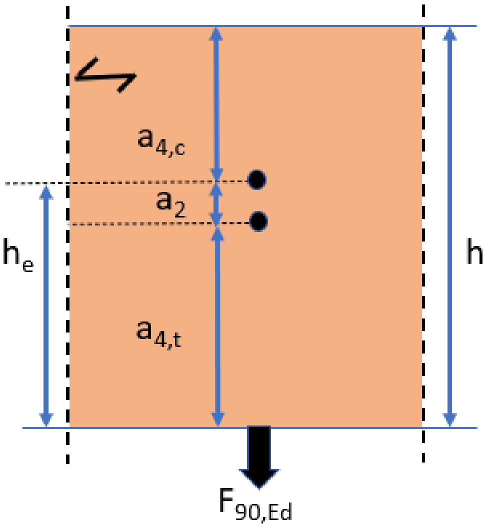


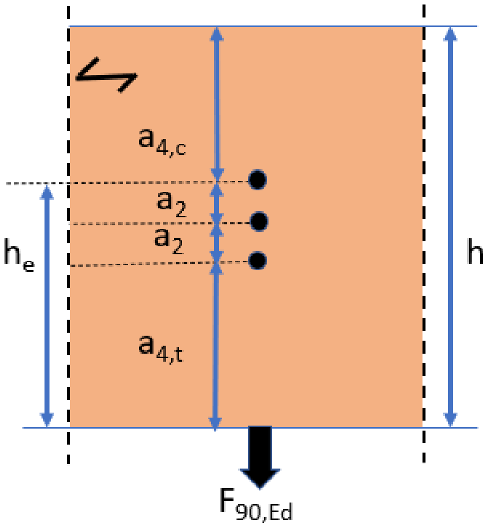
Figure 44: Design splitting resistance with different number of dowels in a row perpendicular to the grain n_{90} and in a row parallel to the grain n_0.



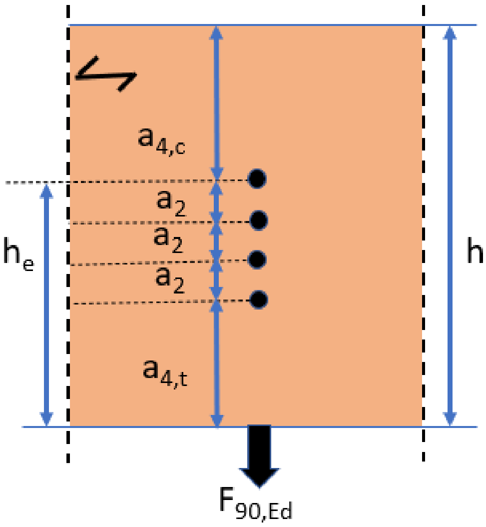
$F_{sp,Rd} = 21.93$, $F_{90,Rd} = 46.52$



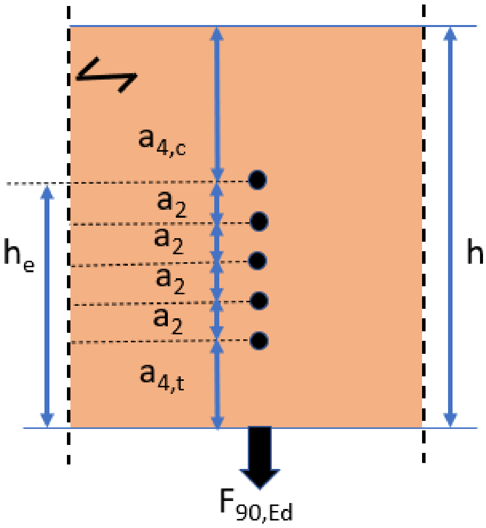
$F_{sp,Rd} = 28.07$, $F_{90,Rd} = 46.52$



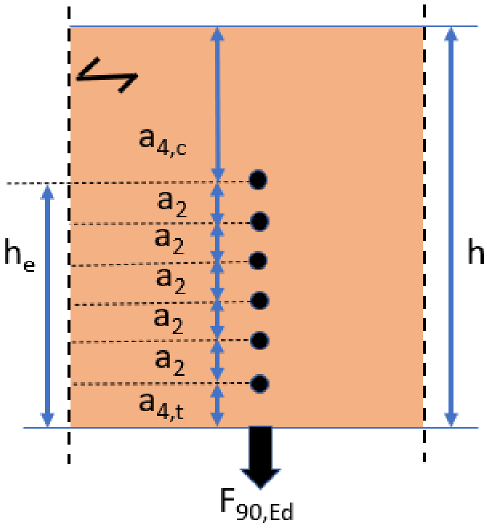
$F_{sp,Rd} = 34.22$, $F_{90,Rd} = 46.52$



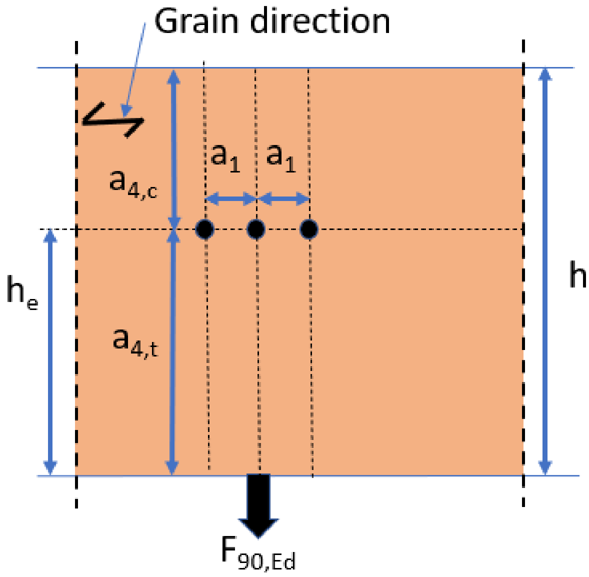
$F_{sp,Rd} = 40.38$, $F_{90,Rd} = 46.52$



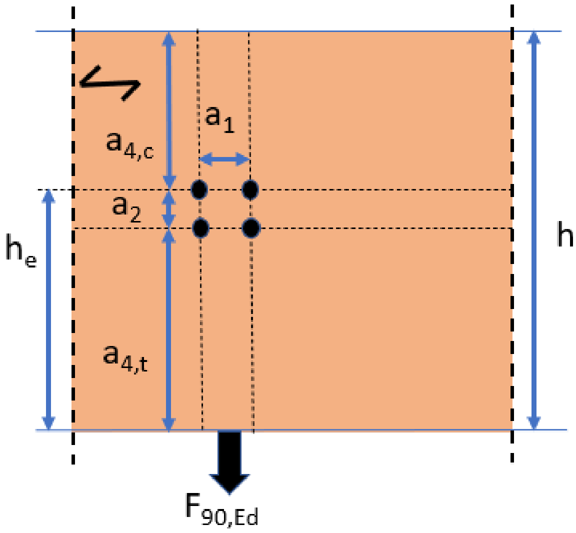
$F_{sp,Rd} = 46.54$, $F_{90,Rd} = 46.52$



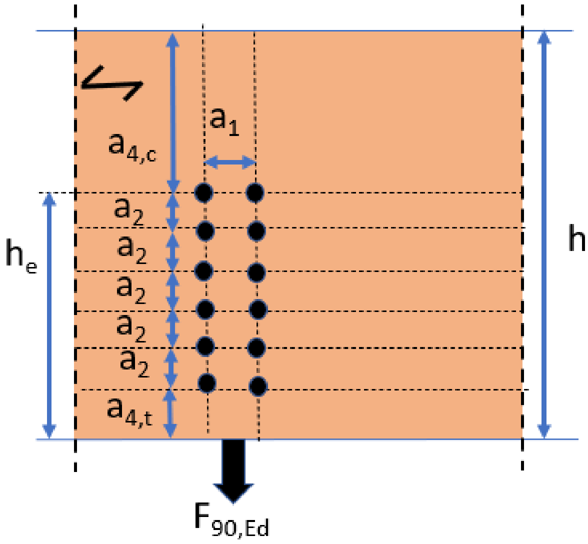
$F_{sp,Rd} = 52.71$, $F_{90,Rd} = 46.52$



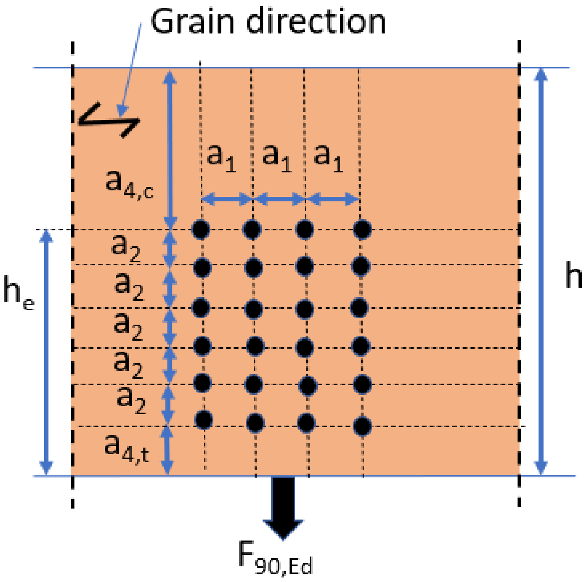
$F_{sp,Rd} = 23.54$, $F_{90,Rd} = 46.52$



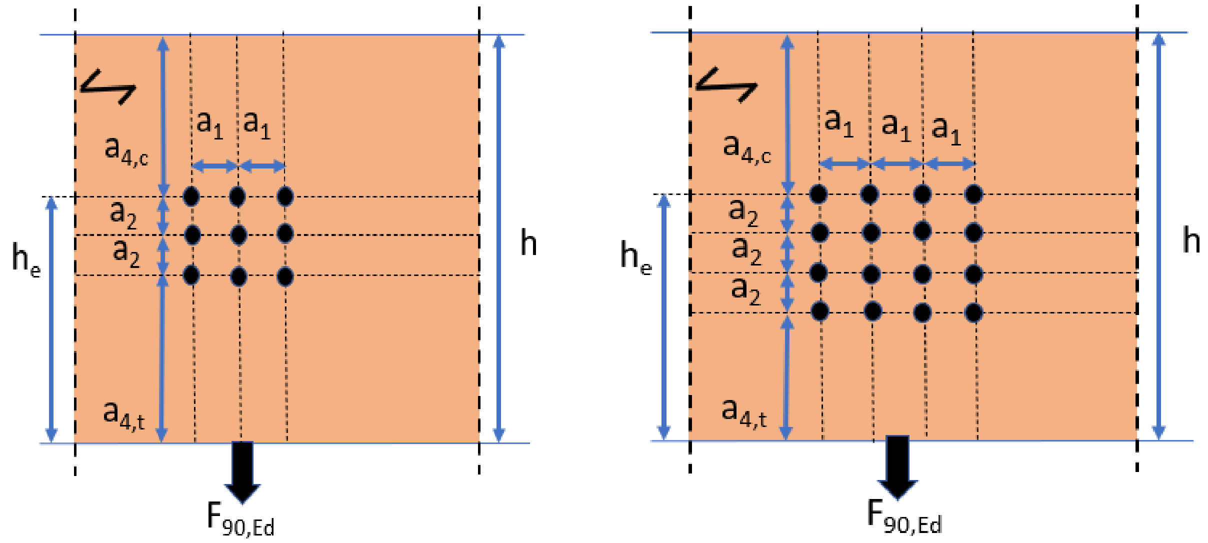
$F_{sp,Rd} = 28.07$, $F_{90,Rd} = 46.52$



$F_{sp,Rd} = 52.71$, $F_{90,Rd} = 46.52$

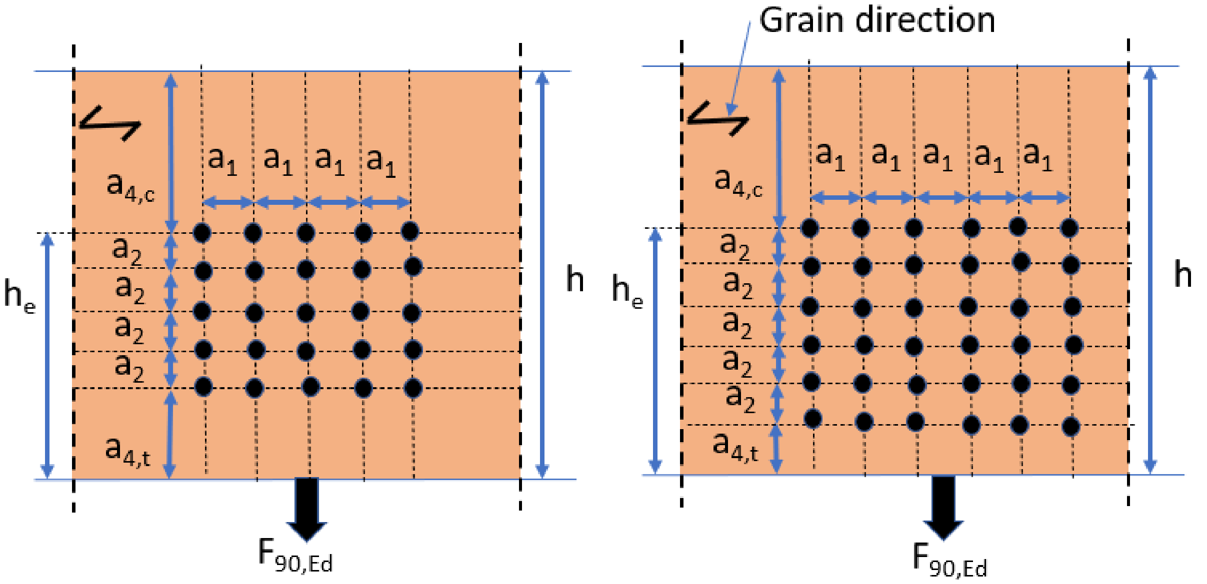


$F_{sp,Rd} = 66.41$, $F_{90,Rd} = 46.52$



$F_{sp,Rd} = 36.73$, $F_{90,Rd} = 46.52$

$F_{sp,Rd} = 50.88$, $F_{90,Rd} = 46.52$



$F_{sp,Rd} = 67.33$, $F_{90,Rd} = 46.52$

$F_{sp,Rd} = 86.08$, $F_{90,Rd} = 46.52$

Figure 45: Arrangements of dowels in rows perpendicular to the grain n_{90} and parallel to the grain n_0 in connections and corresponding values of design splitting resistance in kN.

8 Example cases covering multiple topics

In this chapter some example cases are presented covering multiple topics from different sections. In these example cases a comparison is made between the results of the calculations using the Present Eurocode 5 and the New Eurocode 5. The Present Eurocode 5 and the New Eurocode 5 provide expressions for the design value of a material strength and design value of a resistance. For comparison purposes, only the expressions for the design values provided by the Present Eurocode 5 are used in this chapter. The design values are given by:

Table 51: Design values by the Present Eurocode 5 and the New Eurocode 5.

Design value of a	Present Eurocode 5		New Eurocode 5	
material strength	$f_d = k_{mod} \frac{f_k}{\gamma_M}$	(185)	$f_d = k_{mod} \Pi k_i \frac{f_k}{\gamma_M}$	(186)
resistance	$R_d = k_{mod} \frac{R_k}{\gamma_M}$	(187)	$R_d = k_{mod} \frac{R_k}{\gamma_R}$	(188)

where

f_d is the design value of a strength property;

f_k is the characteristic value of a strength property;

k_{mod} is the modification factor accounting for the effect of the duration of load and moisture content;

Πk_i is the product of applicable modification factors, in addition to k_{mod};

γ_M is the partial factor for a material property;

R_d is the design value of a resistance;

R_k is the characteristic value of a resistance;

γ_R is the partial factor for a resistance.

8.1 Example 1

The case used here is from the lecture notes of TKT4211 Timber Structures 1 [16], named as Example C1, in the spring 2022. The results in this Example 1 using the Present Eurocode 5 are the same as the results in Example C1 given in the lecture notes. The design check for the block shear failure based on the rules on the Present Eurocode 5 is not done in Example C1 of the lecture notes because the expression provided by the Present Eurocode 5 for the determination of the block shear failure resistance is for steel-to-timber connections only. However, the expression provided by the Present Eurocode 5 is used in this Example 1 to perform the design check for the block shear failure as an additional check. The obtained results in this Example 1 using the Present Eurocode 5 and the New Eurocode 5 are compared.

In this example case, as shown in Figure 46, a connection with timber side members subjected to tension is used. The task is to find the maximum design value of the force F (i.e., F_d) in the connection. There are two symmetric connections and the connection on the left side is investigated here.

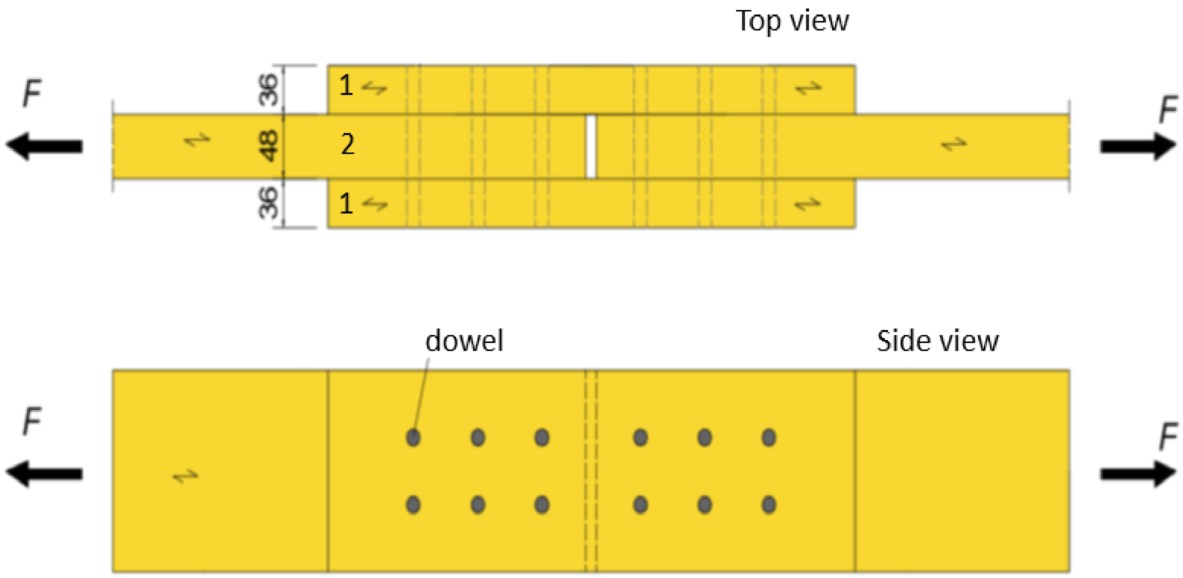


Figure 46: Connection with timber side members subjected to tension [16].

Used parameters:

Service class 2, short-term load: k_{mod} = 0.9

Connections: γ_M = 1.3 (Norwegian national annex [2])

Dowels

Diameter: d = 12 mm

$f_{u,k}$ = 600 N/mm^2

$F_{ax,Rk}$ = 0

Side members (1)

Thickness: t_1 = 36 mm

Timber C24: $\rho_{k,1}$ = 350 kg/m^3

Load-to-grain angle: α_1 = 0°

γ_M = 1.25 (Norwegian national annex [2])

Middle member (2)

Thickness: t_2 = 48 mm

Timber C24: $\rho_{k,2}$ = 350 kg/m^3

Load-to-grain angle: α_2 = 0°

γ_M = 1.25 (Norwegian national annex [2])

8.1.1 Spacing, end and edge distances

Since the load-to-grain angle is zero, α_1 = 0° and α_2 = 0°, the Present Eurocode 5 and the New Eurocode 5 give equal values for the minimum required spacing and end and edge distances for dowels according to Table 43 in section 6.2.3. As shown in Figure 47, there is not a loaded edge and there is not an unloaded end (far away) in the connection. Therefore, the distances corresponding to these ends and edges are not relevant. The values of the spacings and end and edged distances are given in Table 52.

Table 52: Example 1 – spacing and end and edge distances.

Spacing and end and edge distances	**Present Eurocode 5 and New Eurocode 5**			
	Side members		**Middle member**	
	Minimum [mm]	Actual [mm]	Minimum [mm]	Actual [mm]
a_1	60	60	60	60
a_2	36	36	36	36
$a_{3,t}$	84	84	84	84
$a_{3,c}$	Not relevant	Not relevant	Not relevant	Not relevant
$a_{4,t}$	Not relevant	Not relevant	Not relevant	Not relevant
$a_{4,c}$	36	36	36	36

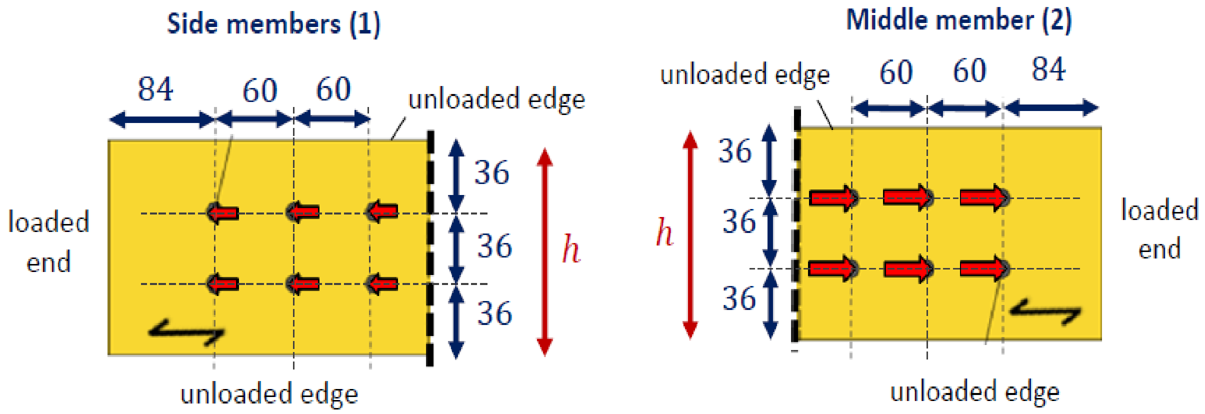


Figure 47: Example 1- spacing and end and edge distances [16].

8.1.2 Design Check

a) Load transfer

As presented in Table 53, the values of the design load-carrying capacity per fastener at load transfer according to the Present Eurocode 5 and the New Eurocode 5 are equal. In the Present Eurocode 5 and the New Eurocode 5 the expressions for the failure modes are the same, but the names of the failure modes are different. Hence, they give equal results.

Table 53: Example 1 – load transfer.

Load transfer	**Present Eurocode 5**		**New Eurocode 5**	
	Value	**Equation**	**Value**	**Equation**
Side members, $f_{h,0,k}$ [N/mm^2]	25.3	(72)	-	-
Middle member, $f_{h,0,k}$ [N/mm^2]	25.3	(72)	-	-
Side members, k_{90}	1.53	(74)	1.53	(75)
Middle member, k_{90}	1.53	(74)	1.53	(75)
Side members, k_{mat}	-	-	1.0	(73)
Middle member, k_{mat}	-	-	1.0	(73)
$f_{h,1,k}$ [N/mm^2]	25.3	(70)	25.3	(71)
$f_{h,2,k}$ [N/mm^2]	25.3	(70)	25.3	(71)
β	1.0	(51)	1.0	(51)

$M_{y,k}$ [Nmm]	115118	(*80*)	115118	(*81*)
n_{shear}	2	-	2	-
Left side of the connection, $n_{fastener}$	6	-	6	-
Rope-effect, $F_{rp,k}$ [N]	0	(*83*)	0	(*84*)
$F_{v,Rk(g)}{}^{*}$ or $F_{D,k(a)}{}^{**}$ [N]	10911	(*45*)	10911	(*45*)
$F_{v,Rk(h)}{}^{*}$ or $F_{D,k(b)}{}^{**}$ [N]	7274	(*46*)	7274	(*46*)
$F_{v,Rk(j)}{}^{*}$ or $F_{D,k(d)}{}^{**}$ [N]	6651	(*48*)	6651	(*48*)
$F_{v,Rk(k)}{}^{*}$ or $F_{D,k(f)}{}^{**}$ [N]	9606	(*50*)	9606	(*50*)
Characteristic load-carrying capacity per shear plane per fastener, $F_{D,k}$ [N]	6651	(*44*)	6651	(*44*)
Characteristic load-carrying capacity per fastener [N], $F_{D,k} = F_{D,k}\, n_{shear}$	13302	-	13302	-
Design load-carrying capacity per fastener [N], $F_{D,Rd} = k_{mod}\frac{F_{D,k}}{\gamma_M}$	9209.23	(*187*)	9209.23	(*187*)
Design force [kN], $F_d = F_{D,Rd} n_{fastener}$	55.26	-	55.26	-
* Dowel-effect contribution due to a failure mode in the Present Eurocode 5. ** Dowel-effect contribution due to a corresponding failure mode in the New Eurocode 5.				

b) Splitting failure

The values of the design load-carrying capacity per row which are calculated based on the rules provided by the Present Eurocode 5 and the New Eurocode 5 are equal as given in Table 54.

Table 54: Example 1 – splitting failure along a row of fasteners loaded parallel to the grain.

Splitting failure	**Present Eurocode 5**		**New Eurocode 5**	
fasteners loaded parallel to grain	**Value**	**Equation**	**Value**	**Equation**
a_1 [mm]	60	Table 52	60	Table 52
n_0	3	-	3	-

n_{ef}	2.12	(*108*)	2.12	(*108*)
n_{row}	2	-	2	-
Characteristic load-carrying capacity per fastener, $F_{v,k}$ [N]	13302	Table 53	13302	Table 53
Design load-carrying capacity per fastener [N], $F_{v,d} = k_{mod}\frac{F_{v,k}}{\gamma_M}$	9209.23	(*187*)	9209.23	(*187*)
Design load-carrying capacity per row [N], $F_{v,Rd} = F_{v,d}n_{ef}$	19493	(*154*)	19493	(*155*)
Design force [kN], $F_d = F_{v,Rd}n_{row}$	38.99	(*152*)	38.99	(*153*)

c) Net tensile failure

The design net tensile failure values, as provided in Table 55, at the critical cross-section of the side members, as depicted in Figure 48, according to the Present Eurocode 5 and the New Eurocode 5 are equal.

Table 55: Example 1 – net tensile failure for side members.

Net tensile failure	**Present Eurocode 5**		**New Eurocode 5**	
Side members	**Value**	**Equation**	**Value**	**Equation**
h_{ref} [mm]	150	[2]	150	[1]
h [mm]	108	Figure 47	108	Figure 47
k_h	1.068	(*168*)	1.068	(*169*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	11.15	(*166*)	11.15	(*167*)
$A_{net} = t_1(h-2d)$ [mm^2]	3024	Section 7.1.9	3024	Section 7.1.9
Number of members, $n_{members}$	2	-	2	-
Design net tensile failure [kN], $F_{d,member} = A_{net}f_{t,0,d}$	33.71	(*164*)	33.71	(*165*)
Design force [kN], $F_d = F_{d,member}\, n_{members}$	67.43	-	67.43	-

The design net tensile failure values, as provided in Table 56, at the critical cross-section of the middle member, as depicted in Figure 48, which are calculated using the rules on the Present Eurocode 5 and the New Eurocode 5 are equal.

Table 56: Example 1 – net tensile failure for middle member.

Net tensile failure	**Present Eurocode 5**		**New Eurocode 5**	
Middle member	**Value**	**Equation**	**Value**	**Equation**
h_{ref} [mm]	150	[2]	150	[1]
h [mm]	108	Figure 47	108	Figure 47
k_h	1.068	(*168*)	1.068	(*169*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	11.15	(*166*)	11.15	(*167*)
$A_{net} = t_2\,(h - 2d)$ [mm^2]	4032	Section 7.1.9	4032	Section 7.1.9
Number of members, $n_{members}$	1	-	1	-
Design net tensile failure [kN], $F_{d,member} = A_{net}\,f_{t,0,d}$	44.95	(*164*)	44.95	(*165*)
Design force [kN], $F_d = F_{d,member}\,n_{members}$	44.95	-	44.95	-

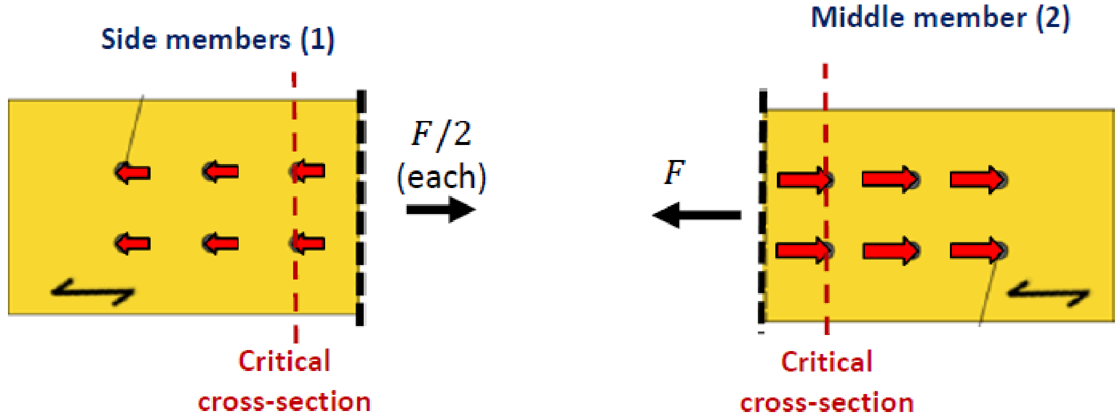


Figure 48: Example 1 – critical cross-section for net tensile failure [16].

d) Block shear failure

The expression provided by the Present Eurocode 5 for the determination of the block shear failure resistance is for steel-to-timber connections only. However, the expression provided by the Present Eurocode 5 is used in this Example 1 to perform the design check for the block shear failure as an additional check. The value of the design block shear failure capacity of the side members, as given in Table 58, obtained by the New Eurocode 5 is 15.03 % lower than the value of the design block shear failure capacity of the side members, as presented in Table 57, obtained by the Present Eurocode 5. The value of the effective thickness of the side members according to the Present Eurocode 5 is more than the value according to the New Eurocode 5. For the value of the design block shear failure capacity of the middle member, the New Eurocode 5 gives 30.76 % higher than the Present Eurocode 5. This is owing to the length of the distances based on the New Eurocode 5, as depicted in Figure 50, is more than the length of the distances based on the Present Eurocode 5, as shown in Figure 49. For the side members and the middle member, the shear failure is decisive for the block shear failure according to the Present Eurocode 5 and the New Eurocode 5.

The expressions for determining the block shear capacity in the Present Eurocode 5 and the New Eurocode 5 are different. Furthermore, the partial factors used to determine the design block shear failure resistance in the New Eurocode 5 and the Present Eurocode 5 are not the same, namely strength property of the material γ_M is used in the New Eurocode 5 and the resistance property γ_R is used in the Present Eurocode 5.

Present Eurocode 5

Table 57: Example 1 – block shear failure using the Present Eurocode 5.

Block shear failure	**Present Eurocode 5**			
	Side members		**Middle member**	
	Value	**Equation**	**Value**	**Equation**
$l_{t,i,fastener} = a_2 - d$ [mm]	24	Figure 49	24	Figure 49
$l_{v,i,fastener} = a_1 - d$ [mm]	48	Figure 49	48	Figure 49
$l_{v,i,end} = a_{3,t} - 0.5d$ [mm]	78	Figure 49	78	Figure 49
$t_{ef(j)}$ [mm]	36	(*144*)	48	(*144*)
$t_{net,t}$ [mm]	36	(*158*)	48	(*158*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{v,k}$ [N/mm^2]	4.0	EN 338	4.0	EN 338
$L_{net,t}$ [mm]	24	(*161*)	24	(*161*)

$L_{net,v}$ [mm]	348	(*160*)	348	(*160*)
$A_{net,t}$ [mm^2]	864	(*158*)	1152	(*158*)
$A_{net,v}$ [mm^2]	12528	(*159*)	16704	(*159*)
$n_{members}$	2	-	1	-
Characteristic block shear failure capacity, $F_{bs,Rk}$ [N]	35078.4	(*157*)	46771.2	(*157*)
Design block shear failure capacity, $F_{bs,Rd}$ [kN]	24.29	(*187*)	32.38	(*187*)
Design force [kN], $F_d = F_{bs,Rd}\, n_{members}$	48.57	-	32.38	-

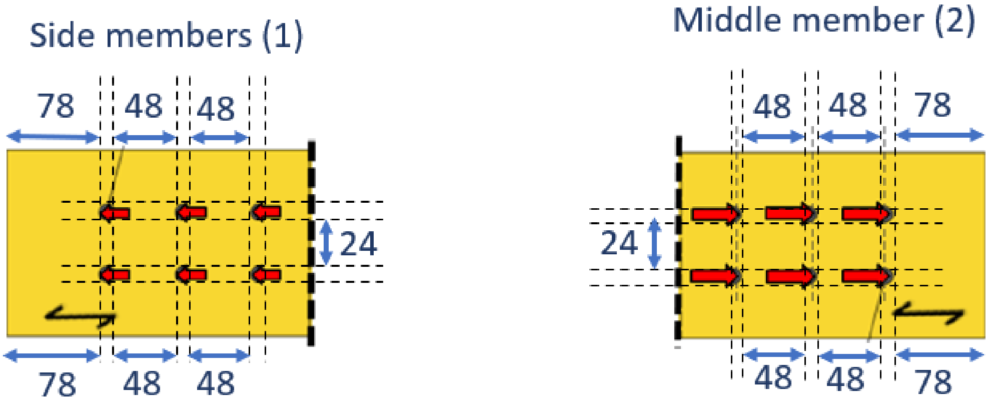


Figure 49: Example 1 – spacings and distances in block shear failure using the Present Eurocode 5 [16].

New Eurocode 5

Table 58: Example 1 – block shear failure using the New Eurocode 5.

Block shear failure	**New Eurocode 5**			
	Side members		**Middle member**	
	Value	**Equation**	**Value**	**Equation**
$d_{hole,max}$ [mm]	12	-	12	-
α_{cl}	0.65	(*147*)	0.65	(*146*)

$f_{v,k}$ [N/mm^2]	4.0	EN 338	4.0	EN 338
$f_{v,d}$ [N/mm^2]	2.88	(*185*)	2.88	(*185*)
G_{mean} [N/mm^2]	690	EN 338	690	EN 338
$E_{0,mean}$ [N/mm^2]	11000	EN 338	11000	EN 338
k_v	0.751	(*135*)	0.751	(*135*)
l_{con} [mm]	204	(*136*)	204	(*136*)
b_{net} [mm]	24	(*142*)	24	(*142*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	10.44	(*185*)	10.44	(*185*)
n_{90}	2	-	2	-
$n_{members}$	2	-	1	-
	Head tensile plane		**Head tensile plane**	
t_{ef} [mm]	$t_1 = 36$	-	$t_2 = 48$	-
$F_{t,Rd}$ [N]	9020.16	(*141*)	12026.88	(*141*)
	Side shear plane		**Side shear plane**	
t_{ef} [mm]	23	(*147*)	48	(*146*)
$F_{v,la,d}$ [N]	10319.72	(*134*)	21168.65	(*134*)
Design block shear failure capacity, $F_{bs,d}$ [kN]	20.64	(*162*)	42.34	(*162*)
Design force [kN], $F_d = F_{bs,d}\, n_{members}$	41.28	-	42.34	-

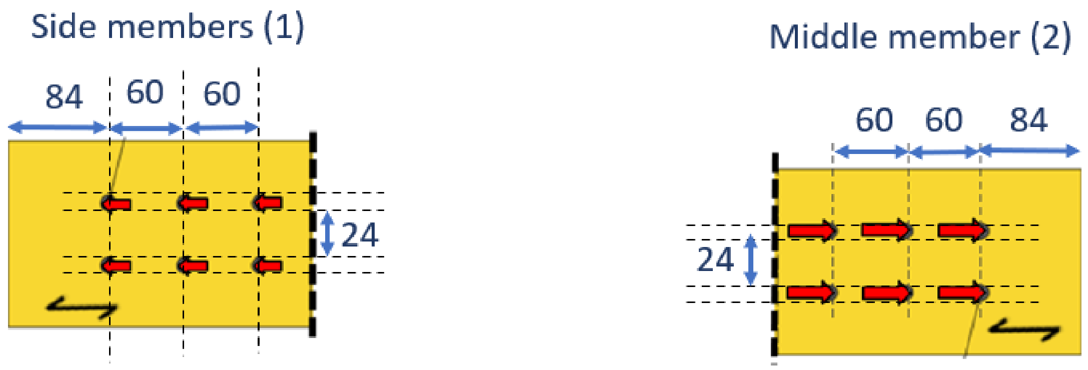


Figure 50: Example 1 – spacings and distances in block shear and row shear failures using the New Eurocode 5 [16].

e) Row shear failure

The calculated value of the design row shear failure capacity using the rules provided by the New Eurocode 5 is given in Table 59. The row shear failure capacity is not covered by the Present Eurocode 5.

Table 59: Example 1 – row shear failure using the New Eurocode 5.

Block shear failure	**New Eurocode 5**			
	Side members		**Middle member**	
	Value	**Equation**	**Value**	**Equation**
n_{90}	2	-	2	-
$n_{members}$	2	-	1	-
$F_{v,la,d}$ [N]	10319.72	Table 58	21168.65	Table 58
Design row shear failure capacity, $F_{rs,d}$ [kN]	41.28	*(156)*	84.67	*(156)*
Design force [kN], $F_d = F_{rs,d}\, n_{members}$	82.56	-	84.67	-

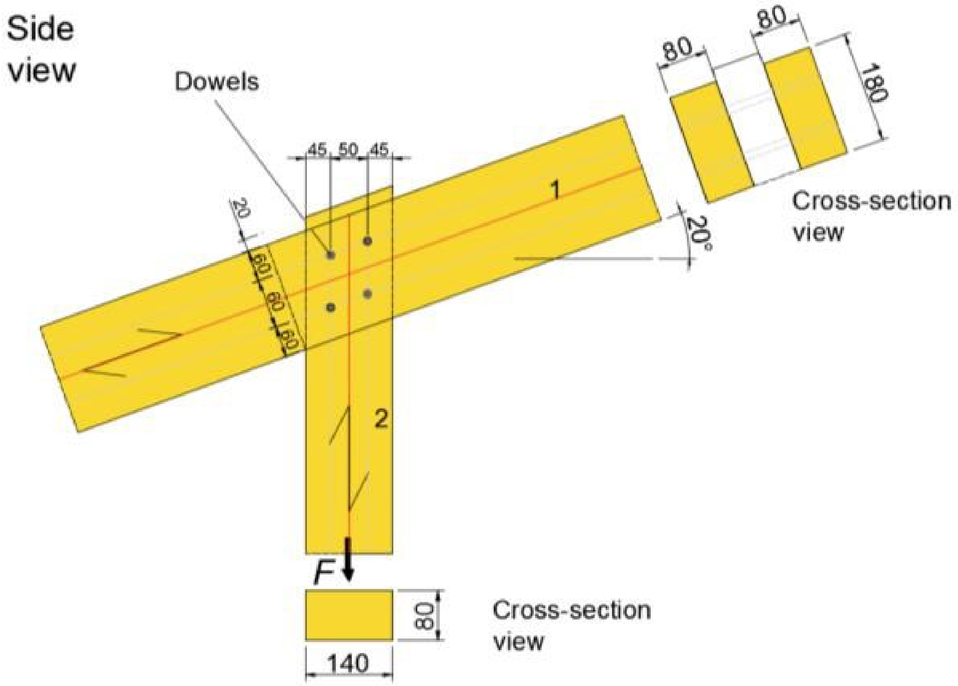
Design force F_d

The design value of the force *F* (i.e., F_d) is the minimum value of the design forces due to the resistance cases evaluated above. In this case, the maximum design value of the force *F* (i.e., F_d) for the connection is F_d = 32.38 kN according to the Present Eurocode 5 and F_d = 38.99 kN according to the New Eurocode 5. The value of the design force F_d obtained by using the New Eurocode 5 is 20.41 % higher than the value of the design force F_d obtained by using the Present Eurocode 5. According to the New Eurocode 5, the splitting failure along a row of fasteners loaded parallel to the grain is decisive for the design of the connection. According to the rules on the Present Eurocode 5, the block shear failure in the middle member is decisive for the design of the connection. This implies that the block shear failure can be decisive for the design of a connection in timber-to-timber connections and not giving provision for the block shear failure in timber-to-timber connections is a shortcoming of the Present Eurocode 5.

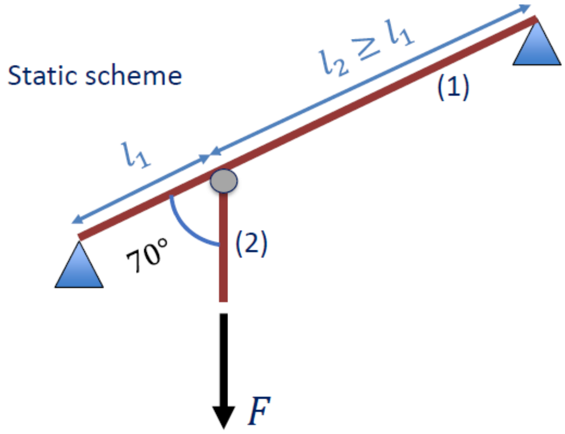
8.2 Example 2

The case used here is from the lecture notes of TKT4211 Timber Structures 1 [16], named as Example C2, in the spring 2022. The design check for the block shear failure based on the rules on the Present Eurocode 5 is not done in Example C2 of the lecture notes owing to the expression provided by the Present Eurocode 5 for the determination of the block shear failure resistance is for steel-to-timber connections only. However, the expression provided by the Present Eurocode 5 is used to perform the design check for the block shear failure as an additional check in this Example 2. The actual values of some spacing and end and edge distances used in the Example C2 of the lecture notes do not comply with the minimum required values for spacing and end and edge distances obtained based on the rules on the New Eurocode 5. Therefore, the results obtained in the Example C2 of the lecture notes based on the Present Eurocode 5 are not relevant for comparison. The actual values of the spacing and end and edge distances used in Example C2 of the lecture notes are altered in Example 2 of this thesis to comply with the actual values of the spacing and end and edge distances obtained by using the New Eurocode 5. By using the new actual values for the spacing and end and edge distances, new results are obtained in Example 2 based on the rules on the Present Eurocode 5. The obtained new results according to the Present Eurocode 5 and the results according to the New Eurocode 5 are compared in this Example 2.

In this example case, as shown in Figure 51, a timber-to-timber connection with dowels and inclined members is investigated. The task is to find the maximum design value of the force F (i.e., F_d) in the connection.



a) Side view of the timber-to-timbe connection.



b) Static scheme of the connection.

Figure 51: Timber-to-timer connection with dowels and inclined members [16].

Used parameters:

Service class 2, short-term load: k_{mod} = 0.9

Connections: γ_M = 1.3 (Norwegian national annex [2])

Dowels

Diameter: d = 12 mm

$f_{u,k}$ = 360 N/mm^2

$F_{ax,Rk}$ = 0

Side members (1)

Thickness: t_1 = 80 mm

Timber C24: $\rho_{k,1}$ = 350 kg/m^3

Load-to-grain angle: α_1 = 70°

γ_M = 1.25 (Norwegian national annex [2])

Middle member (2)

Thickness: t_2 = 80 mm

Timber C24: $\rho_{k,2}$ = 350 kg/m^3

Load-to-grain angle: α_2 = 0°

γ_M = 1.25 (Norwegian national annex [2])

8.2.1 Spacing, end and edge distances

The minimum requirement values for spacing, end and edge distances based on the rules on the Present Eurocode 5 in Example C2 of lecture notes and this Example 2 are equal. The actual values for spacing and end and edge distances used in the Example C2 are changed, as provided in Table 60, to comply with the values calculated for spacing and end and edge distances based on the rules on the New Eurocode 5, as given in Table 61. The actual values inside the brackets in Table 60, which are also shown in Figure 51(a), are the values used in Example C2 and the actual values outside the brackets in Table 60 are the new values which are used in this Example 2. The ends of the side members are far away from the connection. For the middle member, there is not a loaded edge and there is not an unloaded end (far away) in the connection. Therefore, the distances corresponding to these ends and this edge are not relevant.

Table 60: Example 2 – spacing and end and edge distances using the Present Eurocode 5.

Spacing, end and edge distances	**Present Eurocode 5 (Example C2 and Example 2)**			
	Side members		**Middle member**	
	Minimum [mm]	Actual [mm]	Minimum [mm]	Actual [mm]
a_1	44.2	64 [53]	60	64 [64]
a_2	36	60 [60]	36	60 [50]

$a_{3,t}$	Not relevant	Not relevant	84	85 [85]
$a_{3,c}$	Not relevant	Not relevant	Not relevant	Not relevant
$a_{4,t}$	46.6	60 [60]	Not relevant	Not relevant
$a_{4,c}$	36	60 [60]	36	40 [45]

Table 61: Example 2 – spacing and end and edge distances using the New Eurocode 5.

Spacing, end and edge distances	**New Eurocode 5**			
	Side members		**Middle member**	
	Minimum [mm]	Actual [mm]	Minimum [mm]	Actual [mm]
a_1	60	64	60	64
a_2	36	60	36	60
$a_{3,t}$	Not relevant	Not relevant	84	85
$a_{3,c}$	Not relevant	Not relevant	Not relevant	Not relevant
$a_{4,t}$	48	60	Not relevant	Not relevant
$a_{4,c}$	36	60	36	40

8.2.2 Design Check

8.2.2.1 Force parallel to the grain in the middle member

a) Load transfer

When the force is parallel to the grain in the middle member, the calculated values of the design load-carrying capacity per fastener, as presented in Table 62, according to the Present Eurocode 5 and the New Eurocode 5 are equal. In the Present Eurocode 5 and the New Eurocode 5 the names of the failure modes of connections with double shear planes are different, but the expressions for the failure modes are the same. Hence, the results are equal in this case.

Table 62: Example 2 – load transfer when the force is parallel to grain in the middle member.

Load transfer	**Present Eurocode 5**		**New Eurocode 5**	
	Value	**Equation**	**Value**	**Equation**
Side members, $f_{h,0,k}$ [N/mm^2]	25.3	(*72*)	-	-
Middle member, $f_{h,0,k}$ [N/mm^2]	25.3	(*72*)	-	-
Side members, k_{90}	1.53	(*74*)	1.53	(*75*)
Middle member, k_{90}	1.53	(*74*)	1.53	(*75*)
Side members, k_{mat}	-	-	1.47	(*73*)
Middle member, k_{mat}	-	-	1.0	(*73*)
$f_{h,1,k}$ [N/mm^2]	17.2	(*70*)	17.2	(*71*)(*71*
$f_{h,2,k}$ [N/mm^2]	25.3	(*70*)	25.3	(*71*)
β	1.47	(*51*)	1.47	(*51*)
$M_{y,k}$ [Nmm]	69071	(*80*)	69071	(*81*)
n_{shear}	2	-	2	-
Number of fasteners, $n_{fasteners}$	4	-	4	-
Rope-effect, $F_{rp,k}$ [N]	0	(*83*)	0	(*84*)
$F_{v,Rk(g)}{}^{*}$ or $F_{D,k(a)}{}^{**}$ [N]	16516	(*45*)	16516	(*45*)
$F_{v,Rk(h)}{}^{*}$ or $F_{D,k(b)}{}^{**}$ [N]	12123	(*46*)	12123	(*46*)
$F_{v,Rk(j)}{}^{*}$ or $F_{D,k(d)}{}^{**}$ [N]	7075	(*48*)	7075	(*48*)
$F_{v,Rk(k)}{}^{*}$ or $F_{D,k(f)}{}^{**}$ [N]	6698	(*50*)	6698	(*50*)
Characteristic load-carrying capacity per shear plane per fastener, $F_{D,k}$ [N]	6698	(*44*)	6698	(*44*)
Characteristic load-carrying capacity per fastener [N], $F_{D,k} = F_{D,k}\, n_{shear}$	13397	-	13397	-
Design load-carrying capacity	9274.80	(*187*)	9274.80	(*187*)

per fastener [N], $F_{D,Rd} = k_{mod} \frac{F_{D,k}}{\gamma_M}$				
Design force [kN], $F_d = F_{D,Rd}\, n_{fasteners}$	37.10	-	37.10	-
* Dowel-effect contribution due to a failure mode in the Present Eurocode 5. ** Dowel-effect contribution due to a corresponding failure mode in the New Eurocode 5.				

b) Splitting failure

When the force is parallel to the grain in the middle member, the calculated values of the design load-carrying capacity per row of fasteners loaded parallel to the grain according to the Present Eurocode 5 and the New Eurocode 5 are equal as given in Table 63.

Table 63: Example 2 – splitting failure along a row of fasteners loaded parallel to the grain when the force is parallel to the grain in the middle member.

Splitting failure	**Present Eurocode 5**		**New Eurocode 5**	
fasteners loaded parallel to grain	**Value**	**Equation**	**Value**	**Equation**
a_1 [mm]	64	Table 60	64	Table 60
n_0	2	-	2	-
n_{ef}	1.49	(*108*)	1.49	(*108*)
Number of rows parallel to grain, n_{row}	2	-	2	-
Characteristic load-carrying capacity per fastener, $F_{v,k}$ [N]	13397	Table 62	13397	Table 62
Design load-carrying capacity per fastener [N], $F_{v,d} = k_{mod} \frac{F_{v,k}}{\gamma_M}$	9274.80	(*187*)	9274.80	(*187*)
Design load-carrying capacity per row [N], $F_{v,Rd} = F_{v,d}\, n_{ef}$	13843	(*154*)	13843	(*155*)
Design force [kN], $F_d = F_{v,Rd}\, n_{row}$	27.69	(*152*)	27.69	(*153*)

c) Net tensile failure

For the side members, the tensile strength is less than the compressive strength and moment is the largest, therefore check for tension and moment is critical. The value of the moment cannot be determined, and the net-section design check cannot be performed because the lengths of the moment arms (*l₁* and *l₂*) are not given. As given in Table 64, the axial stresses and the bending stresses in the gross cross-section are respectively 15.4 % and 4.7 % higher than in the net cross-section due to reduction of the cross-section by the presence of holes.

Table 64: Example 2 – net tensile failure for side members.

Net tensile failure	**Present Eurocode 5**		**New Eurocode 5**	
Side members	**Value**	**Equation**	**Value**	**Equation**
h_{ref} [mm]	150	[2]	150	[1]
h [mm]	180	-	180	-
k_h	1.00	(*168*)	1.00	(*169*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	10.44	(*166*)	10.44	(*167*)
$f_{m,k}$ [N/mm^2]	24	EN 338	24	EN 338
$f_{m,d}$ [N/mm^2]	17.28	(*185*)	17.28	(*185*)
$f_{c,0,k}$ [N/mm^2]	21	EN 338	21	EN 338
$f_{c,0,d}$ [N/mm^2]	15.12	(*185*)	15.12	(*185*)
$a_{1,min}$	44.2	Table 60	60	Table 60
Staggered spacing < $a_{1,min}/2$	21.84 (OK)	[2]	21.84 (OK)	[1]
$A_{net} = 2t_1\,(h - 2d)$ [mm^2]	24960	-	24960	-
$A_{gross} = 2t_1 h$ [mm^2]	28800	-	28800	-
W_{net} [mm^3]	74257920	-	74257920	-
$W_{gross} = \frac{t_1 h^2}{6}$ [mm^3]	77760000	-	77760000	-
$\frac{A_{gross}}{A_{net}}$	1.154	-	1.154	-
$\frac{W_{gross}}{W_{net}}$	1.047	-	1.047	-

As given in Table 65, the design net tensile failure values calculated at the critical cross-section of the middle member using the rules provided by the Present Eurocode 5 and the New Eurocode 5 are equal.

Table 65: Example 2 – net tensile failure for middle member.

Net tensile failure	**Present Eurocode 5**		**New Eurocode 5**	
Middle member	**Value**	**Equation**	**Value**	**Equation**
h_{ref} [mm]	150	[2]	150	[1]
h [mm]	140	-	140	-
k_h	1.014	(*168*)	1.014	(*169*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	10.59	(*166*)	10.59	(*167*)
$a_{1,min}$	60	Table 60	60	Table 60
Staggered spacing < $a_{1,min}/2$	21.84 (OK)	[2]	21.84 (OK)	[1]
$A_{net} = t_2(h - 2d)$ [mm^2]	9280	Section 7.1.9	9280	Section 7.1.9
Number of members, $n_{members}$	1	-	1	-
Design net tensile failure [kN], $F_{d,member} = A_{net}\, f_{t,0,d}$	98.23	(*164*)	98.23	(*165*)
Design force [kN], $F_d = F_{d,member}\, n_{members}$	98.23	-	98.23	-

d) Block shear failure

The Present Eurocode 5 provides an expression for the determination of the block shear failure resistance for steel-to-timber connections only. However, the expression provided by the Present Eurocode 5 is used in this Example 2 to perform the design check for the block shear failure as an additional check. The end of each side member is not loaded when the force is parallel to the grain in the middle member. Therefore, the block shear failure is not relevant for the side members in this case. When the force is parallel to the grain in the middle member, the value of the design block shear failure capacity of the middle member obtained by using the New Eurocode 5, which is presented in Table 67, is 10.88 % lower than the value obtained by using the Present Eurocode 5 which is given in Table 66. The provided expressions for determining the block shear capacity by the Present Eurocode 5 and the New Eurocode 5 are different. Furthermore, the partial factors used to determine the design block shear failure resistance in the New Eurocode 5 and the Present Eurocode 5 are not the same. In the New Eurocode 5 is γ_M which is for strength property of the material and in the Present Eurocode 5 is γ_R which is for the resistance property. In this case, the tear-out (tensile) failure is decisive for the block shear failure according to the Present Eurocode 5, but the shear failure is decisive for the block shear failure according to the New Eurocode 5.

Present Eurocode 5

Table 66: Example 2 – block shear failure using the Present Eurocode 5 when the force is parallel to the grain in the middle member.

Block shear failure	**Present Eurocode 5**	
	Middle member	
	Value	**Equation**
$l_{t,i,fastener} = a_2 - d$ [mm]	48	-
$l_{v,i,fastener} = a_1 - d$ [mm]	52	-
$l_{v,i,end} = a_{3,t} - 0.5d$ [mm]	79	-
$t_{ef(j)}$ [mm]	80	(*144*)
$t_{net,t}$ [mm]	80	(*158*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338
$f_{v,k}$ [N/mm^2]	4.0	EN 338
$L_{net,t}$ [mm]	48	(*161*)
$L_{net,v}$ [mm]	261.7	(*160*)
$A_{net,t}$ [mm^2]	3840	(*158*)
$A_{net,v}$ [mm^2]	20936.11	(*159*)
$n_{members}$	1	-
Characteristic block shear failure capacity, $F_{bs,Rk}$ [N]	83520	(*157*)
Design block shear failure capacity, $F_{bs,Rd}$ [kN]	57.82	(*187*)
Design force [kN], $F_d = F_{bs,Rd}\, n_{members}$	57.82	-

New Eurocode 5

Table 67: Example 2 – block shear failure using the New Eurocode 5 when the force is parallel to the grain in the middle member.

Block shear failure	**New Eurocode 5**	
	Middle member	
	Value	**Equation**
$d_{hole,max}$ [mm]	12	-
α_{cl}	0.65	(*146*)
$f_{v,k}$ [N/mm^2]	4.0	EN 338
$f_{v,d}$ [N/mm^2]	2.88	(*185*)
G_{mean} [N/mm^2]	690	EN 338
$E_{0,mean}$ [N/mm^2]	11000	EN 338
k_v	0.751	(*135*)
l_{con} [mm]	148.98	(*136*)
b_{net} [mm]	48	(*142*)
$f_{t,0,k}$ [N/mm^2]	14.5	EN 338
$f_{t,0,d}$ [N/mm^2]	10.44	(*185*)
n_{90}	2	-
$n_{members}$	1	-
	Head tensile plane	
t_{ef} [mm]	$t_2 = 80$	-
$F_{t,Rd}$ [N]	40089.6	(*141*)
	Side shear plane	
t_{ef} [mm]	80	(*146*)
$F_{v,la,d}$ [N]	25766.41	(*134*)
Design block shear failure capacity, $F_{bs,d}$ [kN]	51.53	(*162*)
Design force [kN], $F_d = F_{bs,d}\, n_{members}$	51.53	-

e) Row shear failure

For the side members, the end of each member is not loaded when the force is parallel to the grain in the middle member. Therefore, the row shear failure is not relevant for the side members in this situation. When the force is parallel to the grain in the middle member, the value of the design row shear failure capacity of the middle member obtained by using the New Eurocode 5 is given in Table 68. The row shear failure is not covered by the Present Eurocode 5.

New Eurocode 5

Table 68: Example 2 – row shear failure using the New Eurocode 5 when the force is parallel to the grain in the middle member.

Row shear failure	**New Eurocode 5**	
	Middle member	
	Value	**Equation**
n_{90}	2	-
$n_{members}$	1	-
$F_{v,la,d}$ [N]	25766.41	Table 67
Design row shear failure capacity, $F_{rs,d}$ [kN]	103.07	(*156*)
Design force [kN], $F_d = F_{rs,d}\, n_{members}$	103.07	-

8.2.2.2 Force parallel to the grain in the side members

a) Load transfer

When the force is parallel to grain in the side members, the calculated values of the design load-carrying capacity per fastener according to the rules on the Present Eurocode 5 and the New Eurocode 5, which are presented in Table 69, are equal. The names of the failure modes of connections with double shear planes in the New Eurocode 5 and the Present Eurocode 5 are different, but the expressions for the failure modes are the same.

Table 69: Example 2 – load transfer when the force is parallel to grain in the side members.

Load transfer	**Present Eurocode 5**		**New Eurocode 5**	
	Value	**Equation**	**Value**	**Equation**
Side members, $f_{h,0,k}$ [N/mm^2]	25.3	(*72*)	-	-

Middle member, $f_{h,0,k}$ [N/mm^2]	25.3	(*72*)	-	-
Side members, k_{90}	1.53	(*74*)	1.53	(*75*)
Middle member, k_{90}	1.53	(*74*)	1.53	(*75*)
Side members, k_{mat}	-	-	1.00	(*73*)
Middle member, k_{mat}	-	-	1.47	(*73*)
$f_{h,1,k}$ [N/mm^2]	25.3	(*70*)	25.3	(*71*)
$f_{h,2,k}$ [N/mm^2]	17.2	(*70*)	17.2	(*71*)
β	0.68	(*51*)	0.68	(*51*)
$M_{y,k}$ [Nmm]	69071	(*80*)	69071	(*81*)
n_{shear}	2	-	2	-
Number of fasteners, $n_{fasteners}$	4	-	4	-
Rope-effect, $F_{rp,k}$ [N]	0	(*83*)	0	(*84*)
$F_{v,Rk(g)}{}^{*}$ or $F_{D,k(a)}{}^{**}$ [N]	24246	(*45*)	24246	(*45*)
$F_{v,Rk(h)}{}^{*}$ or $F_{D,k(b)}{}^{**}$ [N]	8258	(*46*)	8258	(*46*)
$F_{v,Rk(j)}{}^{*}$ or $F_{D,k(d)}{}^{**}$ [N]	8696	(*48*)	8696	(*48*)
$F_{v,Rk(k)}{}^{*}$ or $F_{D,k(f)}{}^{**}$ [N]	6698	(*50*)	6698	(*50*)
Characteristic load-carrying capacity per shear plane per fastener, $F_{D,k}$ [N]	6698	(*44*)	6698	(*44*)
Characteristic load-carrying capacity per fastener [N], $F_{D,k} = F_{D,k}\, n_{shear}$	13397	-	13397	-
Design load-carrying capacity per fastener [N], $F_{D,Rd} = k_{mod} \frac{F_{D,k}}{\gamma_M}$	9274.80	(*187*)	9274.80	(*187*)
Design force [kN], $F_d = F_{D,Rd}\, n_{fasteners}$	37.10	-	37.10	-

* Dowel-effect contribution due to a failure mode in the Present Eurocode 5.

** Dowel-effect contribution due to a corresponding failure mode in the New Eurocode 5.

b) Splitting failure

When the force is parallel to the grain in the side members, the calculated values of the design load-carrying capacity per row of fasteners loaded parallel to the grain, as provided in Table 70, based on the rules on the Present Eurocode 5 and the New Eurocode 5 are equal.

Table 70: Example 2 – splitting failure along a row of fasteners loaded parallel to grain when the force is parallel to the grain in the side members.

Splitting failure	**Present Eurocode 5**		**New Eurocode 5**	
fasteners loaded parallel to grain	**Value**	**Equation**	**Value**	**Equation**
a_1 [mm]	64	Table 60	64	Table 60
n_0	2	-	2	-
n_{ef}	1.49	(*108*)	1.49	(*108*)
Number of rows parallel to grain, n_{row}	2	-	2	-
Characteristic load-carrying capacity per fastener, $F_{v,k}$ [N]	13397	Table 69	13397	Table 69
Design load-carrying capacity per fastener [N], $F_{v,d} = k_{mod} \frac{F_{v,k}}{\gamma_M}$	9274.80	(*187*)	9274.80	(*187*)
Design load-carrying capacity per row [N], $F_{v,Rd} = F_{v,d}\, n_{ef}$	13843	(*154*)	13843	(*155*)
Design force [kN], $F_d = F_{v,Rd}\, n_{row}/cos(\alpha_2)$	80.95	(*152*)	80.95	(*153*)

When the force is parallel to the grain in the side members, the value of the design splitting failure capacity along a row of fasteners loaded perpendicular to the grain obtained using the New Eurocode 5 is 60.01 % higher than the value of the design splitting failure capacity obtained using the Present Eurocode 5, as presented in Table 71. For determining the splitting capacity along a row of fasteners loaded perpendicular to the grain, the Present Eurocode 5 and the New Eurocode 5 provide different expressions. When the connection is positioned at the support of the beam, the value of design force obtained by the New Eurocode 5 is 60.01 % higher than the value obtained by the Present Eurocode 5. When the connection is positioned at the midspan of the beam, the value of design force obtained by the New Eurocode 5 is 19.99 % lower than the value obtained by the Present Eurocode 5.

Table 71: Example 2 – splitting failure along a row of fasteners loaded perpendicular to grain when the force is parallel to the grain in the side members.

Splitting failure	**Present Eurocode 5**			**New Eurocode 5**	
fasteners loaded perpendicular to grain	**At the support of the beam** $(l_1 = 0)$	**At the midspan of the beam** $(l_1 = l_2)$	**See Figure 51 (b)**	**Connection at any position along the beam length**	
	Value	**Value**	**Equation**	**Value**	**Equation**
w	1.0	1.0	(*177*)	-	-
b or b_{ef} [mm]	160	160	-	160	(*181*)
h [mm]	180	180	-	180	-
h_e [mm]	120	120	-	120	-
k_{mat}	-	-	-	0.6	(*179*)
k_G	-	-	-	19.5	(*180*)
b_{con} [mm]	-	-	-	64	-
h_1 [mm]	-	-	-	60	-
h_2 [mm]	-	-	-	120	-
n_{90}	-	-	-	2	-
$k_{con,0}$	-	-	-	1.2	(*182*)
$k_{con,90}$	-	-	-	1.6	(*183*)
Characteristic splitting capacity, $F_{sp,Rk}$ [N]	42501	42501	(*176*)	68004	(*178*)
Design splitting capacity [N], $F_{sp,Rd} = k_{mod}\frac{F_{sp,Rk}}{\gamma_M}$	29423.78	29423.78	(*187*)	47079.42	(*187*)
Design force [kN], $F_d = F_{sp,Rd}/sin(\alpha_2)$	31.31	62.62	(*174*)	50.10	(*175*)

c) Net tensile failure

The net tensile failure capacity when the force is parallel to the grain in the side members is the same as the net tensile failure capacity when the force is parallel to the grain in the middle member.

d) Block shear failure

For the side members, the distance from the connection to the end of the member (end distance) is very long. Therefore, the block shear failure is not relevant for the side members when the force is parallel to the grain in the side members. For the middle member, the block shear failure capacity when the force is parallel to the grain in the side members is the same as the block shear failure capacity when the force is parallel to the grain in the middle member.

e) Row shear failure

For the side members, the distance from the connection to the end of the member (end distance) is very long. Therefore, the row shear failure is not relevant for the side members when the force is parallel to the grain in the side members. For the middle member, the row shear failure capacity when the force is parallel to the grain in the side members is the same as the row shear failure capacity when the force is parallel to the grain in the middle member.

Design force F_d

The design value of the force F (i.e., F_d) is the minimum value of the design forces due to the resistance cases calculated above. In this case, the maximum design value of the force F (i.e., F_d) for the connection is F_d = 27.69 kN based on the rules on the Present Eurocode 5 and the New Eurocode 5. The splitting failure along a row of fasteners loaded parallel to the grain is the decisive failure for the design of the connection by the Present Eurocode 5 and the New Eurocode 5. The values of the design force F_d obtained by using the New Eurocode 5 and the Present Eurocode 5 are equal.

8.3 Example 3

The case used here is from the lecture notes of TKT4211 Timber Structures 1 [16], named as Example C4, in the spring 2022. The results found in this Example 3 using the Present Eurocode 5 are the same as the results in Example C1 given in the lecture notes. The obtained results based on the rules on the Present Eurocode 5 and the New Eurocode 5 are compared.

In this example case, as depicted in Figure 52, a connection with multiple slotted-in steel plates and dowels is applied. The task is to find the maximum design value of the force F (i.e., F_d) in the connection.

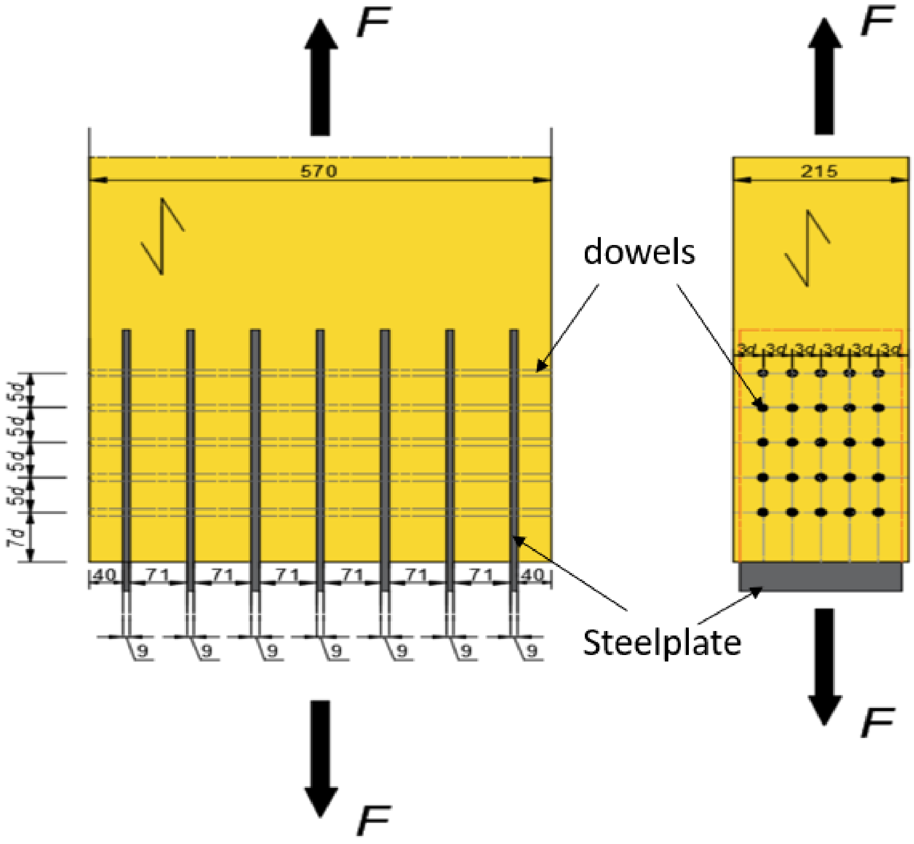


Figure 52: Connection with multiple slotted-in steel plates and dowels [16].

Used parameters:

Service class 2, short-term load: k_{mod} = 0.9

Connections: γ_M = 1.3 (Norwegian national annex [2])

Dowels

Diameter: d = 12 mm

$f_{u,k}$ = 400 N/mm^2

$F_{ax,Rk}$ = 0

Timber member

Thickness of outer timber members: t_1 = 40 mm

Thickness of inner timber members: t_2 = 71 mm

Timber GL32c: ρ_k = 400 kg/m^3

Load-to-grain angle: α = 0°

γ_M = 1.15 (Norwegian national annex [2])

Steel plates

Thickness of steel plates: t_p = 8 mm

Thickness of slots for steel plates: t_s = 9 mm

8.3.1 Spacing, end and edge distances

Since the load-to-grain angle is zero, ɑ = 0°, the rules on the Present Eurocode 5 and the New Eurocode 5 give equal values for the minimum required spacing and end and edge distances for dowels according to Table 43 in section 6.2.3. There is not a loaded edge and there is not an unloaded end (far away) in the connection. Therefore, the distances corresponding to these ends and edges are not relevant. The values of the spacings and end and edged distances are given in Table 72.

Table 72: Example 3 – spacing and end and edge distances.

Spacing and end and edge distances	**Present Eurocode 5 and New Eurocode 5**	
	Minimum [mm]	Actual [mm]
a_1	60	60
a_2	36	36
$a_{3,t}$	84	84
$a_{3,c}$	Not relevant	Not relevant
$a_{4,t}$	Not relevant	Not relevant
$a_{4,c}$	36	36

8.3.2 Design Check

a) Load transfer

For the values of the design load-carrying capacity per fastener, which are presented in Table 73, the New Eurocode 5 gives 1.75 % lower than the Present Eurocode 5. In steel-to-timber connections, the New Eurocode 5 considers the steel plate as a member, but the Present Eurocode 5 does not consider the steel plate as a member. As discussed in section 3.2, the provisions given by the New Eurocode 5 and the Present Eurocode 5 for achieving the compatibility between the members are different.

Table 73: Example 3 – load transfer.

Load transfer	**Present Eurocode 5**		**New Eurocode 5**	
	Value	**Equation**	**Value**	**Equation**
	Side members		**Side members**	
$f_{h,0,k}$ [N/mm^2]	28.9	(*72*)	-	-
k_{90}	1.53	(*74*)	1.53	(*75*)
k_{mat}	-	-	1.00	(*73*)
$f_{h,1,k}$ [N/mm^2]	28.9	(*70*)	28.9	(*71*)
n_{shear}	2	-	2	-
Rope-effect, $F_{rp,k}$ [N]	0	(*83*)	0	(*84*)
$F_{v,Rk(c)}{}^{*}$ or $F_{D,k(a)}{}^{**}$ [N]	13855	(*53*)	13855	(*45*)
$F_{D,k(b)}{}^{**}$ [N]	-	-	28800	(*46*)
$F_{v,Rk(d)}{}^{*}$ or $F_{D,k(d)}{}^{**}$ [N]	8287	(*53*)	8549	(*48*)
$F_{v,Rk(e)}{}^{*}$ or $F_{D,k(f)}{}^{**}$ [N]	11858	(*53*)	11583	(*50*)
Characteristic load-carrying capacity per shear plane per fastener, $F_{D,k}$ [N]	8287	(*53*)	-	-
Characteristic load-carrying capacity per fastener [N], $F_{D,k} = F_{D,k}\, n_{shear}$	16574	-	-	-
	Middle members		**Middle members**	
$f_{h,0,k}$ [N/mm^2]	28.9	(*72*)	-	-
k_{90}	1.53	(*74*)	1.53	(*75*)
k_{mat}	-	-	1.00	(*73*)
$f_{h,2,k}$ [N/mm^2]	28.9	(*70*)	28.9	(*71*)
n_{shear}	12	-	12	-
Rope-effect, $F_{rp,k}$ [N]	0	(*83*)	0	(*84*)

${F_{D,k(a)}}^{**}$ [N]	-	-	57600	(*45*)
${F_{v,Rk(l)}}^{*}$ or ${F_{D,k(b)}}^{**}$ [N]	12296	(*56*)	12296	(*46*)
${F_{v,Rk(m)}}^{*}$ or ${F_{D,k(f)}}^{**}$ [N]	11858	(*56*)	11583	(*50*)
Characteristic load-carrying capacity per shear plane per fastener, $F_{D,k}$ [N]	11858	(*56*)	-	-
Characteristic load-carrying capacity per fastener [N], $F_{D,k} = F_{D,k}\, n_{shear}$	142296	-	-	-
	Entire connection		**Entire connection**	
$n_{fasteners}$	25	-	25	-
$A_{(a),(a)}$ [kN]	-	-	718.9	Figure 11
$B_{(b),(b)}$ [kN]	-	-	205.2	Figure 11
$C_{(d),(f)}$ [kN]	-	-	156.1	Figure 11
$D_{(f),(f)}$ [kN]	-	-	162.2	Figure 11
Characteristic load-carrying capacity per fastener, $F_{D,k}$ [kN]	158.87	Section 3.2	156.1	Section 3.2
Design load-carrying capacity per fastener [kN], $F_{D,Rd} = k_{mod} \frac{F_{D,k}}{\gamma_M}$	109.99	(*187*)	108.07	(*187*)
Design force [kN], $F_d = F_{D,Rd}\, n_{fasteners}$	2749.72	-	2701.63	-
* Dowel-effect contribution due to a failure mode in the Present Eurocode 5. ** Dowel-effect contribution due to a corresponding failure mode in the New Eurocode 5.				

b) Splitting failure

For the values of the design load-carrying capacity per row, as given in Table 74, the New Eurocode 5 gives 1.74 % lower than the Present Eurocode 5. This is due to the difference between the calculated values of the design load-carrying capacity per fastener according to the Present Eurocode 5 and the New Eurocode 5.

Table 74: Example 3 – splitting failure along a row of fasteners loaded parallel to grain.

Splitting failure	**Present Eurocode 5**		**New Eurocode 5**	
fasteners loaded parallel to grain	**Value**	**Equation**	**Value**	**Equation**
a_1 [mm]	60	Table 72	60	Table 72
n_0	5	-	5	-
n_{ef}	3.35	(*108*)	3.35	(*108*)
Number of rows parallel to grain, n_{row}	5	-	5	-
Characteristic load-carrying capacity per fastener, $F_{v,k}$ [kN]	158.87	Table 73	156.1	Table 73
Design load-carrying capacity per fastener [N], $F_{v,d} = k_{mod}\frac{F_{v,k}}{\gamma_M}$	109.99	(*187*)	108.07	(*187*)
Design load-carrying capacity per row [N], $F_{v,Rd} = F_{v,d}\, n_{ef}$	368.7	(*154*)	362.3	(*155*)
Design force [kN], $F_d = F_{v,Rd}\, n_{row}$	1843.52	(*152*)	1811.28	(*153*)

c) Net tensile failure

As presented in Table 75, the value of the design net tensile failure resistance obtained by the New Eurocode 5 is 0.10 % lower than the value obtained by the Present Eurocode 5. This is due to the difference in k_h values according to the Present Eurocode 5 and the New Eurocode 5.

Table 75: Example 3 – net tensile failure.

Net tensile failure	**Present Eurocode 5**		**New Eurocode 5**	
Side members	**Value**	**Equation**	**Value**	**Equation**
h_{ref} [mm]	150	[2]	150	[1]
h [mm]	570	-	570	-
k_h	1.005	(*170*)	1.004	(*171*)
$f_{t,0,k}$ [N/mm^2]	19.5	EN 14080	19.5.	EN 14080

$f_{t,0,d}$ [N/mm^2]	15.34	(*166*)	15.32	(*167*)
n_{90}	5	-	5	-
A_{net} [mm^2]	78585	Section 7.1.9	78585	Section 7.1.9
Design net tensile failure [kN], $F_d = A_{net}\, f_{t,0,d}$	1205.44	(*164*)	1204.21	(*165*)
Design force, F_d [kN]	1205.44	-	1204.21	-

d) Block shear failure

The value of the design block shear failure capacity obtained by using the New Eurocode 5, which is presented in Table 77, is 24.64 % lower than the value obtained by using the Present Eurocode 5 which is given in Table 76. The provided expressions for determining the block shear capacity by the Present Eurocode 5 and the New Eurocode 5 are different. Furthermore, the partial factors used to determine the design block shear failure resistance in the New Eurocode 5 and the Present Eurocode 5 are not the same. In the New Eurocode 5 is γ_M which is for strength property of the material and in the Present Eurocode 5 is γ_R which is for the resistance property. In this case, the tear-out (tensile) failure is decisive for the block shear failure according to the New Eurocode 5 and the Present Eurocode 5.

Present Eurocode 5

Table 76: Example 3 – block shear failure using the Present Eurocode 5.

Block shear failure	**Present Eurocode 5**	
	Value	**Equation**
$l_{t,i,fastener} = a_2 - d$ [mm]	24	-
$l_{v,i,fastener} = a_1 - d$ [mm]	48	-
$l_{v,i,end} = a_{3,t} - 0.5\, d$ [mm]	78	-
$t_{ef(d)}$ [mm]	24	(*144*)
$t_{net,t}$ [mm]	507	(*158*)
$f_{t,0,k}$ [N/mm^2]	19.5	EN 14080
$f_{v,k}$ [N/mm^2]	3.5	EN 14080
$L_{net,t}$ [mm]	96	(*161*)

$L_{net,v}$ [mm]	540	(*160*)
$A_{net,t}$ [mm^2]	48672	(*158*)
	Middle members	
$A_{net,v}$ [mm^2]	230040	(*159*)
	Side members	
	Assumed 3 shear planes	
$A_{net,v}$ [mm^2]	38839	(*159*)
	Assumed 2 shear planes	
$A_{net,v}$ [mm^2]	21600	(*159*)
	Entire member	
$A_{net,v}$ [mm^2]	273240	-
$n_{members}$	1	-
Characteristic block shear failure capacity, $F_{bs,Rk}$ [N]	1423656	(*157*)
Design block shear failure capacity, $F_{bs,Rd}$ [kN]	985.61	(*187*)
Design force [kN], $F_d = F_{bs,Rd}\, n_{members}$	985.61	-

New Eurocode 5

Table 77: Example 3 – block shear failure using the New Eurocode 5.

Block shear failure	**New Eurocode 5**	
	Value	**Equation**
$d_{hole,max}$ [mm]	12	-
$\alpha_{cl,in}$	1.00	(*146*)
$\alpha_{cl,out}$	0.65	(*147*)
$f_{v,k}$ [N/mm^2]	3.5	EN 14080
$f_{v,d}$ [N/mm^2]	2.74	(*185*)

G_{mean} [N/mm^2]	650	EN 14080
$E_{0,mean}$ [N/mm^2]	13500	EN 14080
k_v	0.707	(*135*)
l_{con} [mm]	324	(*136*)
b_{net} [mm]	96	(*142*)
$f_{t,0,k}$ [N/mm^2]	19.5	EN 14080
$f_{t,0,d}$ [N/mm^2]	15.26	(*185*)
n_{90}	5	-
$n_{members}$	1	-
	Head tensile plane	
t_{ef} [mm]	507	-
$F_{t,Rd}$ [N]	742777	(*141*)
	Inner members side shear plane	
t_{ef} [mm]	71	(*146*)
$F_{v,la,d}$ [N]	267367.2	(*134*)
	Outer members side shear plane	
t_{ef} [mm]	26	(*147*)
$F_{v,la,d}$ [N]	32140.78	(*134*)
	Entire member side shear plane	
$F_{v,la,d}$ [N]	299508	(*134*)
Design block shear failure capacity, $F_{bs,d}$ [kN]	742.78	(*162*)
Design force [kN], $F_d = F_{bs,d}\, n_{members}$	742.78	-

e) Row shear failure

The row shear failure is not covered by the Present Eurocode 5. The value of the design row shear failure capacity obtained by using the New Eurocode 5 is given in Table 78.

Table 78: Example 3 – row shear failure using the New Eurocode 5.

Row shear failure	**New Eurocode 5**	
	Value	**Equation**
n_{90}	5	-
$n_{members}$	1	-
	Entire member side shear plane	
$F_{v,la,d}$ [N]	299508	Table 77
Design block shear failure capacity, $F_{rs,d}$ [kN]	2995.08	(*156*)
Design force [kN], $F_d = F_{rs,d}\, n_{members}$	2995.08	-

Design force *F*$_d$

The design value of the force *F* (i.e., F_d) is the minimum value of the design forces due to the resistance cases investigated above. In this case, the maximum design value of the force *F* (i.e., F_d) for the connection is F_d = 985.61 kN according to the rules on the Present Eurocode 5 and F_d = 742.78 kN based on the rules on the New Eurocode 5. According to the Present Eurocode 5 and the New Eurocode 5, the block shear failure is the decisive failure for the design of the connection. The value of the design force F_d obtained by using the New Eurocode 5 is 24.64 % lower than the value of the design force F_d obtained by using the Present Eurocode 5.

9 Bonded-in rods

Bonded-in rods are not covered by the Present Eurocode 5, but they are included in the New Eurocode 5. Hence, all the descriptions and expressions about bonded-in rods in this chapter are according to the New Eurocode 5.

Bonded-in rods are commonly used in tension and compression connections. Bonded-in rods are mainly efficient for transferring or carrying of tensile and compressive loads along their axis. Bonded-in rods may also be loaded perpendicular to their axis. In a connection with bonded-in rods, shear forces are also created in addition to the tensile and compressive forces. Tensile forces are transferred from the wood to the rod through the glue or the adhesive and compressive forces are transferred by direct contact between the wood and the rod. Shear forces in the connection are transmitted by the embedment of wood and the rod cross-section. Bonded-in rods can be applied in timber-to-timber, steel-to-timber, and concrete-to-timber connections. Bonded-in rods can be used in a connection in parallel or perpendicular to the grain direction. The following failure modes can appear in a connection with axially loaded bonded-in rods in service classes 1 and 2 and the load-carrying resistance of the connection must be verified for these failure modes [1]:

a) tension failure of the rod

b) compression (buckling) failure of the rod

c) failure of the adhesive in the bond line and its bond to rod and timber

d) shear failure of the timber adjacent to the bond line

e) splitting of the timber departing from the bonded-in rods

f) timber failure of the member in the surrounding of the bonded-in rod (e.g., net-section failure or block shear failure in a connection with multiple bonded-in rods)

9.1 Effects of the changes of moisture content

Within a specific ranges of moisture content and temperature, the properties of the adhesive and its bond to the rod and timber must be permanent throughout the service life of the structure according to the New Eurocode 5. The timber must be treated close to the final equilibrium moisture content during gluing. The risk of splitting in the timber due to the variations in moisture content must be considered in a connection with bonded-in rods perpendicular to the grain.

9.2 Material requirements

Materials used in a connection with bonded-in rods are timber, rod, and adhesive. The types of timber that can be used in such connections are glued laminated timber (GL) or glued solid timber (GST), laminated veneer lumber (LVL) and glued laminated veneer lumber (GLVL) and cross laminated timber (CLT). Two types of rods with diameters of 6 mm up to 30 mm can be used in a connection with bonded-in rods and they are ribbed rods of reinforcing steel in compliance with EN 10080 and metric rods with coarse thread in compliance with EN ISO 898-1. The type of an adhesive which is applied in a connection with bonded-in rods is according to EN 17334. The values of the characteristic withdrawal strengths of bonded-in rods $f_{w,k}$, which are used in a connection with bonded-in rods, are equal to at least the values given in Table 79.

Table 79: Minimum characteristic withdrawal strength of bonded-in rods for softwood and hardwood $f_{w,k}$ [1].

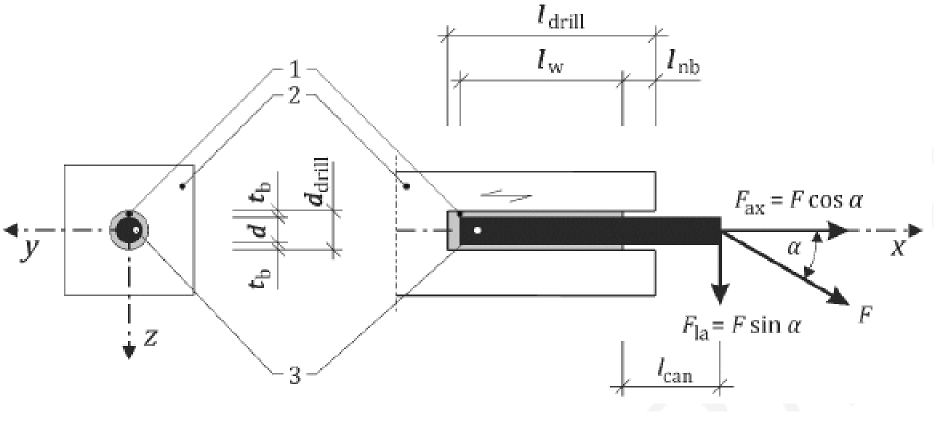
	Effective withdrawal length $l_{w,ef}$ of the rod according to (*194* in mm		
	$l_{w,ef} \leq 250$ mm	$250 < l_{w,ef} \leq 500$ mm	$500 < l_{w,ef} \leq 1000$ mm
$F_{w,k}$ in N/mm^{2} [a]	4.0	$5.25 - 0.005\, l_{w,ef}$	$3.5 - 0.0015\, l_{w,ef}$
[a] The load-carrying resistance determined for $l_{w,ef} = \min(40d; 1000)$ in mm is applied for applications in which $l_{w,ef} > \min(40d; 1000)$ in mm.			

9.3 Geometric requirements for bonded-in rods

The withdrawal length of the bonded-in rods l_w, as shown in Figure 53, must satisfy the requirement given by:

$$l_w \geq \max\begin{cases} 0.4\, d^2 \\ 8\, d \end{cases} \tag{189}$$

where *d* is the diameter of the bonded-in rod.



Key:

1	Adhesive	d_{drill}	Drill hole diameter

2	Timber	d	Diameter of the rod
3	Rod	l_{can}	Distance between bond-line and the lateral load
l_{drill}	Drill hole length	α	Angle between load and rod axis
l_w	Withdrawal length	F	Force
l_{nb}	Not bonded length	F_{la}	Lateral force
t_b	Bond line thickness	F_{ax}	Axial force

Figure 53: An example of a bonded-in rod [1].

9.4 Axial resistance of a connection with bonded-in rods

9.4.1 Tension resistance of the rod in the connection

In the New Eurocode 5, the design axial tensile resistance of the bonded-in rod in tension is determined by:

$$F_{ax,Rd} = \min\begin{cases} F_{t,d} \\ F_{w,d} \end{cases} \tag{190}$$

with

$$F_{t,d} = \begin{cases} \min\left[\dfrac{A_s f_{y,k}}{\gamma_{M,0}}; \dfrac{0.9 A_s f_{u,k}}{\gamma_{M,2}}\right] & \text{for threaded rods} \\ \dfrac{A_s f_{y,k}}{\gamma_{M,0}} & \text{for ribbed rods} \end{cases} \tag{191}$$

$$F_{w,d} = \frac{k_{mod}}{\gamma_M} F_{w,k} \tag{192}$$

$$F_{w,k} = \min\begin{cases} \pi d l_{w,ef} f_{w,k} \\ E_s A_s \varepsilon_{u,timber} \end{cases} \tag{193}$$

$$l_{w,ef} = \min\begin{cases} l_w \\ 40d \\ 1000\text{ mm} \end{cases} \tag{194}$$

where

$F_{ax,Rd}$	is the design axial resistance of the bonded-in rod, in N;
$F_{t,d}$	is the design tensile resistance of the rod, in N;
$F_{w,d}$	is the design withdrawal resistance of the bonded-in rod, in N;

A_s is the nominal stress area according to EN ISO 898-1 for threaded rods and the nominal cross-sectional area according to EN 10080 for ribbed rods;

$f_{y,k}$ is the characteristic yield strength of the bonded-in rod;

$f_{u,k}$ is the characteristic ultimate strength of the bonded-in rod;

d is the diameter of the bonded-in rod;

l_w is the withdrawal length;

$l_{w,ef}$ is the effective withdrawal length;

$F_{w,k}$ is the characteristic withdrawal strength, defined as $f_{vr,k}$ according to EN 17334;

$\gamma_{M,0}$ is the partial factor for material properties;

$\gamma_{M,2}$ is the partial factor for material properties;

γ_M is the partial factor for material properties;

$\varepsilon_{u,timber}$ is the partial factor for material properties;

For softwood timber $\varepsilon_{u,timber}$ = 2.4 ‰.

In a connection with bonded-in rods, ductile failure is preferred to brittle failure of the connection. If failure mode (a), which is the tensile failure, of the rod occurs prior to the other failure modes presented in section 9, ductile behavior of axially loaded connections with bonded-in rods is achieved. Equation (*195*) must be satisfied to achieve ductility in the connection.

$$F_{t,0.95} < F_{w,k} \tag{195}$$

$$F_{t,0.95} = A_s f_{y,0.95} \tag{196}$$

where

$F_{t,0.95}$ is the 95th-percentile of the resistance of the bonded-in rod;

$F_{w,k}$ is the characteristic withdrawal resistance of the bonded-in rod;

A_s is the nominal stress area according to EN ISO 898-1 for threaded rods and the nominal cross-sectional area according to EN 10080 for ribbed rods;

$f_{y,0.95}$ is the 95th-percentile of the yield stress of the bonded-in rod;

The requirement in Equation (*195*) can be attained by fulfilling another requirement in Equation (*197*), if a steel rod with a given strength is applied.

$$\frac{F_{w,d}}{F_{t,d}} \geq 1.5 \tag{197}$$

where

$F_{w,d}$ is the design withdrawal resistance of the bonded-in rod, in N;

$F_{t,d}$ is the design tensile resistance of the rod, in N;

9.4.2 Compression resistance of the rod in the connection

The design axial compressive (buckling) resistance of the bonded-in rod in compression can be determined according to section 2.4.

9.4.3 Resistance of the timber member in the connection

9.4.3.1 Tensile resistance of the timber member

When determining the tensile resistance of the timber member in a connection with bonded-in rods, the net cross-sectional area is considered by the reduction of the timber cross-section for the diameters of the predrilled holes. For achieving a balanced stiffness between the timber and the rods parallel to the grain, the bonded-in rods must be uniformly distributed over the timber cross-section or within a group of rods acting together according to the New Eurocode 5.

For a single bonded-in rod inserted parallel to grain where the effective timber area A_{ef} of the given rod, as depicted in Figure 54, cannot be greater than a square of maximum 6*d* ($A_{ef} \leq 36d^2$), the design tensile resistance of the timber member parallel to the grain $F_{t,0,Rd}$ is determined by Equation (*198*). The effective timber area A_{ef} is neglected when the spacing between the adjacent rods is less than 6*d* as shown in Figure 54.

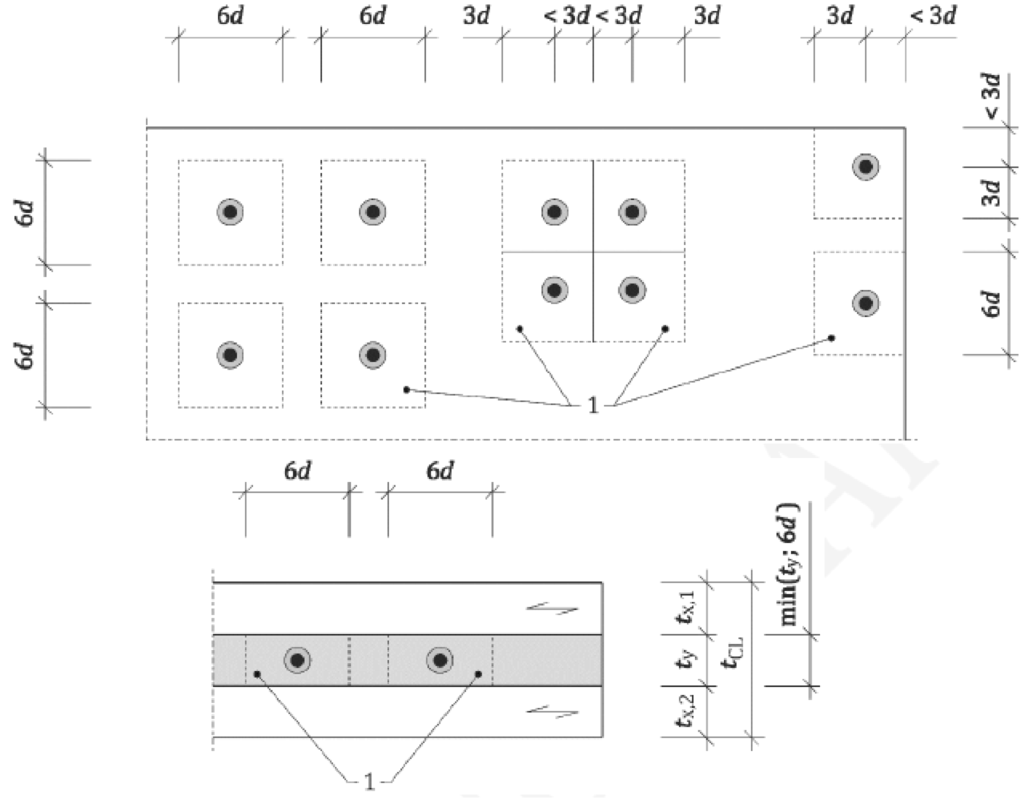
$$F_{t,0,Rd} = f_{t,0,d} A_{ef} \tag{198}$$

where

$f_{t,0d}$ is the design tensile strength of the timber;

A_{ef} is the effective timber area, see Figure 54;

d is the diameter of the bonded-in rod.



Key:

1 Effective timber area A_{ef}

Figure 54: Effective timber areas for bonded-in rods parallel to the grain [1].

9.4.3.2 Splitting resistance of the timber member

For a single bonded-in rod inserted at an angle to the grain, the design splitting resistance of the timber member is determined according to the provisions given in section 7.2. As depicted in Figure 55, h_e is the distance from the loaded edge to the end of the rod, and b_{ef} is the effective width with a maximum of 6*d* per rod.

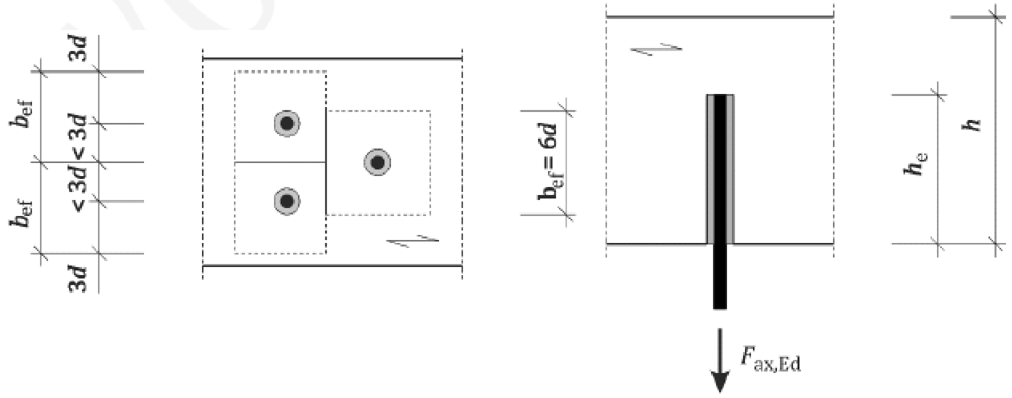


Figure 55: Effective timber areas for bonded-in rods at an angle to the grain [1].

9.5 Lateral resistance of a connection with bonded-in rods

The design of the lateral resistance of the bonded-in rods is determined according to the provisions given in section 4.2. The embedment strength for dowels and bolts according to section 3.3.2 is applied for the laterally loaded bonded-in rods inserted perpendicular to the grain (ε = 90°). The embedment strength for the laterally loaded bonded-in rods inserted parallel to the grain (ε = 0°) is 10 % of the embedment strength for the laterally loaded bonded-in rods inserted perpendicular to the grain (ε = 90°). The embedment strength for the laterally loaded bonded-in rods inserted at an angle to the grain is determined by linear interpolation between the embedment strengths for the laterally loaded bonded-in rods inserted perpendicular to the grain (ε = 90°) and parallel to the grain (ε = 0°). The characteristic value of the dowel-effect contribution $F_{D,k}$ for a bonded-in rod is calculated by Equation (*199* for loads acting at a distance *e* > 0, which is depicted in Figure 58, by considering the failure modes (a1) and (b1) depicted in Figure 56.

$$F_{D,k} = \min \begin{cases} d f_{h,k} \left(\sqrt{(l_h + 2 l_{can})^2 + {l_h}^2} - l_h - 2 l_{can} \right) & \text{(a1)} \\ d f_{h,k} \left(\sqrt{{l_{can}}^2 + \frac{2 M_{y,k}}{d f_{h,k}}} - l_{can} \right) & \text{(b1)} \end{cases} \qquad (199)$$

where

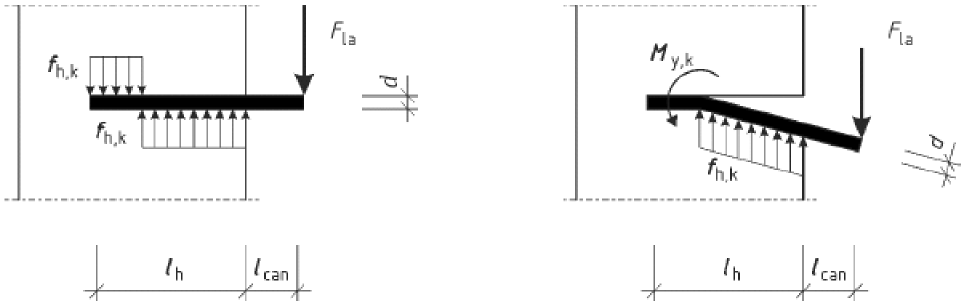
d is the nominal diameter of the bonded-in rod;

$f_{h,k}$ is the characteristic embedment strength according to section 9.5;

l_{can} is the distance between load and bond-line, see Figure 56;

l_h is the embedment depth;

$M_{y,k}$ is the characteristic yield moment of the rod, see section 3.4.2.



a) Failure mode a1

b) Failure mode b1

Figure 56: Failure modes (a1) and (b1) for a bonded-in rod loaded at a distance l_{can} from the bond-line [1].

9.6 Spacing, edge and end distances

For laterally loaded bonded-in rods as shown in Figure 58, the minimum spacings and end and edge distances provided in Table 80 are applied for adhesives not exceeding 150 % of the required value of the characteristic withdrawal strength $f_{w,k}$ according to Table 79. The denotations of spacings and edge and end distances of axially loaded bonded-in rods are given in Figure 57 and the denotations of spacings and edge and end distances of laterally loaded bonded-in rods are given in Figure 58.

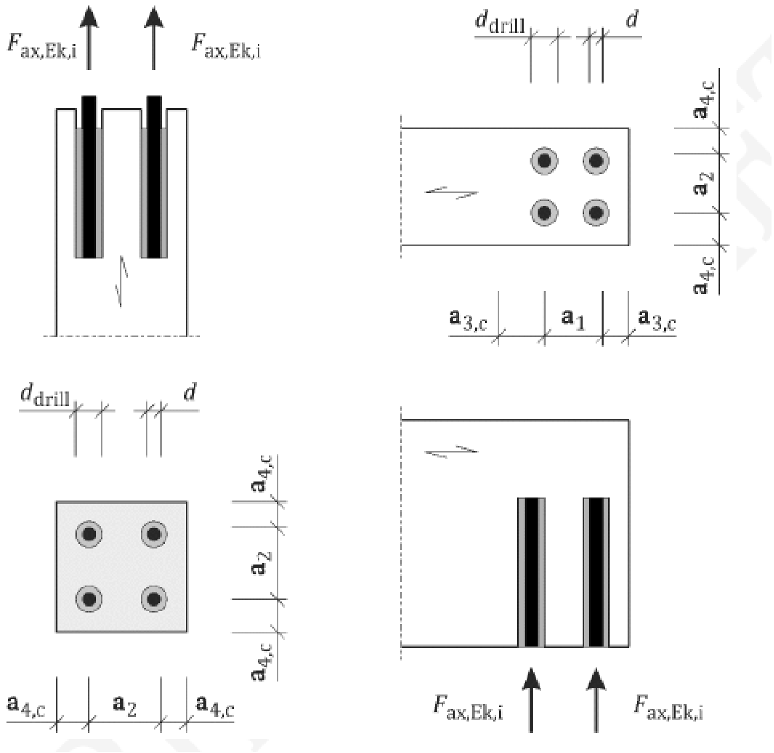


Figure 57: Denotation of spacings and edge and end distances of axially loaded bonded-in rods [1].

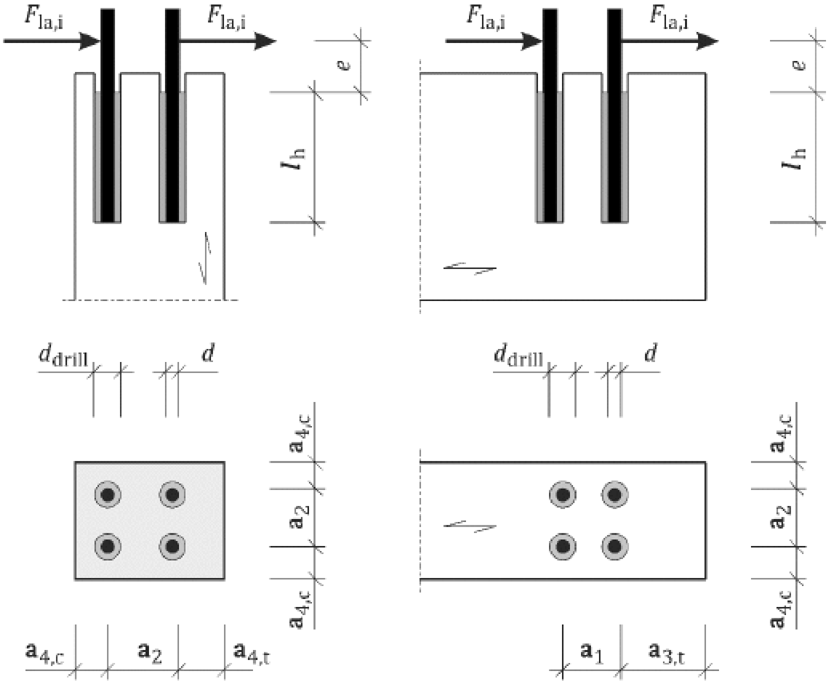


Figure 58: Denotation of spacings and edge and end distances of laterally loaded bonded-in rods [1].

Table 80: Minimum spacings and distances for bonded-in rods for GL, GST, LVL and GLVL [1].

Bonded-in rods	**Axially loaded rods**	**Laterally loaded rods**
Parallel to grain	$a_2 = 5d$ $a_{4,c} = 2.5d$	$a_2 = 5d$ $a_{4,c} = 2.5d$ $a_{4,t} = 4d$
Perpendicular to grain	$a_1 = 4d$ $a_2 = 4d$ $a_{3,c} = 2.5d$ $a_{4,c} = 2.5d$	The New Eurocode 5 informs the user to see in Table 11.17 to 11.19 [1], but no explicit values for bonded-in rods are given in Table 11.17 to 11.19 [1].

The minimum spacings and distances in Table 80 are reduced by 30 % for axially loaded rods bonded-in parallel to the grain with adhesives not exceeding the required value of the characteristic withdrawal strength $f_{w,k}$ according to Table 79. When an unbonded length of $l_{nb} \geq 5d$ is used, the values of these reduced spacings and distances are applied for adhesives not exceeding 125 % of the required value of the characteristic withdrawal strength $f_{w,k}$ according to Table 79. Linear interpolation can be applied when an unbonded length of $3d \leq l_{nb} < 5d$ is used.

10 Shear connectors

Shear connectors are different from the metal dowel-type fasteners. Shear connectors are used to transfer shear between the contact surfaces of adjacent members. They are more efficient than the dowel-type fasteners in transferring shear stresses. When transferring shear stresses, the shear connectors distribute the shear stresses over a large area, but the dowel-type fasteners concentrate the shear stresses at a very small area (a point). The design of a connection with shear connectors consists of determining the resistance of a fastener, spacing and edge and end distances and design of the connection. In this chapter, most of the expressions provided by the Present Eurocode 5 and the New Eurocode 5 are the same. Unless it is specified, the presented expressions are according to both the New Eurocode 5 and the Present Eurocode 5. The difference in the nomenclature of parameters in the expressions provided by the Present Eurocode 5 and the New Eurocode 5 is given in Table 86.

10.1 Split-ring and shear plate connectors

In the New Eurocode 5 and the Present Eurocode 5, the characteristic load-carrying resistance parallel to grain $F_{v,0,k}$ per connector per shear plane is determined by Equation (*200*) for shear connections with split-ring connectors of type A or shear plate connectors of type B according to EN912 and EN14545, and with diameter not bigger than 200 mm ($d_{con} \leq 200$ mm). In the Present Eurocode 5, there is no parameter k_5 in the condition (a) in Equation (*200*).

$$F_{v,0,k} = \min \begin{cases} k_1 k_2 k_3 k_4 k_5 \left(35\ d_{con}{}^{1.5}\right) & \text{(a)} \\ k_1 k_3 t_h (31.5\ d_{con}) & \text{(b)} \end{cases} \qquad (200)$$

$$k_1 = \min \begin{cases} 1 \\ \dfrac{t_1}{3t_h} \\ \dfrac{t_2}{5t_h} \end{cases} \qquad (201)$$

The factor k_2 applies to a loaded end (-30° ≤ α ≤ 30°) and is determined by:

$$k_2 = \min \begin{cases} k_a \\ \dfrac{a_{3,t}}{2d_{con}} \end{cases} \qquad (202)$$

with

$$k_a = \begin{cases} 1.25 & \text{for connections with one connector per shear plane} \\ 1.0 & \text{for connections with more than one connector per shear plane} \end{cases} \qquad (203)$$

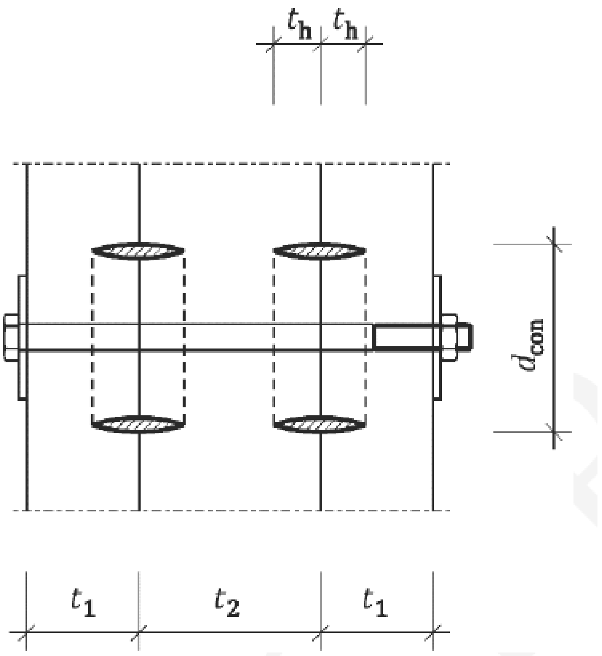
For other values of α, $k_2 = 1.0$.

$$k_3 = \min\begin{cases} 1.75 \\ \dfrac{\rho_k}{350} \end{cases} \tag{204}$$

$$k_4 = \begin{cases} 1.0 & \text{for timber} - \text{to} - \text{timber connections} \\ 1.1 & \text{for steel} - \text{to} - \text{timber connections} \end{cases} \tag{205}$$

$$k_5 = 1.0 \quad \text{for SL and PL} \tag{206}$$

The expression (a) in Equation (*200*) is neglected for connections with one connector per shear plane which is loaded in an unloaded end situation. The minimum required thickness is 2.25t_h for the outer timber member and 3.75t_h for the inner timber member, see Figure 59 as a reference.



Key:

t_h	Embedment depth
t_1	Thickness of the outer member
t_2	Thickness of the inner member
d_{con}	Shear connector diameter

Figure 59: Dimensions for connections with split-ring and shear plate connectors [1].

The characteristic load-carrying resistance $F_{v,\alpha,k}$, for a force at an angle α to the grain, per connector per shear plane is determined by:

$$F_{v,\alpha,k} = \frac{F_{v,0,k}}{k_{90} sin^2 \alpha + cos^2 \alpha} \tag{207}$$

with

$$k_{90} = 1.3 + 0.001d \tag{208}$$

10.1.1 Spacing and edge and end distances

The expressions for the minimum spacing and end and edge distances for ring and shear plate connectors provided in the Present Eurocode 5 include the load to grain angle α, but the expressions provided in the New Eurocode 5 do not include the load to grain angle α. The minimum spacings and edge and end distances for ring and shear plate connectors in the Present Eurocode 5 and the New Eurocode 5 is given in Table 81.

Table 81: Minimum spacings and edge and end distances for ring and shear plate connectors.

	Present Eurocode 5		**New Eurocode 5**
Spacings and end and edge distances	**Load to grain angle** **α**	**Minimum spacing or distance**	**Minimum spacing or distance**
a_1 (parallel to grain)	0° ≤ α ≤ 360°	$(1.2 + 0.8 \mid \cos \alpha \mid) d_c$	$2.0\ d_{con}$
a_2 (perpendicular to grain)	0° ≤ α ≤ 360°	$1.2\ d_c$	$1.2\ d_{con}$
$a_{3,t}$ (loaded end)	-90° ≤ α ≤ 90°	$2.0\ d_c$	$2.0\ d_{con}$
$a_{3,c}$ (unloaded end)	90° ≤ α < 150° 150° ≤ α < 210° 210° ≤ α ≤ 270°	$(0.4 + 1.6 \mid \sin \alpha \mid) d_c$ $1.2\ d_c$ $(0.4 + 1.6 \mid \sin \alpha \mid) d_c$	$1.5\ d_{con}$
$a_{4,t}$ (loaded edge)	0° ≤ α ≤ 180°	$(0.6 + 0.2 \mid \sin \alpha \mid) d_c$	$0.8\ d_{con}$
$a_{4,c}$ (unloaded edge)	180° ≤ α ≤ 360°	$0.6\ d_c$	$0.6\ d_{con}$

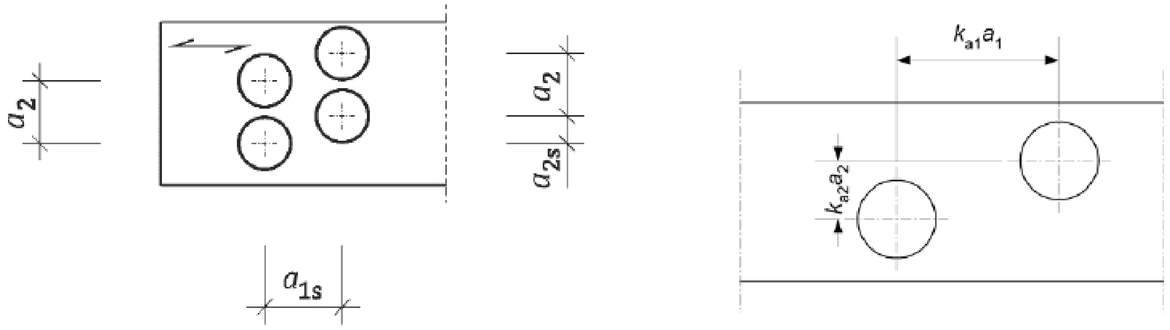
The minimum spacings parallel to the grain a_1 and perpendicular to the grain a_2 for staggered shear connectors in the New Eurocode 5 as depicted in Figure 60(a), and in the Present Eurocode 5 as shown in Figure 60(b), must comply with the expressions given in Table 82.

Table 82: Requirement for minimum spacings parallel and perpendicular to the grain for staggered shear connectors.

Present Eurocode 5		**New Eurocode 5**	
$(k_{a1})^2 + (k_{a2})^2 \geq 1$	(209)	$\frac{a_{2s}}{a_2} \geq 1 - \left(\frac{a_{1s}}{a_1}\right)^2$	(210)
with $\begin{cases} 0 \leq k_{a1} \leq 1 \\ 0 \leq k_{a2} \leq 1 \end{cases}$	(211)	with $a_{1s}/a_1 \leq 1$ and $a_{2s}/a_2 \leq 1$	(212)

If $a_2 < 0.5a_1$, the shear connectors are considered as aligned parallel to the grain according to the New Eurocode 5. If $k_{a2}a_2 < 0.5k_{a1}a_1$, the shear connectors are considered as aligned parallel to the grain according to the Present Eurocode 5. In the condition to be fulfilled to consider the connectors as positioned parallel to the grain, the actual spacings a_1 and a_2 are used in the New Eurocode 5, but the reduced spacings $k_{a1}a_1$ and $k_{a2}a_2$ are applied in the Present Eurocode 5. The spacings a_1 in the New Eurocode 5 and $k_{a1}a_1$ in the Present Eurocode 5 are multiplied by a reduction factor $k_{s,red}$, $0.5 \leq k_{s,red} \leq 1.0$, given the resistance in Equation (*200*) is multiplied by a reduction factor $k_{s,red}$.

$$k_{r,red} = 0.2 + 0.8k_{s,red} \tag{213}$$



a) Spacing for staggered shear connectors in the New Eurocode 5 [1]

b) Spacing for staggered shear connectors in the Present Eurocode 5 [2]

Key:

a_{1s}	is the staggered spacing of dowel-type fasteners parallel to the grain, in mm;
a_{2s}	is the staggered spacing of dowel-type fasteners perpendicular to grain, in mm;
a_2	is the spacing of dowel-type fasteners perpendicular to the grain, in mm;
k_{a1}	is a reduction factor for the minimum distance a_1 parallel to the grain;
k_{a2}	is a reduction factor for the minimum distance a_2 perpendicular to the grain.

Figure 60: Spacing for staggered shear connectors.

It is considered that the load-carrying capacity of a connection with multiple connectors of the same type and dimension, can be lower than the summation of the individual capacities of each connector. The effective number of connectors n_{ef} is not covered by the New Eurocode 5. In the Present Eurocode 5, the effective number of connectors n_{ef} in a row of connectors parallel to the grain for determining the load-carrying capacity parallel to the grain is given by:

$$n_{ef} = 2 + (1 - \frac{n}{20})(n - 2) \tag{214}$$

where

n_{ef} is the effective number of connectors;

n is the number of connectors in a line parallel to the grain.

10.1.2 Cross-section reduction of members

When the split-ring and shear connectors are used in a connection, there is a reduction in the size of the members in the connection. The cross-section reduction of the members in a connection with connectors is not covered by the Present Eurocode 5. The cross-section reduction of the members in a connection with split-ring connectors of type A or shear connectors of type B according to EN 912 and EN 14545, and with a diameter of the connectors not bigger than 200 mm is provided in Table 11.25 in the New Eurocode 5 [1].

10.2 Toothed plate connectors

The characteristic load-carrying resistance of connections with toothed-plate connectors is the sum of the characteristic load-carrying resistance of the shear connectors and the bolts in the connections. Section 3 is applied for determining the characteristic load-carrying resistance of the bolts used with the toothed-plate connectors. In the New Eurocode 5 and the Present Eurocode 5, the characteristic load-carrying resistance $F_{v,0,k}$ per toothed-plate connector of type C according to EN 912 and EN 1445 is given in Equations (*215*) and (*216*) respectively.

According to EN 912:

Single-sided connectors: type C2, C4, C7, C9 and C11

Double-sided connectors: type C1, C3, C5, C6, C8 and C10

New Eurocode 5

$$F_{v,0,k} = \min\begin{cases} 18k_1k_2k_3\, {d_{con}}^{1.5} & \text{for types C1 to C9} \\ 25k_1k_2k_3\, {d_{con}}^{1.5} & \text{for types C10 and C11} \end{cases} \tag{215}$$

Present Eurocode 5

$$F_{v,Rk} = \min\begin{cases} 18k_1k_2k_3\, {d_c}^{1.5} & \text{for single} - \text{sided types} \\ 25k_1k_2k_3\, {d_c}^{1.5} & \text{for double} - \text{sided types} \end{cases} \tag{216}$$

The New Eurocode 5 says that the first expression in Equation (*215*) is for types C1 to C9 which are not all single-sided types according to EN 912 and the second expression in Equation (*215*) is for types C10 and C11 only. The Present Eurocode 5 says that the first expression in Equation (*216*) is for single-sided types of connectors and the second expression in Equation (*216*) is for double-sided types of connectors according to EN 912.

$$k_1 = \min\begin{cases} 1 \\ \dfrac{t_1}{3t_h} \\ \dfrac{t_2}{5t_h} \end{cases} \tag{217}$$

- For types C1 to C9

$$k_2 = \min\begin{cases} 1 \\ \dfrac{a_{3,t}}{1.5\, d_{con}} \end{cases} \tag{218}$$

with

$$a_{3,t} = \max\begin{cases} 1.1\, d_{con} \\ 7d \\ 80 \text{ mm} \end{cases} \tag{219}$$

- For types C10 and C11

$$k_2 = \min\begin{cases} 1 \\ \dfrac{a_{3,t}}{2.0\, d_{con}} \end{cases} \tag{220}$$

with

$$a_{3,t} = \max\begin{cases} 1.5\, d_{con} \\ 7d \\ 80 \text{ mm} \end{cases} \tag{221}$$

$$k_3 = \min\begin{cases} 1.5 \\ \dfrac{\rho_k}{350} \end{cases} \tag{222}$$

According to the New Eurocode 5, the first expression in Equation (*215*) is neglected for connections with one toothed-plate connector per shear plane which is loaded in an unloaded end situation. According to the Present Eurocode 5, the minimum required thickness is $2.25t_h$ for the outer timber member and $3.75t_h$ for the inner timber member in connection with toothed-plate connector, see Figure 59 as a reference.

10.2.1 Spacing and edge and end distances

The expressions for the minimum spacing and end and edge distances for toothed-plate connectors provided in the Present Eurocode 5 include the load to grain angle α, but the expressions provided in the New Eurocode 5 do not include the load to grain angle α. According to the New Eurocode 5 and the Present Eurocode 5, the minimum spacing and edge and end distances for toothed-plate connectors of types C1 to C9 and types C10 and C11 are given in Table 83 and Table 84 respectively. In the New Eurocode 5, the minimum spacing and edge and end distances for staggered shear connectors of type C1, C2, C6 and C7 with circular shape is given by the values presented in Table 83 multiplied by a factor of 0.85. In the Present Eurocode 5, the minimum spacing and edge and end distances for staggered shear connectors of type C1, C2, C6 and C7 with circular shape must comply with the expressions given in Table 82.

Table 83: Minimum spacings and edge and end distances for toothed-plate connector types C1 to C9.

	Present Eurocode 5		**New Eurocode 5**
Spacings and end and edge distances	**Load to grain angle** **α**	**Minimum spacing and end and edge distances**	**Minimum spacings and end and edge distances**
a_1 (parallel to grain)	$0° \le \alpha \le 360°$	$(1.2 + 0.3 \mid \cos \alpha \mid)\, d_c$	$2.0\, d_{con}$
a_2 (perpendicular to grain)	$0° \le \alpha \le 360°$	$1.2\, d_c$	$1.2\, d_{con}$
$a_{3,t}$ (loaded end)	$-90° \le \alpha \le 90°$	$1.5\, d_c$	$2.0\, d_{con}$
$a_{3,c}$ (unloaded end)	$90° \le \alpha < 150°$ $150° \le \alpha < 210°$ $210° \le \alpha \le 270°$	$(0.9 + 0.6 \mid \sin \alpha \mid)\, d_c$ $1.2\, d_c$ $(0.9 + 0.6 \mid \sin \alpha \mid)\, d_c$	$1.5\, d_{con}$
$a_{4,t}$ (loaded edge)	$0° \le \alpha \le 180°$	$(0.6 + 0.2 \mid \sin \alpha \mid)\, d_c$	$0.8\, d_{con}$
$a_{4,c}$ (unloaded edge)	$180° \le \alpha \le 360°$	$0.6\, d_c$	$0.6\, d_{con}$

Table 84: Minimum spacings and edge and end distances for toothed-plate connector types C10 and C11.

	Present Eurocode 5		**New Eurocode 5**
Spacings and end and edge distances	**Load to grain angle** **α**	**Minimum spacing or distance**	**Minimum spacing or distance**
a_1 (parallel to grain)	$0° \leq \alpha \leq 360°$	$(1.2 + 0.8 \mid \cos \alpha \mid) d_c$	$2.0\ d_{con}$
a_2 (perpendicular to grain)	$0° \leq \alpha \leq 360°$	$1.2\ d_c$	$1.2\ d_{con}$
$a_{3,t}$ (loaded end)	$-90° \leq \alpha \leq 90°$	$2.0\ d_c$	$2.0\ d_{con}$
$a_{3,c}$ (unloaded end)	$90° \leq \alpha < 150°$	$(0.4 + 1.6 \mid \sin \alpha \mid) d_c$	$1.5\ d_{con}$
	$150° \leq \alpha < 210°$	$1.2\ d_c$	
	$210° \leq \alpha \leq 270°$	$(0.4 + 1.6 \mid \sin \alpha \mid) d_c$	
$a_{4,t}$ (loaded edge)	$0° \leq \alpha \leq 180°$	$(0.6 + 0.2 \mid \sin \alpha \mid) d_c$	$0.8\ d_{con}$
$a_{4,c}$ (unloaded edge)	$180° \leq \alpha \leq 360°$	$0.6\ d_c$	$0.6\ d_{con}$

10.2.2 Cross-section reduction of the members

There is a reduction in the size of the members when toothed-plate connectors of type C are used in a connection. The cross-section reduction of the members in a connection with toothed-plate connectors of type C according to EN 912 and EN 14545 is provided in Table 11.26 in the New Eurocode 5 [1]. The cross-section reduction of the members in a connection with toothed-plate connectors is not covered by the Eurocode 5.

10.3 Split-ring and shear plate connectors in end grain

The split-ring and shear plate connectors in a connection in an end grain of members is not covered by the Present Eurocode 5. In the New Eurocode 5 for members of solid wood with the moisture content less than 20 %, glued lumber (GL) and glued structural timber (GST) in a connection, the following shear connectors according to EN 912 may be used in the end grain of the members:

- split-ring connectors of type A1 with diameters $d_{con} \leq 126$ mm;

- tooth-plate connectors of type C1 with diameters $d_{con} \leq 140$ mm;

- spiked shear plate of type C10.

Table 85: Requirements for bolt diameters d in end-grain connections [1].

Shear connector	**Type**	**Connector diameter d_{con}** [mm]	**Bolt diameter d** [mm]
Split-ring	A1	≤ 130	$12 \leq d \leq 24$
Toothed or spiked shear plate	C1	≤ 75	$12 \leq d \leq d_{con,1}$ [a]
		≥ 95	$10 \leq d \leq 30$
	C10		$10 \leq d \leq 30$
[a] $d_{con,1}$ is the diameter of the center hole of the shear connector, in mm.			

Members with a characteristic density of less than 350 kg/m^3 must not be used in an end-grain connection according to the New Eurocode 5. For an end-grain connection with split-ring connectors of type A1 and members with a characteristic density of at least 350 kg/m^3 ($\rho_k \geq 350$ kg/m^3), the characteristic load-carrying capacity $F_{v,H,k}$ is determined by:

$$F_{v,H,k} = \frac{k_H}{(1.3 + 0.001\, d_{con})} F_{v,0,k} \tag{223}$$

$k_H = 0.65$ for one or two successively arranged dowels

$k_H = 0.80$ for three, four or five successively arranged dowels

For an end-grain connection with toothed-plate connectors of type C1 and spiked shear plate connectors of type C10 and members with a characteristic density of at least 350 kg/m^3 and not more than 500 kg/m^3 (350 kg/m^3 $\leq \rho_k <$ 500 kg/m^3), the characteristic load-carrying capacity $F_{v,H,k}$ is determined by:

$$F_{v,H,k} = 14{d_{con}}^{1.5} + 0.85 F_{v,90,k} \tag{224}$$

For end-grain connections with split-ring and shear plate connectors, the design load-carrying capacity $F_{v,H,Rd}$ is given by:

$$F_{v,H,Rd} = n_{con} \frac{k_{mod} F_{v,H,Rk}}{\gamma_R} \tag{225}$$

The nomenclature used in the shear connectors in the New Eurocode 5 and the Present Eurocode 5 is provided in Table 86.

Table 86: Nomenclature used in the shear connectors.

Present Eurocode 5	New Eurocode 5	Meaning
$F_{v,0,Rk}$	$F_{v,0,k}$	characteristic resistance parallel to grain per connector per shear plane, in N
d_c	d_{con}	shear connector diameter, in mm
h_e	t_h	embedment depth, in mm
t_1	t_1	thickness of outer member, in mm
t_2	t_2	thickness of inner member, in mm
$a_{3,t}$	$a_{3,t}$	loaded end distance parallel to grain, in mm
ρ_k	ρ_k	characteristic density of timber member, in kg/m^3
$F_{v,\alpha,Rk}$	$F_{v,\alpha,k}$	characteristic resistance per shear connector per shear plane for a force at an angle ɑ to grain, in N
d_c	d_{con}	- toothed-plate connector diameter for types C1, C2, C6, C7, C10 and C11, in mm - toothed-plate connector side length for types C5, C8 and C9, in mm - square root of the product of both side lengths for types C3 and C4, in mm
	$F_{v,90,k}$	characteristic resistance per connector per shear plane for a force perpendicular to grain, in N
	$F_{v,H,Rk}$	characteristic load-carrying resistance of the respective bolt or threaded rod, in N
	n_{con}	number of shear connector units in a connection, with $n_{con} \leq 5$
	k_{mod}	modification factor accounting for the effect of the duration of load and moisture content
	γ_R	partial factor for connections

11 Punched metal plate fasteners (PMPF)

The section for connections with punched metal plate fasteners (PMPF) is given in a normative Annex P in the New Eurocode 5 and within chapter 8 in the Present Eurocode 5. The provision given by the New Eurocode 5 for connections with punched metal plate fasteners is more detailed and include many expressions and illustrative figures than the provision given by the Present Eurocode 5.

11.1 Design resistance

The expression for the design resistance of a punched metal plate fastener (PMPF) is not explicitly given in the Present Eurocode 5. In the New Eurocode 5, the design value of a resistance R_d of a punched metal fastener is given by:

$$R_d = k_{sys} k_{mod} \frac{R_k}{\gamma_M} \tag{226}$$

The values of k_{mod} and the values of partial factors γ_M for resistances of connections with punched metal fasteners (PMPF) are given in Table P.3 and Table P.2 respectively, in the New Eurocode 5 [1]. Furthermore, requirements for moisture content at a time of fabrication of structural timber members connected with the punched metal plate fasteners (PMPF) are given in Table P.1 in the New Eurocode 5 [1].

11.2 Forces at an angle to the grain in a connection

The section of forces acting at an angle to the grain in a connection with punched metal plate fasteners (PMPF) is not included in the Present Eurocode 5. Hence, this section is according to the New Eurocode 5 only.

For connections with punched metal plate fasteners (PMPF), h_e is the distance between the loaded timber edge and the most distant edge or corner of the PMPF as depicted in Figure 61. When a force acts at an angle to the grain in a connection with punched metal plate fasteners (PMPF) where $h_e < 0.8h$, splitting caused by the tensile force component $F_{Ed}\sin\varphi$ perpendicular to the grain is considered. The splitting caused by the tensile force component $F_{Ed}\sin\varphi$ perpendicular to the grain must satisfy the requirement given by:

$$F_{Ed}\sin\varphi \leq F_{90,Rd} \tag{227}$$

The characteristic splitting capacity $F_{90,Rk}$ perpendicular to the grain of a connection with PMPF, as shown in Figure 61, is determined by:

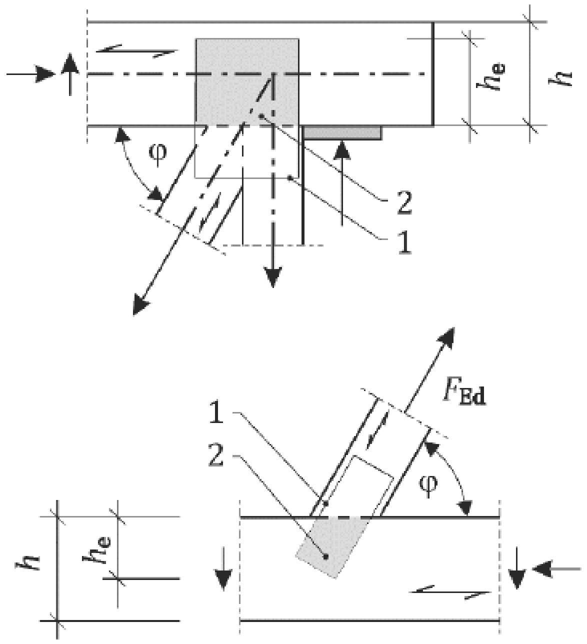
$$F_{90,Rk} = k_G\, k_{mat}\, b\, k_w \sqrt{\frac{h_{e,net}}{\left(1 - \frac{h_{e,net}}{h}\right)}} \tag{228}$$

$$k_G = \begin{cases} 2 + 0.05\rho_k & \text{for ST, FST and GL} \\ 6 + 0.05\rho_k & \text{for LVL} - \text{P} \end{cases} \tag{229}$$

$$k_{mat} = \min\begin{pmatrix} 0.5 \\ 0.5\left(\frac{l_1}{l_{ref}}\right) \end{pmatrix} + \min\begin{pmatrix} 0.5 \\ 0.5(l_2/l_{ref}) \end{pmatrix} \tag{230}$$

$$k_w = \max\begin{cases} \left(\frac{b_{PMPF,0}}{100\ \text{mm}}\right)^{0.35} \\ 1.0 \end{cases} \tag{231}$$

$$h_{e,net} = h_e - (c - 5\ \text{mm}) \tag{232}$$



Key:

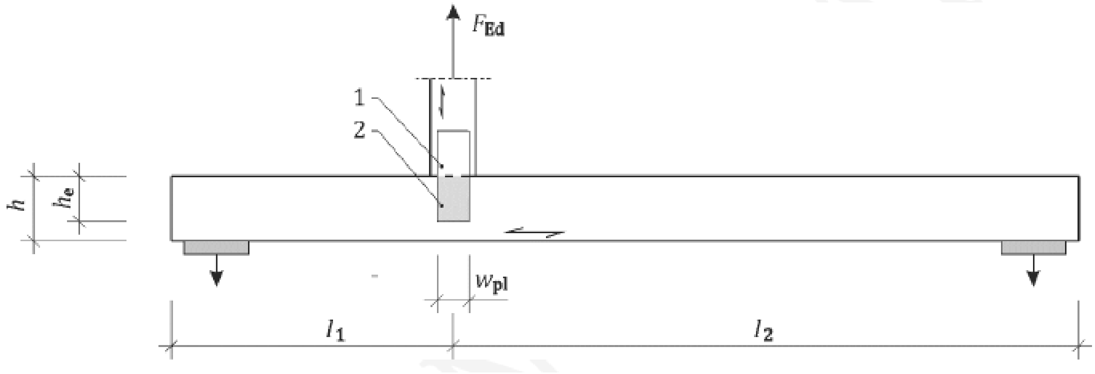
1 Punched metal plate fastener;

2 Overlap area A_{olap} of PMPF with member being loaded perpendicular to grain.

Figure 61: PMPF connection with member loaded in tension perpendicular to grain [1].

When punched metal plate fasteners are applied not parallel to the loaded edge of the member in the connection, the width of the plate w_{pl}, as shown in Figure 62, is determined by:

$$w_{pl} = \frac{A_{olap}}{h_{e,net}} \tag{233}$$



Key:

1 Punched metal plate fastener;

2 Overlap area A_{olap} of PMPF with member being loaded perpendicular to grain.

Figure 62: Dimensions h_e, w_{pl}, l_1 and l_2 for PMPF with an edge parallel to the member loaded in tension perpendicular to the grain [1].

11.3 Plate geometry

The same geometry of a punched metal plate fastener, as shown in Figure 64(a), is given in the New Eurocode 5 and the Present Eurocode 5. There are two more figures in the New Eurocode 5 than in the Present Eurocode 5 to give additional information about the effective area of the total contact surface between the plate and the timber as depicted in Figure 63 and the force in the anchorage area as shown in Figure 64(b).

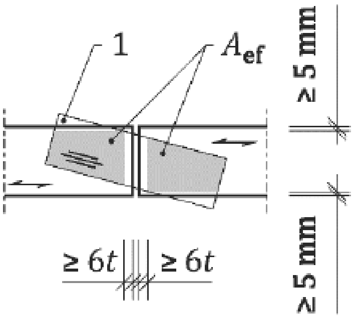
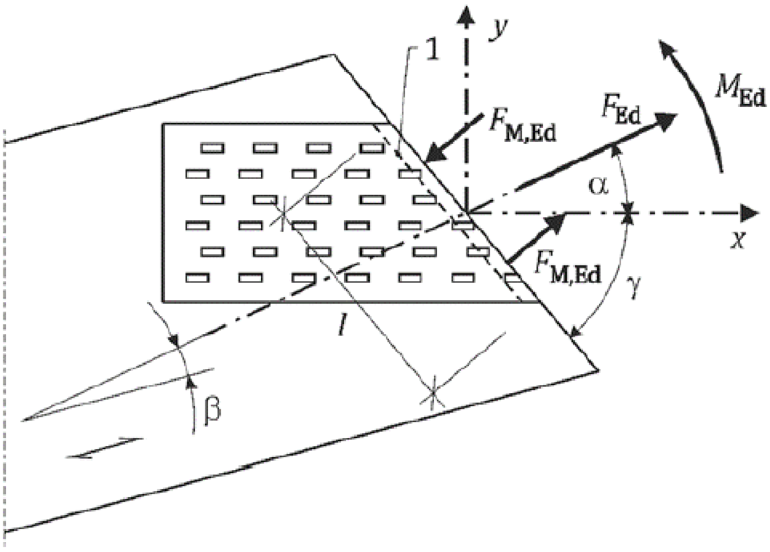
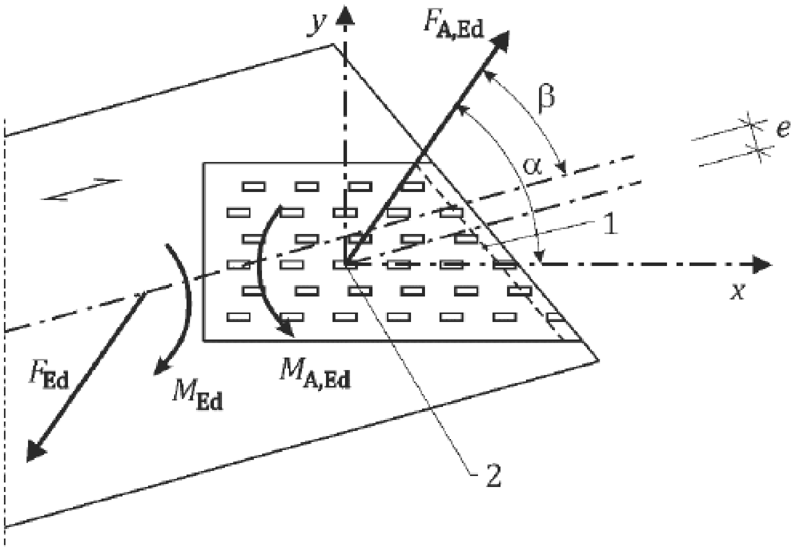


Figure 63: Effective anchorage area [1].



a) Geometry where each plate is loaded by F_{Ed} and M_{Ed} [1] [2].



b) Anchorage area loaded by $F_{A,Ed}$ and $M_{A,Ed}$ [1].

Key:

1	Border of effective area
2	Plate anchorage area centroid
e	Eccentricity from timber centerline to plate centroid
l	Length of the plate measured along the connection line
$F_{M,Ed}$	Design force from the moment on a single plate ($F_{M,Ed} = 2M_{Ed}/l$)

F_{Ed}	Design force acting on a single plate
$F_{A,Ed}$	Design force acting on a single plate at the centroid of the effective area (i.e. half of the total force in the timber member)
M_{Ed}	Design moment acting on a single plate
$M_{A,Ed}$	Design moment acting on a single plate at the centroid of the effective area
α	Angle between the x-direction and the force (0° ≤ α ≤ 90°)
β	Angle between the grain-direction and the force (0° ≤ β ≤ 90°)
γ	Angle between the x-direction and the connection line (0° ≤ γ ≤ 90°)

Figure 64: Geometry and anchorage area [1].

11.4 Plate strength and stiffness properties

11.4.1 Characteristic anchorage strengths

In accordance with EN 14545, the characteristic anchorage strengths of the plate are given below. For ST and GL, the characteristic values are determined at a reference characteristic timber density $\rho_{k,ref}$ in kg/m^3 in the New Eurocode 5. In the Present Eurocode 5, the characteristic values are determined at a characteristic timber density ρ_k in kg/m^3. The Present Eurocode 5 provides the anchorage strength per unit area for values of only 0° and 90° for both ɑ and β as presented below.

Present Eurocode 5

$f_{a,0,0}$	is the anchorage strength per unit area for $\alpha = 0°$ and $\beta = 0°$, in N/mm^2;
$f_{a,90,90}$	is the anchorage strength per unit area for $\alpha = 90°$ and $\beta = 90°$, in N/mm^2;

New Eurocode 5

$f_{a,0,0,k,ref}$	is the anchorage strength per unit area for $\alpha = 0°$ and $\beta = 0°$, in N/mm^2;
$f_{a,30,0,k,ref}$	is the anchorage strength per unit area for $\alpha = 30°$ and $\beta = 0°$, in N/mm^2;
$f_{a,60,0,k,ref}$	is the anchorage strength per unit area for $\alpha = 60°$ and $\beta = 0°$, in N/mm^2;
$f_{a,90,0,k,ref}$	is the anchorage strength per unit area for $\alpha = 90°$ and $\beta = 0°$, in N/mm^2;
$f_{a,90,90,k,ref}$	is the anchorage strength per unit area for $\alpha = 90°$ and $\beta = 90°$, in N/mm^2;

11.4.2 Characteristic steel plate strengths

In accordance with EN 14545, the characteristic steel plate strengths given in the New Eurocode 5 and the Present Eurocode 5 are the same and the only difference is the nomenclature of the symbols used. The name of each characteristic steel plate strength in the Present Eurocode 5 does not include the alphabets p and k. For instance, the characteristic tension strength per unit width of the plate for $\alpha = 0°$ is given by $f_{t,0}$ in the Present Eurocode 5 and $f_{t,p,0,k}$ in the New Eurocode 5.

Present Eurocode 5 and New Eurocode 5

$f_{t,p,0,k}$	is characteristic tension strength per unit width of the plate for $\alpha = 0°$, in N/mm;
$f_{c,p,0,k}$	is characteristic compressive strength per unit width of the plate for $\alpha = 0°$, in N/mm;
$f_{v,p,0,k}$	is characteristic shear strength per unit width of the plate in the x-direction, in N/mm;
$f_{t,p,90,k}$	is characteristic tension strength per unit width of the plate for $\alpha = 0°$, in N/mm;
$f_{c,p,90,k}$	is characteristic compressive strength per unit width of plate for $\alpha = 90°$, in N/mm;
$f_{v,p,90,k}$	is characteristic shear strength per unit width of the plate in the y-direction, in N/mm;
k_v, γ_0	are the plate steel property constants in the Present Eurocode 5 and New Eurocode 5;
k_1, k_2, α_0	are constants in the Present Eurocode 5;

11.5 Plate anchorage strengths

The characteristic anchorage strength per plate in the New Eurocode 5 is determined for plates installed into different types of timber members with characteristic timber density ρ_k in kg/m^3 and with reference characteristic timber density $\rho_{k,ref}$ in kg/m^3. The expressions, which are given below from the New Eurocode 5, are in accordance with the types of timber members considered in this thesis. The characteristic anchorage strength per plate $f_{a,\alpha,\beta,k}$ in the Present Eurocode 5 is determined for plates installed into all types of timber members of characteristic timber density ρ_k in kg/m^3.

Present Eurocode 5

The characteristic anchorage strength per plate $f_{a,\alpha,\beta,k}$ for the characteristic timber density ρ_k in kg/m^3 is determined from tests or obtained by:

$$f_{a,\alpha,\beta,k} = \max\begin{cases} f_{a,\alpha,0,k} - \left(f_{a,\alpha,0,k} - f_{a,90,90,k}\right)\frac{\beta}{45°} \\ f_{a,0,0,k} - \left(f_{a,0,0,k} - f_{a,90,90,k}\right)\sin\left(\max(\alpha,\beta)\right) \end{cases} \quad \text{for } \beta \leq 45° \tag{234}$$

or

$$f_{a,\alpha,\beta,k} = f_{a,0,0,k} - \left(f_{a,0,0,k} - f_{a,90,90,k}\right)\sin\left(\max(\alpha,\beta)\right) \qquad \text{for } 45° < \beta \leq 90° \tag{235}$$

New Eurocode 5

The characteristic anchorage strength per plate $f_{a,\alpha,\beta,k,ref}$ for the reference characteristic density of structural (ST) or glued laminated (GL) timber is determined by:

$$f_{a,\alpha,\beta,k,ref} = \max\begin{cases} f_{a,\alpha,0,k,ref} - \left(f_{a,\alpha,0,k,ref} - f_{a,90,90,k,ref}\right)\frac{\beta}{45°} \\ f_{a,0,0,k,ref} - \left(f_{a,0,0,k,ref} - f_{a,90,90,k,ref}\right)\sin\left(\max(\alpha,\beta)\right) \end{cases} \qquad \text{for } \beta \leq 45° \tag{236}$$

or

$$f_{a,\alpha,\beta,k,ref} = f_{a,0,0,k,ref} - \left(f_{a,0,0,k,ref} - f_{a,90,90,k,ref}\right)\sin\left(\max(\alpha,\beta)\right) \qquad \text{for } 45° < \beta \leq 90° \tag{237}$$

The characteristic anchorage strength per plate $f_{a,\alpha,\beta,k}$ for different timber types of characteristic timber density ρ_k in kg/m^3 is derived from tests in accordance with EN 14545 or obtained from:

- for plates installed into structural timber (ST) or homogenous glued laminated (GL) timber

$$f_{a,\alpha,\beta,k} = f_{a,\alpha,\beta,k,ref}\left(\frac{\rho_k}{\rho_{k,ref}}\right)^{0.5} \tag{238}$$

- for plates installed into combined glued laminated (GL) timber

$$f_{a,\alpha,\beta,k} = f_{a,\alpha,\beta,k,ref}\left(\frac{0.9\rho_k}{\rho_{k,ref}}\right)^{0.5} \tag{239}$$

In the Present Eurocode 5, the expression for determining the characteristic anchorage strength per plate parallel to the grain includes the constants k_1, k_2 and α_0. The values of the constants k_1, k_2 and α_0 are obtained from anchorage tests in accordance with EN 1075 and for the actual plate type in accordance with EN 14545. The characteristic anchorage strength per plate parallel to the grain is for the characteristic timber density ρ_k in the Present Eurocode 5. The characteristic anchorage strength per plate parallel to the grain is for the reference characteristic timber density $\rho_{k,ref}$ in the New Eurocode 5. The characteristic anchorage strength per plate parallel to the grain is determined by:

Present Eurocode 5

$$f_{a,\alpha,0,k} = \begin{cases} f_{a,0,0,k} + k_1\alpha & \text{when } \alpha \leq \alpha_0 \\ f_{a,0,0,k} + k_1\alpha_0 + k_2(\alpha - \alpha_0) & \text{when } \alpha_0 < \alpha \leq 90° \end{cases} \tag{240}$$

New Eurocode 5

$$f_{a,\alpha,0,k,ref}=\begin{cases} f_{a,0,0,k,ref}+\dfrac{\alpha}{30^\circ}\left(f_{a,30,0,k,ref}-f_{a,0,0,k,ref}\right) & \text{when } \alpha\leq 30^\circ \\ f_{a,30,0,k,ref}+\dfrac{(\alpha-30^\circ)}{30^\circ}\left(f_{a,60,0,k,ref}-f_{a,30,0,k,ref}\right) & \text{when } 30^\circ<\alpha\leq 60^\circ \\ f_{a,60,0,k,ref}+\dfrac{(\alpha-60^\circ)}{30^\circ}\left(f_{a,90,0,k,ref}-f_{a,60,0,k,ref}\right) & \text{when } \alpha>60^\circ \end{cases} \tag{241}$$

11.6 Plate withdrawal strengths

The characteristic withdrawal strength of punched metal plate fastener is not covered by the Present Eurocode 5. According to the New Eurocode 5, the characteristic withdrawal strength per unit width of connection line $f_{w,k}$ for different timber types of characteristic timber density ρ_k in kg/m^3 is determined from tests or obtained from:

- for plates installed into structural timber (ST) or homogenous glued laminated (GL) timber

$$f_{w,k}=f_{w,k,ref}\left(\frac{\rho_k}{\rho_{k,ref}}\right)^{1.5} \tag{242}$$

- for plates installed into combined glued laminated (GL) timber

$$f_{w,k}=f_{w,k,ref}\left(\frac{0.9\rho_k}{\rho_{k,ref}}\right)^{1.5} \tag{243}$$

11.7 Plate slip modulus

The Present Eurocode 5 does not cover the slip modulus of punched metal plate fasteners. According to the New Eurocode 5 for plates installed into solid timber or glued laminated timber of mean density ρ_{mean} in kg/m^3, the mean slip modulus of each anchorage area for both plates k_{SLS} is determined from:

$$k_{SLS}=2k_{SLS,ref}A_{ef}\frac{\rho_{mean}}{\rho_{mean,ref}} \tag{244}$$

According to the New Eurocode 5 for plates installed into solid timber or glued laminated timber of mean density ρ_{mean} in kg/m^3, the mean rotational slip modulus of each anchorage area for both plates $k_{SLS,rot}$ is determined from:

$$k_{SLS,rot} = 2k_{SLS,rot,ref}I_p \frac{\rho_{mean}}{\rho_{mean,ref}} \tag{245}$$

11.8 Connection strength verification in-plane of timber assembly

The strength verification of a connection is divided into in-plane and out-of-plane of timber assembly in the New Eurocode 5. In the Present Eurocode 5 the strength verification of a connection is in-plane of timber assembly, but it is not explicitly specified.

11.8.1 Internal forces

In the New Eurocode 5, the contact pressure between the timber members in chord splices is either in compression when $F_{Ed} \leq 0$ or in tension when $F_{Ed} > 0$. The contact pressure between the timber members in chord splices provided in Present Eurocode 5 is only in compression. In the Present Eurocode 5 and the New Eurocode 5, the contact pressure between the timber members in chord splices in compression is considered by designing the single plate for a design force $F_{A,Ed}$ and a design moment $M_{A,Ed}$ given by:

Present Eurocode 5 and New Eurocode 5

$$F_{A,Ed} = \frac{F_x}{|F_x|}\sqrt{{F_x}^2 + (F_{Ed}\sin\beta)^2} \tag{246}$$

$$M_{A,Ed} = \frac{M_{Ed}}{2} \tag{247}$$

with

$$F_x = \frac{F_{Ed}\cos\beta}{2} + \frac{3|M_{Ed}|}{2h} \tag{248}$$

In the New Eurocode 5 when $F_{Ed} > 0$, the contact pressure between the timber members in chord splices in tension is considered by designing the single plate for a design force $F_{A,Ed}$ and a design moment $M_{A,Ed}$ according to:

$$F_{A,Ed} = \sqrt{\left(F_{Ed}\cos\beta + \frac{3(1-\mu_t)|M_{Ed}|}{2h}\right)^2 + (F_{Ed}\sin\beta)^2} \tag{249}$$

$$M_{A,Ed} = \frac{(1+\mu_t)M_{Ed}}{2} \tag{250}$$

with

$$\mu_t = \min\begin{cases}\dfrac{2F_{Ed}\cos\beta}{f_{a,0,0,d}A_{ef}}\\ 1\end{cases} \tag{251}$$

11.8.2 Plate anchorage capacity

The same expressions are provided in the Present Eurocode 5 and the New Eurocode 5 for the design anchorage stress $\tau_{F,d}$ on a single punched metal plate fastener due to a force $F_{A,Ed}$ and the design anchorage stress $\tau_{M,d}$ due to a moment $M_{A,Ed}$. The expressions are given by:

$$\tau_{F,d} = \frac{F_{A,Ed}}{A_{ef}} \tag{252}$$

$$\tau_{M,d} = \frac{M_{A,Ed}}{W_{pl}} \tag{253}$$

with

$$W_{pl} = \int_{A_{ef}} r dA \tag{254}$$

The New Eurocode 5 and the Present Eurocode 5 provide expressions for the requirement to be satisfied for the verification of the plate anchorage capacity. The expression provided by the Present Eurocode 5, as given in Equation (*255*), is without a square root. The expression given by the New Eurocode 5, as presented in Equation (*256*), is under a square root.

$$\left(\frac{\tau_{F,d}}{f_{a,\alpha,\beta,d}}\right)^2 + \left(\frac{\tau_{M,d}}{f_{a,0,0,d}}\right)^2 \leq 1 \tag{255}$$

$$\sqrt{\left(\frac{\tau_{F,d}}{f_{a,\alpha,\beta,d}}\right)^2 + \left(\frac{\tau_{M,d}}{f_{a,0,0,d}}\right)^2} \leq 1 \tag{256}$$

11.8.3 Plate capacity

The Present Eurocode 5 and the New Eurocode 5 provide expressions for the plate capacity. The New Eurocode 5 provides a more detailed information by using additional sign parameters k_{sigx} and k_{sigy} in the expressions and illustrative figures, as shown in

Figure 65 and Figure 66. The parameters k_{sigx} and k_{sigy} in the expressions give the signs for the directions of the forces. The Figure 65 and Figure 66 give illustrations on the values of the sign parameters and the directions of the forces. The forces in the two main directions are taken for both ends for each joint interface as:

Present Eurocode 5

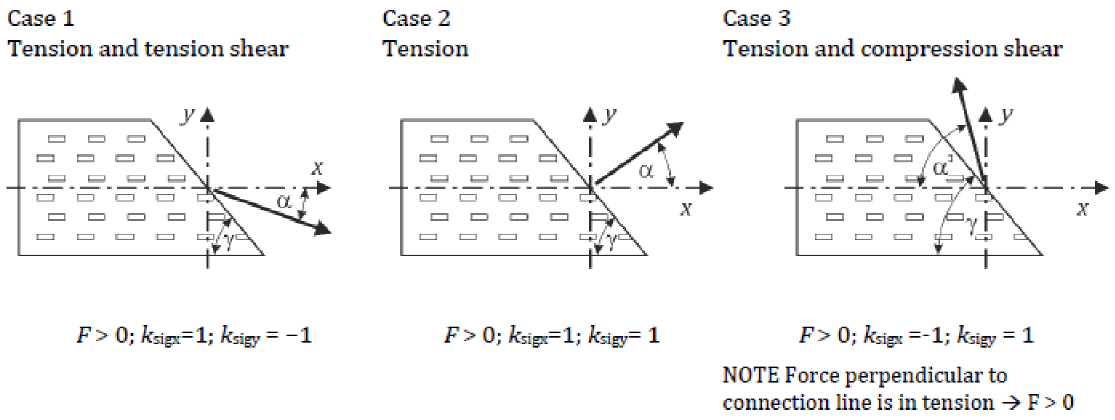
$$F_{x,Ed} = F_{E,d}\cos(\alpha) \pm 2F_{M,Ed}\sin(\gamma) \tag{257}$$

$$F_{y,Ed} = F_{E,d}\sin(\alpha) \pm 2F_{M,Ed}\cos(\gamma) \tag{258}$$

New Eurocode 5

$$\begin{aligned} F_{x1} &= k_{sigx}F_{E,d}\cos(\alpha) + 2F_{M,Ed}\sin(\gamma) \\ F_{y1} &= k_{sigy}F_{E,d}\sin(\alpha) + 2F_{M,Ed}\cos(\gamma) \end{aligned} \tag{259}$$

$$\begin{aligned} F_{x2} &= k_{sigx}F_{E,d}\cos(\alpha) - 2F_{M,Ed}\sin(\gamma) \\ F_{y2} &= k_{sigy}F_{E,d}\sin(\alpha) - 2F_{M,Ed}\cos(\gamma) \end{aligned} \tag{260}$$



Case 1
Tension and tension shear

$F > 0$; $k_{sigx}=1$; $k_{sigy} = -1$

Case 2
Tension

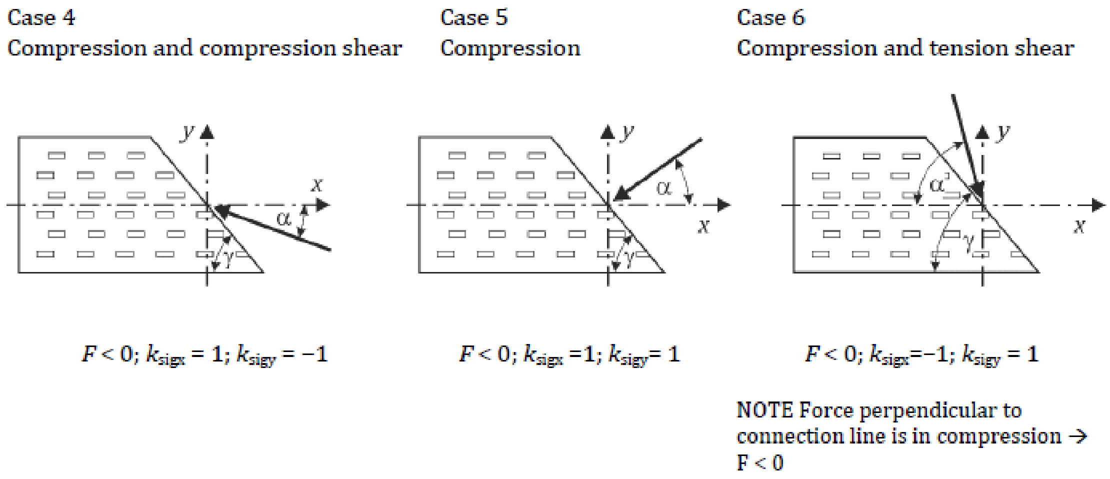
$F > 0$; $k_{sigx}=1$; $k_{sigy}= 1$

Case 3
Tension and compression shear

$F > 0$; $k_{sigx} =-1$; $k_{sigy} = 1$

NOTE Force perpendicular to connection line is in tension → F > 0

Figure 65: Values of k_{sigx} and k_{sigy} for connections under tension [1].



Case 4
Compression and compression shear

$F < 0$; $k_{sigx} = 1$; $k_{sigy} = -1$

Case 5
Compression

$F < 0$; $k_{sigx} = 1$; $k_{sigy} = 1$

Case 6
Compression and tension shear

$F < 0$; $k_{sigx} = -1$; $k_{sigy} = 1$

NOTE Force perpendicular to connection line is in compression → F < 0

Figure 66: Values of k_{sigx} and k_{sigy} for connections under compression [1].

The New Eurocode 5 and the Present Eurocode 5 provide expressions for the requirement to be satisfied for the verification of the plate capacity. The expression provided by the Present Eurocode 5 is without a square root and for the two main directions taken without separating the ends as given in Equation (*261*). The expressions given by the New Eurocode 5 are under square root and for the two main directions taken separately for both ends as presented in Equation (*262*).

$$\left(\frac{F_{x,Ed}}{F_{x,Rd}}\right)^2 + \left(\frac{F_{y,Ed}}{F_{y,Rd}}\right)^2 \leq 1 \tag{261}$$

$$\sqrt{\left(\frac{F_{x1,Ed}}{F_{x1,Rd}}\right)^2 + \left(\frac{F_{y1,Ed}}{F_{y1,Rd}}\right)^2} \leq 1 \qquad \sqrt{\left(\frac{F_{x2,Ed}}{F_{x2,Rd}}\right)^2 + \left(\frac{F_{y2,Ed}}{F_{y2,Rd}}\right)^2} \leq 1 \tag{262}$$

According to the New Eurocode 5 and the Present Eurocode 5, the plate capacities are obtained from the maximum of the characteristic capacities at sections parallel or perpendicular to the main axes. The characteristic plate capacities in the main axes are determined based upon the expressions given below.

Present Eurocode 5 and New Eurocode 5

$$F_{x,Rk} = \max\begin{cases} f_{n,p,0,k}\ l \sin\left(\gamma - \gamma_0 \sin\left(2\gamma\right)\right) \\ f_{v,p,0,k}\ l \cos\gamma \end{cases} \tag{263}$$

$$F_{y,Rk} = \max\begin{cases} f_{n,p,90,k}\ l \cos\gamma \\ k f_{v,p,90,k}\ l \sin\gamma \end{cases} \tag{264}$$

with

$$f_{n,p,0,k} = \begin{cases} f_{t,p,0,k} & \text{for } F_{x,Ed} > 0 \\ f_{c,p,0,k} & \text{for } F_{x,Ed} \leq 0 \end{cases} \tag{265}$$

$$f_{n,p,90,k} = \begin{cases} f_{t,p,90,k} & \text{for } F_{y,Ed} > 0 \\ f_{c,p,90,k} & \text{for } F_{y,Ed} \leq 0 \end{cases} \tag{266}$$

$$k = \begin{cases} 1 + k_v \sin(2\gamma) & \text{for } F_{x,Ed} > 0 \\ 1 & \text{for } F_{x,Ed} \leq 0 \end{cases} \tag{267}$$

11.9 Connection strength verification out-of-plane of timber assembly

The strength verification of a connection out-of-plane of timber assembly is not covered by the Present Eurocode 5. In the New Eurocode 5, the design withdrawal stress $\sigma_{w,d}$ on a single punched metal plate fastener must satisfy the requirement given by:

$$\sigma_{w,d} \leq f_{w,d} \tag{268}$$

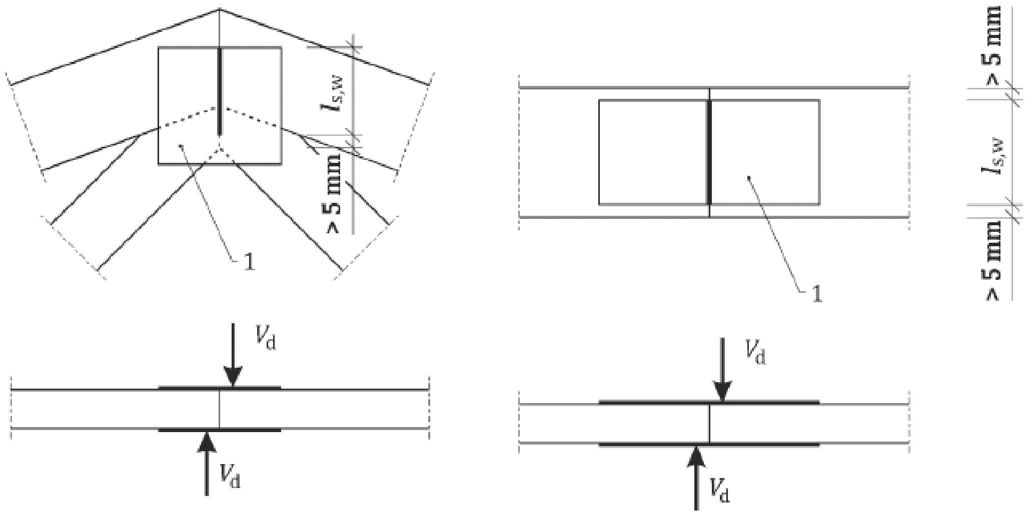
The design withdrawal stress $\sigma_{w,d}$ on a single punched metal plate fastener due to a shear force acting out-of-plane of timber assembly is determined by:

$$\sigma_{w,d} = \frac{v_d}{2l_{s,w}} \tag{269}$$

where

$l_{s,w}$ is the length of the punched metal plate fastener along the connection line reduced, where applicable, by an edge distance of 5 mm, see Figure 67

v_d is the shear force out of the plane of timber assembly, see Figure 67



a) Side and plan view of ridge joint

b) Side and plan view of splice joint

Figure 67: Out of plane shear force acting on ridge joint or chord splice joint [1].

The nomenclature used in the connections with punched metal fasteners (PMPF) in the New Eurocode 5 and the Present Eurocode 5 is provided in Table 87.

Table 87: Nomenclature used in the connections with punched metal fasteners (PMPF).

Present Eurocode 5	New Eurocode 5	Meaning
	k_{sys}	system strength factor
	k_{mod}	modification factor accounting for the effect of duration of load and moisture content
	R_k	characteristic load-carrying capacity of PMPF
	γ_M	partial factor for material properties of PMPF
	$F_{90,Rd}$	design splitting capacity, in N
	$F_{90,Rk}$	characteristic splitting capacity, in N
	k_G	fracture parameter, in N/mm$^{1.5}$
	k_{mat}	reduction factor accounting for distance of PMPF connection from either end of member or from an adjacent PMPF
	b	member thickness, in mm

	$b_{PMPF,0}$	width of PMPF parallel to grain, in mm
	ρ_k	characteristic timber density, in kg/m^3
	$\rho_{k,ref}$	reference characteristic timber density, in kg/m^3
	h_e	distance between the loaded timber edge and the most distant edge or corner of the PMPF, in mm
	h_{net}	loaded edge distance reduced by the allowed geometrical deviation due to misalignment, in mm
	$l_1, \quad l_2$	dimensions from member end to the intersection point of a perpendicular line passing through the plate's anchorage area centroid, see Figure 62
	l_{ref}	reference length with $l_{ref} = 500$ mm
	$f_{a,\alpha,\beta,k,ref}$	characteristic anchorage strength per plate for the reference characteristic density $\rho_{k,ref}$
	$f_{w,k,ref}$	characteristic withdrawal strength per width of connection line for the reference characteristic density $\rho_{k,ref}$
	$k_{SLS,ref}$	mean translational slip modulus per mm^2 for $\rho_{mean,ref}$, in N/mm^3
	ρ_{mean}	mean timbe density, in kg/m^3
	$\rho_{mean,ref}$	reference mean timbe density, in kg/m^3
	$k_{SLS,rot,ref}$	mean rotational slip modulus per mm^2 for $\rho_{mean,ref}$, in N/mm^3
	I_p	Polar moment of inertia of the plate effective anchorage area
$F_{A,Ed}$	$F_{A,Ed}$	design force acting on a single plate at the centroid of the effective area (i.e. half of the total force in the timber member), in N
$M_{A,Ed}$	$M_{A,Ed}$	design moment acting on a single plate on the centroid of the effective area, in Nmm
F_{Ed}	F_{Ed}	design force of the chord acting on a single plate (compression or zero), in N
M_{Ed}	M_{Ed}	design moment of the chord acting on a single plate, in Nmm

h	h	height of the member, in mm
	μ_t	modification factor for plate moment in tension splices
$f_{a,0,0,d}$	$f_{a,0,0,d}$	design anchorage strength per unit area of plate when the force is parallel to the x-direction and the grain direction
A_{ef}	A_{ef}	plate effective anchorage area, in mm^2
r	r	distance from the center of gravity of the effective plate area to the segmental plate area dA
W_p	W_{pl}	plastic rotation of section modulus
$f_{a,\alpha,\beta,d}$	$f_{a,\alpha,\beta,d}$	design anchorage strength per unit area of plate for angle α and angle β
$F_{M,Ed}$	$F_{M,Ed}$	design force from the moment on a single plate ($F_{M,Ed} = 2M_{Ed}/l$), in Nmm
	k_{sigx}	Sign as given in Figure 65 and Figure 66
	k_{sigy}	Sign as given in Figure 65 and Figure 66
	$F_{x1,Ed}$	design force acting in the x-direction at end 1
	$F_{y1,Ed}$	design force acting in the y-direction at end 1
	$F_{x2,Ed}$	design force acting in the x-direction at end 2
	$F_{y2,Ed}$	design force acting in the y-direction at end 2
	$F_{x1,Rd}$	design plate capacity in the x-direction at end 1
	$F_{y1,Rd}$	design plate capacity in the y-direction at end 1
	$F_{x2,Rd}$	design plate capacity in the x-direction at end 2
	$F_{y2,Rd}$	design plate capacity in the y-direction at end 2
$F_{x,Ed}$， $F_{y,Ed}$	$F_{x,Ed}$， $F_{y,Ed}$	design forces acting in x- and y-direction
$F_{x,Rd}$， $F_{y,Rd}$	$F_{x,Rd}$， $F_{y,Rd}$	design plate capacity in x- and y-direction
	$f_{w,d}$	design withdrawal strength per unit width of connection line

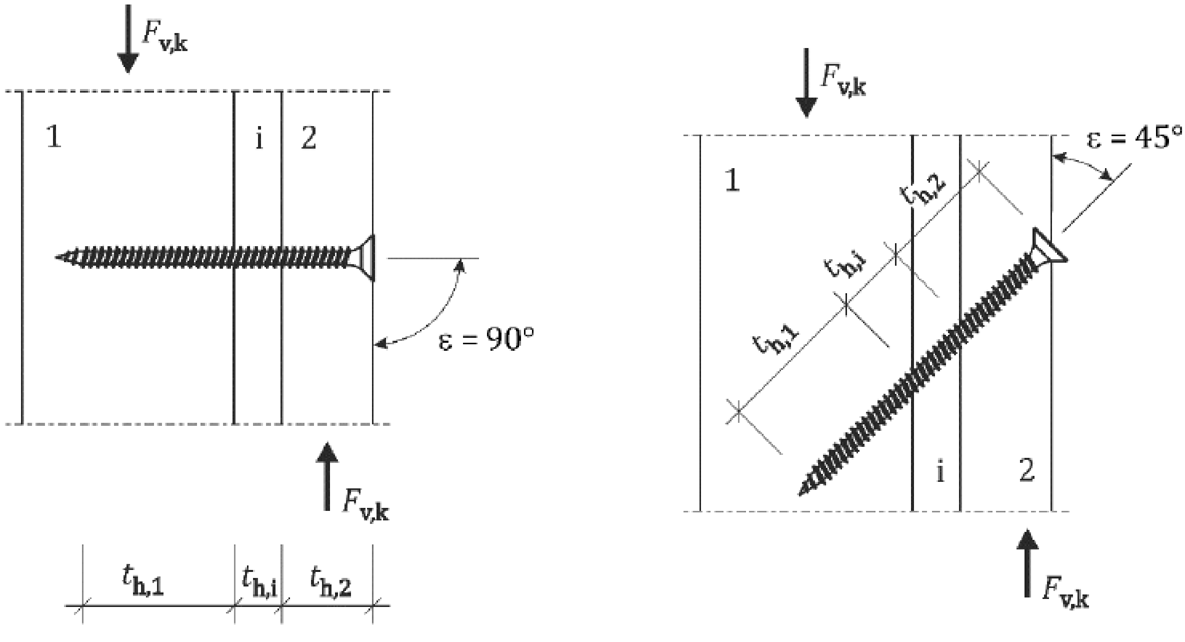
12 Connections with interlayers

Connections with interlayers are not covered by the Present Eurocode 5. In the New Eurocode 5, the topic of connections with interlayers is provided in the normative Annex S. In this thesis, the structure of Annex S is introduced without providing the review of the rules for connections with interlayers. The normative Annex S gives provisions for the connections with interlayers. Interlayer is a layer between two structural members in a connection. The structural member in a connection can be either timber or steel. In the Annex S, the connections with interlayers are distinguished into two sections, namely timber-to-timber and steel-to-timber connections. There are two subsections for each section of timber-to-timber and steel-to-timber connections. The first is when there is no connection between interlayer and timber, and the second is when there is connection between interlayer and timber.

When there is no connection between the interlayer and the timber member in the timber-to-timber connections, expressions for three failure modes (a), (b) and (c) are provided. The characteristic load-carrying resistance per shear plane per fastener is the minimum of the values of these three failure modes (a), (b) and (c).

Expressions for three failure modes (a), (b) and (c) are provided, when there is connection between the interlayer and the timber in the timber-to-timber connections. The characteristic load-carrying resistance per shear plane per fastener is the minimum of the values of these three failure modes (a), (b) and (c).

In timber-to-timber connections, when there is connection and no connection between interlayer and timber member, expressions for the mean slip modulus per fastener are given for screwed connections with ε = 90°, as shown in Figure 68(a), and for connections with fully threaded screws and ε = 45°, as depicted in Figure 68(b).



a) Screw normal to shear plane

b) Inclined screw regarding shear plane

Key:

$F_{v,k}$ is the characteristic load-carrying resistance per shear plane per fastener;

$t_{h,1}$ is the thickness of timber member 1;

$t_{h,2}$ is the thickness of timber member 2;

$t_{h,i}$ is the thickness of the interlayer i;

ε is the angle between the fastener axis and the grain direction.

Figure 68: Screwed timber-to-timber connection [1].

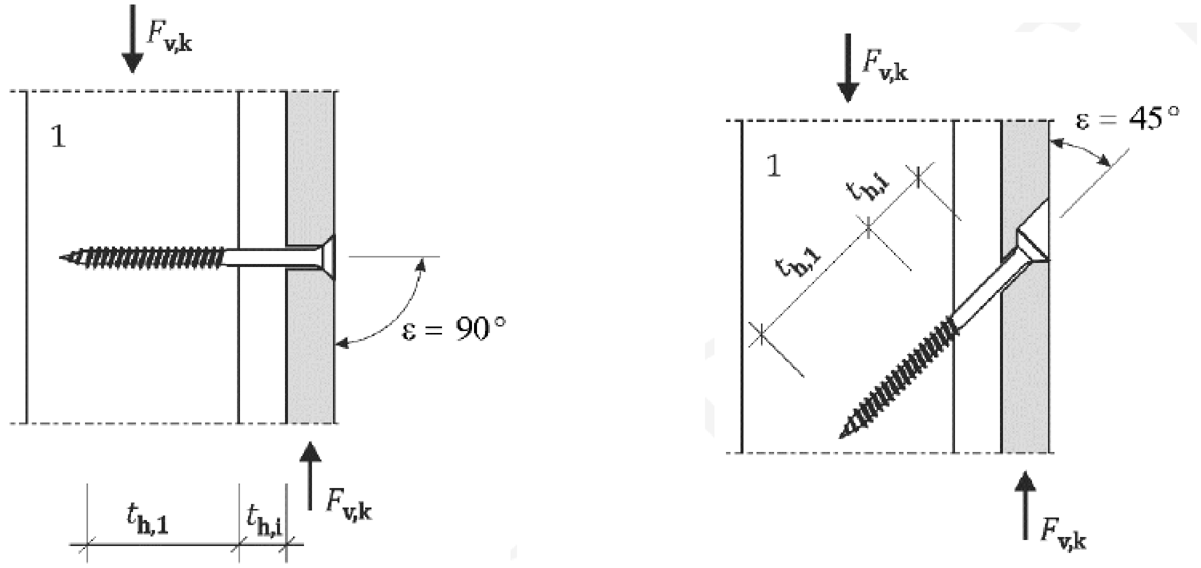
When there is no connection between the interlayer and the timber member in steel-to-timber connections with thick steel plates, expressions for three failure modes (a), (b) and (c) are provided. The characteristic load-carrying resistance per shear plane per fastener for joints with thick steel plates is the minimum of the values of these three failure modes (a), (b) and (c).

Expressions for two failure modes (a) and (b) are provided, when there is no connection between the interlayer and the timber in the steel-to-timber connections with thin steel plates. The characteristic load-carrying resistance per shear plane per fastener for joints with thin steel plates is the minimum of the values of these two failure modes (a) and (b).

When there is connection between the interlayer and the timber member in steel-to-timber connections with thick steel plates, expressions for three failure modes (a), (b) and (c) are provided. The characteristic load-carrying resistance per shear plane per fastener for joints with thick steel plates is the minimum of the values of these three failure modes (a), (b) and (c).

Expressions for two failure modes (a) and (b) are provided, when there is connection between the interlayer and the timber in the steel-to-timber connections with thin steel plates. The characteristic load-carrying resistance per shear plane per fastener for joints with thin steel plates is the minimum of the values of these two failure modes (a) and (b).

For screwed connections with $\varepsilon = 90°$, as depicted in Figure 69(a), and for connections with fully threaded screws and $\varepsilon = 45°$, as shown in Figure 69(b), expressions for the mean slip modulus per fastener are given when there is connection and no connection between interlayer and timber in steel-to-timber connections.



a) Screw normal to shear plane b) Inclined screw regarding shear plane

Key:

$F_{v,k}$ is the characteristic load-carrying resistance per shear plane per fastener;

$t_{h,1}$ is the thickness of timber member 1;

$t_{h,i}$ is the thickness of the interlayer i;

ε is the angle between the fastener axis and the grain direction.

Figure 69: Screwed steel-to-timber connection [1].

13 Conclusion

The main objective of this thesis is to review the design rules for connections in timber structures on the New Eurocode 5 and compare them to the Present Eurocode 5. The thesis explores and highlights the changes or differences between the design rules for connections in timber structures on the New Eurocode 5 and the Present Eurocode 5. The main differences or changes found are the following:

- For the determination of the characteristic value of the dowel-effect contribution of a fastener, the New Eurocode 5 provides the same set of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is treated as a member in steel-to-timber connections. The Present Eurocode 5 provides different sets of failure modes for timber-to-timber and steel-to-timber connections and the steel plate is not treated as a member in steel-to-timber connections. For connections with more than two shear planes, four compatible failure mode combinations (A), (B), (C) and (D) are given by the New Eurocode 5, but the compatibility between the failure modes must be checked by the designer according to the Present Eurocode 5.

- In the New Eurocode 5, the design splitting resistance of a connection with fasteners loaded perpendicular to the grain must be equal to the sum the values of the two shear forces on the sides of the connection and does not depend on the position of the connection along the beam length. In the Present Eurocode 5, it must be equal to or greater than the maximum of the shear force values on the sides of the connection and depends on the position of the connection along the beam length.

- When determining the characteristic withdrawal capacity of connections with axially loaded screws and rods with wood screw thread, the range of diameters and ratio of inner thread diameter to outer thread diameter are changed from 6 mm $\leq d \leq$ 12 mm and $0.6 \leq d_1/d \leq 0.75$ in the Present Eurocode 5 to 3.5 mm $\leq d \leq$ 22 mm and $0.55 \leq d_1/d \leq 0.76$ in the New Eurocode 5 respectively. Furthermore, the requirement for the minimum withdrawal length is changed from $6d$ in the Present Eurocode 5 to $5d$ in the New Eurocode 5.

- The compression (buckling) resistance of a connection with axially loaded screws and rods with wood screw thread is included in the New Eurocode 5, but it is not covered by the Present Eurocode 5.

- For laterally loaded metal dowel-type fasteners and shear connectors, the expressions provided by the New Eurocode 5 for determining the minimum values of spacing and end and edge distances do not include the load to grain angle α, but the load to grain angle α is included in the Present Eurocode 5.

- When determining the withdrawal and head pull-through capacities of connections with axially loaded screws and rods with wood screw thread, a withdrawal length of $l_w \leq 20d$ must be used for small angles $0° \leq \varepsilon \leq 30°$ according to the New Eurocode 5. The angle between the fastener axis and the grain direction α cannot be lower than 30 degrees ($\alpha \geq 30°$) according to the Present Eurocode 5.

- The New Eurocode 5 gives provision for the brittle failure mode of connections with fasteners loaded parallel to the grain. The Present Eurocode 5 does not include this explicitly and it only considers the block shear and plug shear failures in its informative Annex A directly.

- The expressions provided by the New Eurocode 5 for the determination of the resistances of the block shear and plug shear failures are for both timber-to-timber and steel-to-timber connections, but the expression provided by the Present Eurocode 5 is for steel-to-timber connections only.

- For axially loaded screws and rods with wood screw thread, the New Eurocode 5 provides the minimum values of spacing and end and edge distances for screws with inner diameter d_1 less than or equal to 6 mm ($d_1 \leq 6$ mm) and not predrilled members, and for screws with inner diameter d_1 greater than 6 mm ($d_1 > 6$ mm) and predrilled members. The Present Eurocode 5 provides the minimum values without distinguishing between the predrilled and not predrilled members and between the size of screws.

- The withdrawal, head pull-through and tensile resistances of a connection with axially loaded screws and rods with wood screw thread are based on the actual number of fasteners acting together in the connection in the New Eurocode 5 and on the effective number of fasteners in the connection in the Present Eurocode 5.

- The provision given by the New Eurocode 5 in its normative Annex P for connections with punched metal plate fasteners (PMPF) is more detailed and includes more expressions and illustrative figures than the provision given by the Present Eurocode 5.

- Expression for the determination of the characteristic tensile resistance of bolts and nails are provided by the New Eurocode 5 from EN 1993-1-8:2005. The Present Eurocode 5 only mentions the characteristic tensile resistance of bolts without providing additional information but does not cover for nails.

- The structure of the chapter of connections in the New Eurocode 5 is changed to ease the navigation through the chapter. For example, the characteristic embedment strengths of the metal dowel-type fasteners are gathered and provided in a table and the spacing, edge and end distances of the metal dowel-type fasteners and connectors are collected and provided in a new subsection.

- The axial slip modulus of connections with fasteners loaded in their axial direction and the effective slip modulus of a connection with a combined axial and lateral loading of the fasteners are included in the New Eurocode 5. The Present Eurocode 5 does not include any of them.

- Bonded-in rods and connections with interlayers, which is provided in the normative Annex S, are covered by the New Eurocode 5, but they are not covered by the Present Eurocode 5.

- The split-ring and shear plate connectors in a connection in an end grain of members is covered by the New Eurocode 5, but this is not covered by the Present Eurocode 5.

- The New Eurocode 5 does not cover the withdrawal capacity of axially loaded bolts, but the Present Eurocode 5 does.

13.1 Further work

Some of the topics under the chapter of connections in the New Eurocode 5 are not covered in this thesis. Further work that would be relevant to be done are:

- Compare experimental results and/or worked examples to the results or predictions obtained by using the rules for bonded-in rods, shear connectors, punched metal plate fasteners and connections with interlayers on the New Eurocode 5.

- Reviewing and exploring of the design rules for reinforced connections and carpentry connections provided by the New Eurocode 5.

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