COST Action FP1101
Assessment, Reinforcement and Monitoring of Timber Structures

Short Scientific Mission Report
STSM-FP1101-071014-049676

By
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This report cover research activities carried out during a stay
From 07/10/2014 to 16/10/2014
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Eindhoven, Netherland

Purpose of the STSM

The objective of the STSM was to produce an overview of all accessible information on design rules for carpenter joints available in EC5, in national NCCI documents and in previous National codes of the countries who have participated in the development of EC5. This information should then be discussed mainly based on assumed and observed failure modes.

Description of the work carried out

As a first step we asked a lot of the experts in Europe if they could send us information on earlier and existing design rules for their country on carpentry joints. The answer from these experts resulted in copies of parts of 9 standards, [1-9] in addition to Eurocode 5, [10]. We also received a lot of articles within the subject from the same experts. Literature search completed the document quantity with both articles and textbooks.

The work started with making an overview of the most commonly described carpentry joints in the reviewed literature. We limited the work to joints carrying loads in plane structures. Then we focused on yield and failure criteria used in the standards to describe the strength of the joints. The last subject was the design rules for the geometry of joints.

The collected literature was too large to review all of it properly within a ten days research project, but ten days STSM in Eindhoven was a good start. The purpose of the STSM is fulfilled, and the literature will be basis for further research.

Acknowledgements

I would like to thank the COST Action FP1101 for supporting this STSM. The stay in Eindhoven wouldn’t be possible without this support.

Andre Jorissen has been a perfect discussion partner and host. I hope it is possible to carry out further joint activities with him concerning the same or related topics. I also want to thank his college Ad Leijten and the TU/e for a pleasant stay in Eindhoven.

And last but not least; thanks to all the colleagues who helped us with collecting literature.

Carpentry Joints

Jan Siem and André Jorissen

Introduction

Eurocode 5 does not give distinct design rules on so called Carpentry joints. The code covers the basis for designing joints, such as material parameters and stress criteria, but not capacity rules, construction rules, failure modes and so on.

When evaluating existing structures with carpentry joints it is important to understand the logic in the load path within the joint, the most important failure modes and the consequence of humidity changes.

CNC machines have made it possible to produce carpentry joints with new technology where, as a consequence of the new production method, the design will be slightly different from traditional carpentry joints.

To facilitate the evaluation and design of carpentry joints we wanted to get an overview of typical carpentry joints for structural purposes. We then wanted to look into previous design standards, for the different countries, to find out which types of joints there had been or are design rules for. If possible we also wanted to find the basis of these design rules.

Research method

As a first step we asked a lot of the experts in Europe if they could send us information on earlier and existing design rules for their country on carpentry joints. The answer from these experts resulted in copies of parts of 9 standards, [1-9] in addition to Eurocode 5, [10]. We also received a lot of articles within the subject from the same experts. Literature search completed the document quantity with both articles and textbooks.

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Overview of some carpentry joints

Within Cost action FP1101 a state of the art article on analysing and strengthening of carpentry joints has been carried out, [11]. A lot of textbooks are showing the geometry of carpentry joints, explaining how to build them or explaining how to calculate them. We looked into some of the books, [12-31], and as a starting point we made an overview of the most common carpentry joints in these books. We limited the review to joints transferring loads in a plane structure. We chose to classify the joints by geometry and by the global forces acting on them as shown in Figure 1. The matrix was inspired by [17].

All the joints are given a code with two numbers and a letter. The two numbers explain the position in the matrix and thus the geometry and global forces acting on them, and the letter states the alternative joint.

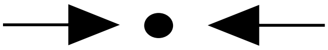
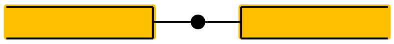
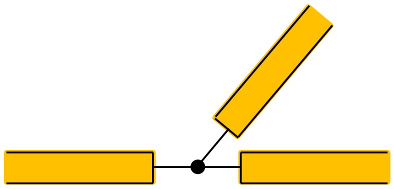
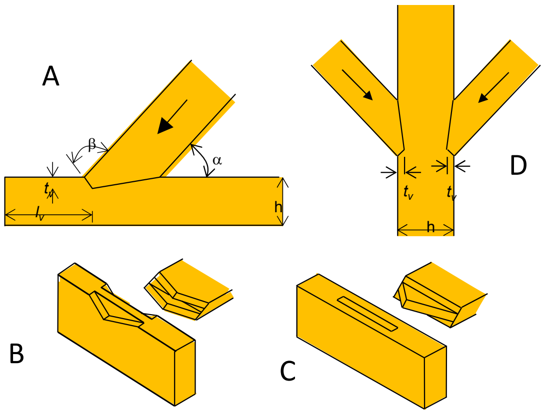
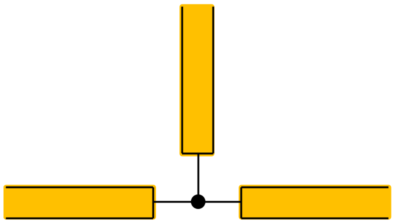
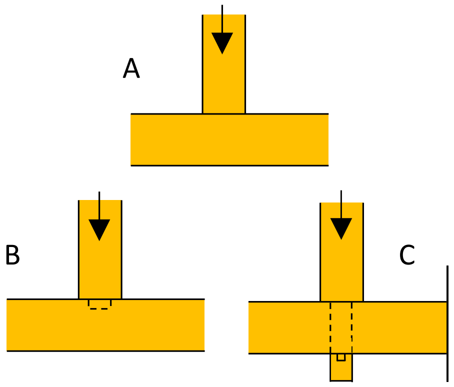
Global forces Geometry	
	1.1 
	1.2 
	1.3 

Figure 1 Most common carpentry joints in plane structures – left side

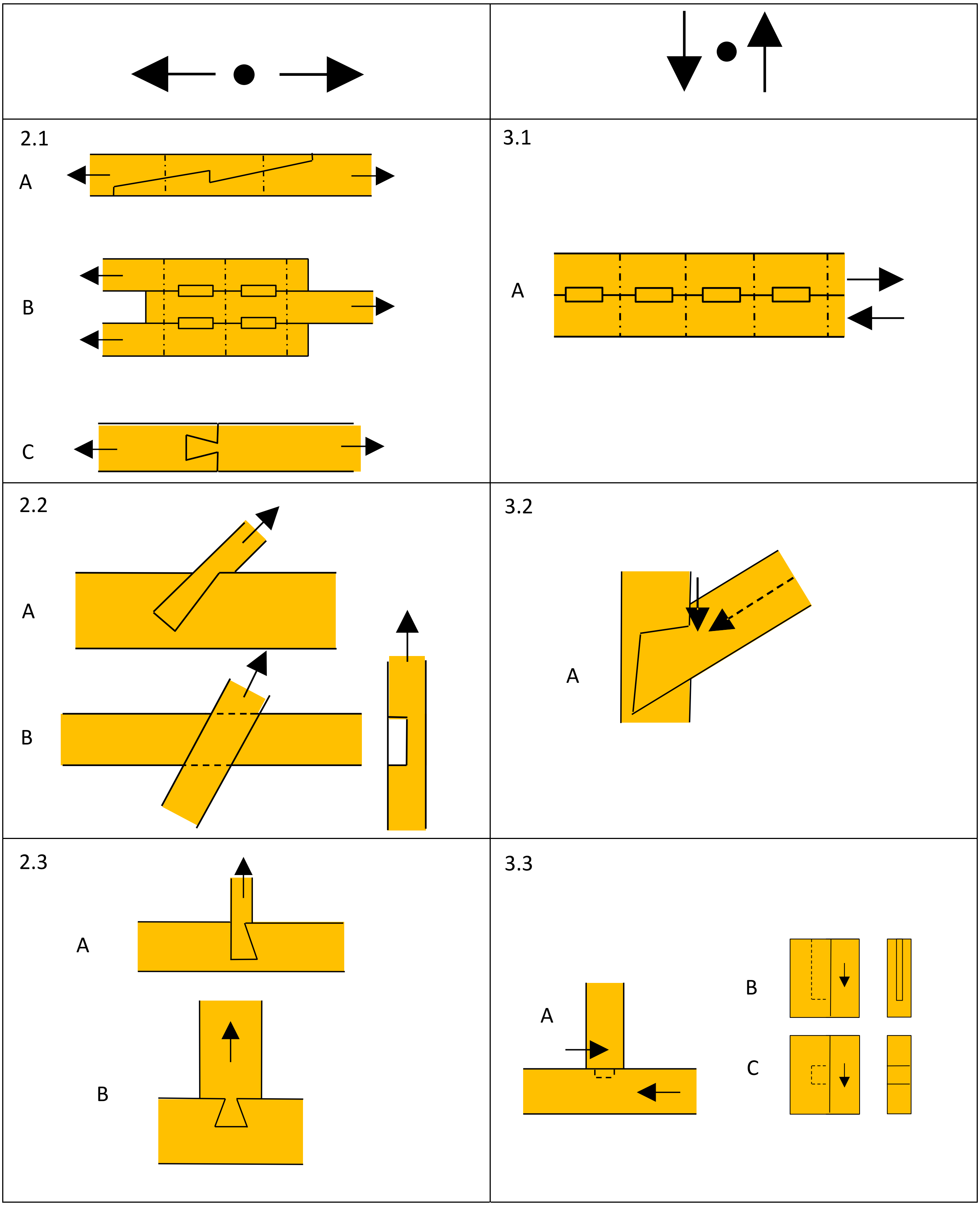


Figure 1 Most common carpentry joints in plane structures – right side

The most common joints in the literature are the step joint 1.2.A, the scarf joint 2.1.A, the dovetail joint 2.2.A, the half lap joint 2.2.B and the tenon and mortise joint 1.2.C or 3.3.A. In the literature a lot of different names were used. As example all the different names we found for the single step joint are referred in 1.2.A. For the other joints, just the most common English names are used.

1.1.A. In the reviewed literature, we didn’t find joints along compression elements. In theory the shown joint can be calculated by [10], but the design doesn't prevent buckling. With low compression forces some of the scarf joints designed to withstand bending can be used (2.1.A).

1.2.A. This is the most important carpentry connection in the literature, it is present in all the standards we have reviewed and in a lot of the literature. It is used with different names: Versätz (D)[1,2], Versats (D) [12, 20], Stirnversatz (D) [19, 25, 26], Tandverbinding (NL) [4, 5, 6], Forsats (N) [7], Versatz (Ch) [8], Unione a dente singolo (I) [9], Notched joint (GB) [11], Single step joint (GB) [16,24], Cogging joint (GB)[14], Framed joint with notch(GB)[14], Framed connection with a notch (GB) [3], Oblique dado (GB) [27], Embrèvement simple (F)[17], Embrèvement avant (F)[26], Forsats (DK)[18]. The joint is discussed later in this paper together with two sided step joint, double step joints, heal step joints and heal joint. To prevent transverse displacements in the joint, bolts are used or the joint is designed as 1.2.B/C.

1.2.B Bridle joint (GB) [21]

1.2.C Oblique tenon joint (GB) [21]

1.3.A Compression transverse fibre direction. To secure the joint against transverse deformation, it can be combined with a mortise and tenon joint, 1.3.B. If the joint may also have tension, a design with a key like 2.3.C can be added, 1.3.C.

2.1.A Scarf joint (GB)[11]. There are a lot of different geometries in the literature for example in [13, 26]

2.2.A Dovetail (GB) [11], Examples in [21,26]

2.3.A Dovetail (GB) [11], Examples in [26]

3.1.A Dowel joint, [7,18]

3.2.A Dovetail (GB) [11], Examples in [21,26]

3.3.A Mortise and tenon joints (GB) [11], 24 geometries in [13], and some in [15, 16],

Strength of joints

General

As mentioned, the most important load transferring carpentry joint in the reviewed literature was the single step joint, Figure 2. As can be seen in the figure, the stress situation is complex; stresses occur in the fibre direction, perpendicular to the fibre direction, with an angle to the fibre direction and shear stresses. As the first discussion we want to look at the stress criteria used in Eurocode and discuss them.

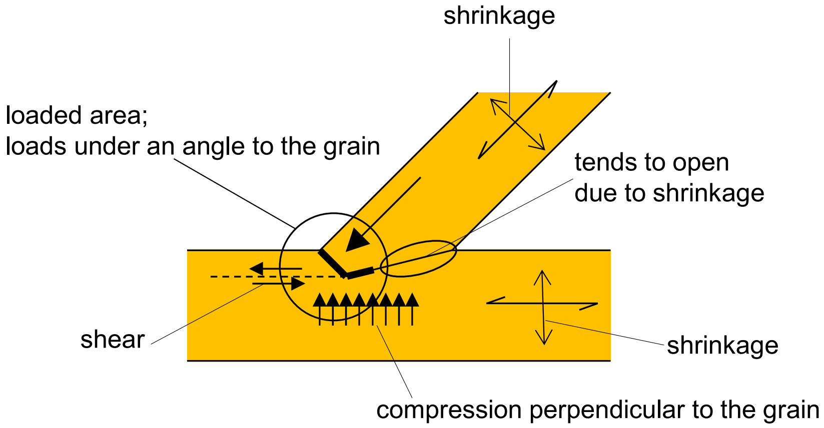


Figure 2 Single step joint.

Yield and failure criteria

When materials are loaded and obtain complex stress situations, yield or failure criteria can be used to mathematically describe the situation. Yield criteria is used if the material is ductile and failure criteria if the material is brittle. When the loads are transferred under an angle to the grain, such a complex stress situation occurs. In the next pages we sum up and discuss some of the background for some criteria often used for wood.

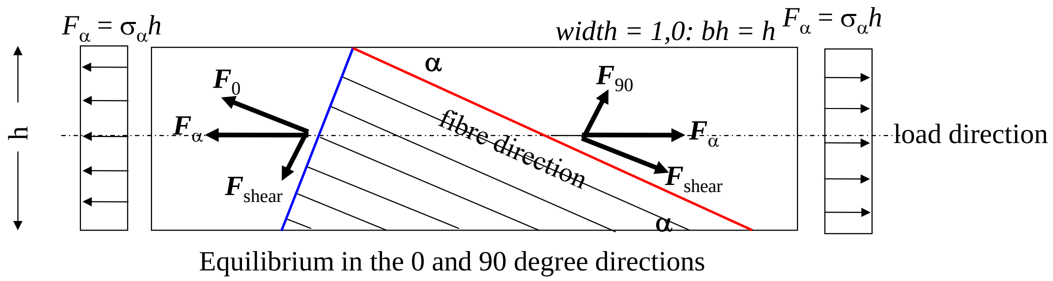
The strength of timber loaded under an angle to the grain was first described by Hankinson in 1921, expressed by equation (1), [32].

$$f_{\propto} = \frac{f_0 f_{90}}{f_0 sin^n(\propto) + f_{90} cos^n(\propto)} \tag{1}$$

In this equation f_0 and f_{90} are strength values parallel (0 degrees) and perpendicular (90 degrees) to the grain respectively. f_α is the stress value for loading under an angle α to the grain, and n is the exponent. Hankinson used n =2 in [32]. As shown by equation (1) the shear strength is not included by Hankinson.

In [33], Kollmann assert that n-values between 1.5 and 2 in equation (1) are satisfactory to describe tension and that 2.5 may be chosen for compression.

Figure 3, [34], shows a piece of wood loaded with a force F_α with an angle to the grain. The piece has the height h. The figure shows the decomposed forces in the fibre direction and perpendicular to the fibre direction and the equilibrium considerations. The new symbol σ is normal stresses caused by forces, and τ is shear stresses. As the figure shows, the stress with an angle to the fibre can be expressed by the stress in fibre direction, perpendicular to the fibre direction and shear.



$$F_\alpha = \sigma_\alpha h$$
$$F_{90} = \sigma_{90}\frac{h}{\sin(\alpha)}$$
$$F_{90} = F_\alpha \sin(\alpha)$$
$$\sigma_{90}\frac{h}{\sin(\alpha)} = \sigma_\alpha h \sin(\alpha)$$
$$\sigma_\alpha = \frac{\sigma_{90}}{\sin^2(\alpha)} \le \frac{f_{90}}{\sin^2(\alpha)}$$

$$F_\alpha = \sigma_\alpha h$$
$$F_{shear} = \tau\frac{h}{\sin(\alpha)}$$
$$F_{shear} = F_\alpha \cos(\alpha)$$
$$\tau\frac{h}{\sin(\alpha)} = \sigma_\alpha h \cos(\alpha)$$
$$\sigma_\alpha = \frac{\tau(\le f_v)}{\sin(\alpha)\cos(\alpha)}$$

$$F_\alpha = \sigma_\alpha h$$
$$F_0 = \sigma_0\frac{h}{\cos(\alpha)}$$
$$F_0 = F_\alpha \cos(\alpha)$$
$$\sigma_0\frac{h}{\cos(\alpha)} = \sigma_\alpha h \cos(\alpha)$$
$$\sigma_\alpha = \frac{\sigma_0}{\cos^2(\alpha)} \le \frac{f_0}{\cos^2(\alpha)}$$

$$F_\alpha = \sigma_\alpha h$$
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$$F_{shear} = F_\alpha \sin(\alpha)$$
$$\tau\frac{h}{\cos(\alpha)} = \sigma_\alpha h \sin(\alpha)$$
$$\sigma_\alpha = \frac{\tau(\le f_v)}{\sin(\alpha)\cos(\alpha)}$$

Figure 3 Equilibrium equations of a timber element loaded under an angle to the grain, [34].

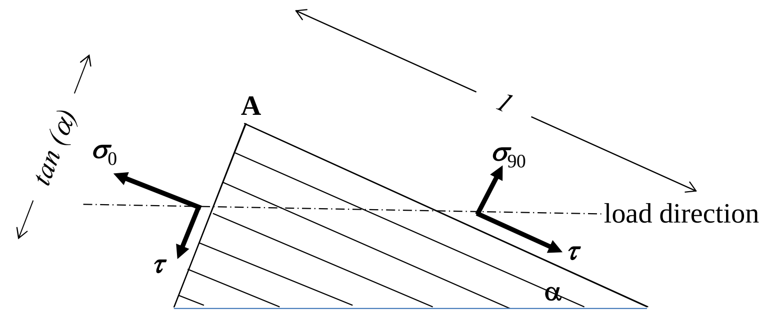
Norris, [35], evaluated the stresses under an angle to the grain in 1962 using Equation (2). In the equation σ_v has the same meaning as τ. The index v means shear.

$$\left(\frac{\sigma_0}{f_0}\right)^2 + \left(\frac{\sigma_v}{f_v}\right)^2 + \left(\frac{\sigma_{90}}{f_{90}}\right)^2 \le 1{,}0 \tag{2}$$

Figure 4, [34], is based on Figure 3 and expresses stresses and equilibrium equations. As shown Equation (3) and Equation (4) can be derived. When these are substituted into (2), Equation (5) can be expressed.

$$\sigma_v = \sigma_0 \tan\alpha \tag{3}$$

$$\sigma_{90} = \sigma_0 tan^2\alpha \tag{4}$$



$$(1)\quad \sum \text{parallel} = 0 \quad \sigma_0 \tan(\alpha) = \tau$$

$$(2)\quad \sum \text{perpendicular} = 0 \quad \sigma_{90} = \tau \tan(\alpha)$$

$$\text{From (1) and (2) it follows that } \sigma_{90} = \sigma_0 \tan^2(\alpha)$$

$$(3)\quad \sum M_A = 0 \quad \frac{1}{2}\sigma_{90} - \frac{1}{2}\sigma_0 \tan^2(\alpha) = 0 \text{ of course also results in } \sigma_{90} = \sigma_0 \tan^2(\alpha)$$

Figure 4 Equilibrium in a piece of wood loaded under an angle to the grain.

$$\sigma_0 \leq \frac{f_0}{\sqrt{1 + \left(\frac{f_0}{f_v}\right)^2 tan^2\alpha + \left(\frac{f_0}{f_{90}}\right)^2 tan^4\alpha}} \tag{5}$$

If the load direction has an angle α to the grain direction, Equation (6) can be derived. Substituted into Equation (5), Equation (7) and Equation (8) can be expressed.

$$\sigma_0 = \sigma_\alpha cos^2\alpha \tag{6}$$

$$\sigma_\alpha \leq \frac{f_0}{cos^2\alpha \sqrt{1 + \left(\frac{f_0}{f_v}\right)^2 tan^2\alpha + \left(\frac{f_0}{f_{90}}\right)^2 tan^4\alpha}} \tag{7}$$

$$\sigma_\alpha \leq \frac{f_0}{\sqrt{cos^4\alpha + \left(\frac{f_0}{f_v}\right)^2 sin^2\alpha \cdot cos^2\alpha + \left(\frac{f_0}{f_{90}}\right)^2 sin^4\alpha}} \tag{8}$$

Both Hankinson, the empirical equation (1), and Norris, equation (2), are together with the equilibrium equations shown in Figure 3, plotted in Figure 5 by Jorissen, [34]. When comparing the different equations, Jorissen chose the exponent n = 1.5 to express tension and n=2 to express compression in Hankinson's equation (1). The motivation for choosing n=2 is that this is the exponent used by Eurocode, as will be discussed later. As can be seen, the tension strength is lower than the compression strength for the same angle to the grain. Norris equation leads to slightly lower strength values than Hankinson. The equilibrium equations derived in Figure 3 shows generally a lot higher strength values compared to Hankinson. The use of Hankinson and Norris in Eurocode will be discussed later.

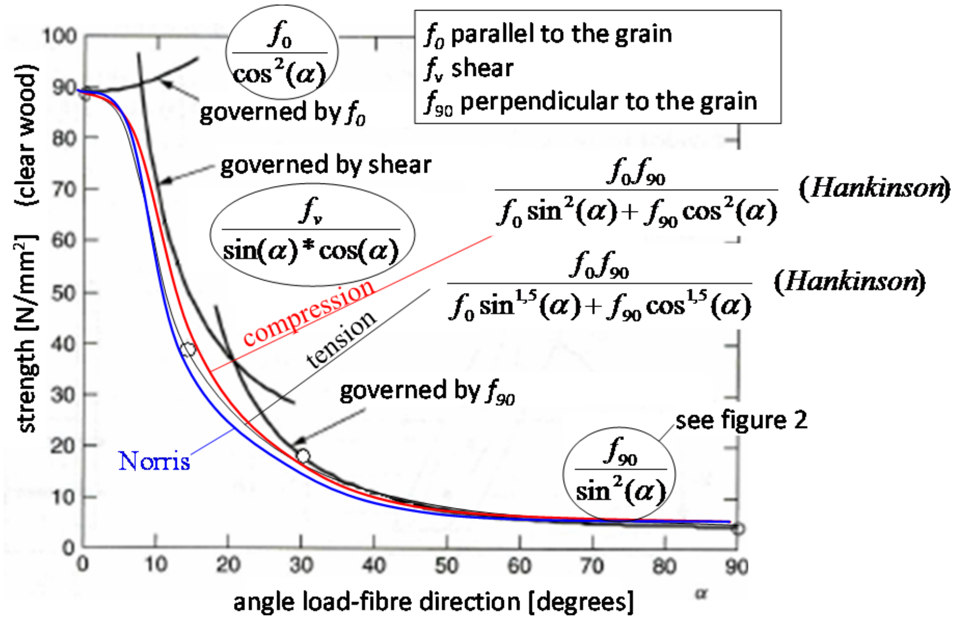


Figure 5 Comparison between Hankinson, Equation (1) and Norris, Equation (3), [34].

Eurocode 5

In Cost FP1101 a state of the art report on Carpentry Joints, [11] describes important groups of carpentry joints. As pointed out in the report, Eurocode 5 does not have specific design rules for carpentry joints. Eurocode 5 has general design rules for stresses in one principal direction, for compression under an angle to the grain (Hankinson) and for a combination of stresses parallel to the grain (both tension and compression), perpendicular to the grain (both tension and compression) and shear (Norris).

Regarding Hankinson, Equation (1) is slightly modified into Equation (9).

$$\sigma_{c,\propto,d} \le \frac{f_{c,0,d}}{\frac{f_{c,0,d}}{k_{c,90} f_{c,90,d}} sin^2(\propto) + cos^2(\propto)} \tag{9}$$

In which $f_{c,0,d}$ and $f_{c,90,d}$ are design compressive stress values parallel and perpendicular to the grain respectively.

The factor $k_{c,90}$ is a factor depending on geometry which takes the spreading of the stresses perpendicular to the grain into the timber into account. Since design rules for carpentry connections are not defined in Eurocode 5, $k_{c,90}$ is not defined for this type of connections either and should be $k_{c,90}$= 1,0. Then Equation (9) gives the same result as Equation (1). Other symbols used in Equation (8) are explained in Figure 5.

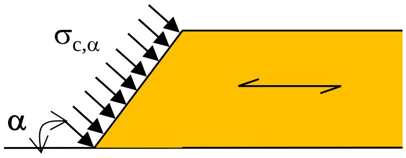


Figure 6 Symbols used in Equation (8).

Eurocode 5 also defines a slightly modified Equation (5), Norris, which in this standard is only defined for non-prismatic timber elements (e.g. tapered beams); see Equation (10) and Figure 7, in which $\sigma_{m,\alpha,d}$, a stress parallel to the grain, is defined.

$$\sigma_{0,d} = \sigma_{m,\alpha,d} \leq \frac{f_{m,d}}{\sqrt{1 + \left(\frac{f_{m,d}}{k f_{v,d}}\right)^2 tan^2\alpha + \left(\frac{f_{m,d}}{f_{90,d}}\right)^2 tan^4\alpha}} \tag{10}$$

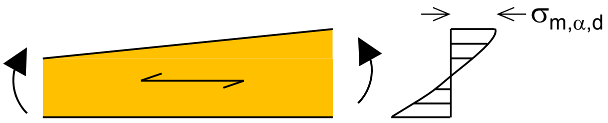


Figure 7 Non prismatic timber beam.

For $f_{90,d}$, being the design value for compression perpendicular to the grain, Eurocode 5 defines k = 1,5.

German National Annex to Eurocode 5

Regarding the step joint, the German National Annex to Eurocode 5 defines a connection as shown in Figure 8.

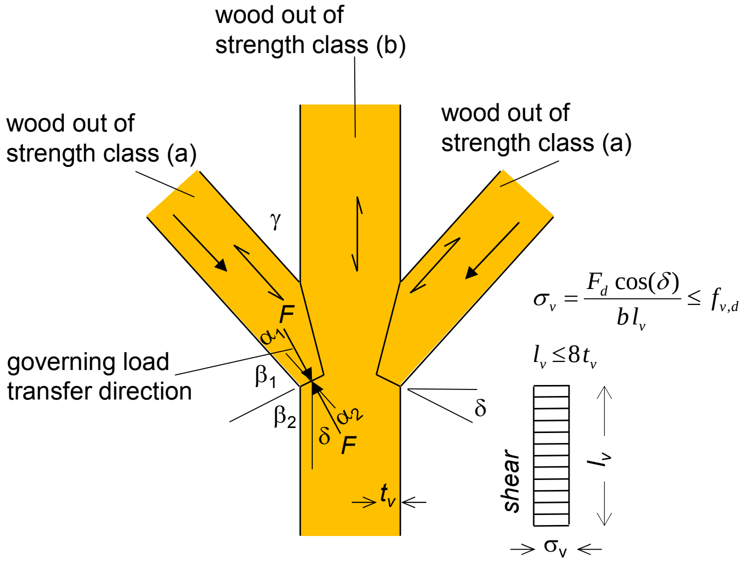


Figure 8 Two-sided step joint.

The design rule given in the German National Annex to Eurocode 5 is given by Equation (11).

$$\sigma_{c,\alpha,d} = \frac{F_{c,\alpha,Ed}}{A} \leq \frac{f_{c,0,d}}{\sqrt{\cos^4\alpha + \left(\frac{f_{c,0,d}}{2 \cdot f_{v,d}}\right)^2 \sin^2\alpha \cdot \cos^2\alpha + \left(\frac{f_{c,0,d}}{2 \cdot f_{c,90,d}}\right)^2 \sin^4\alpha}} \qquad (11)$$

The National Annex does not clearly describe the determination of the cross section A and the load $F_{c,\alpha,d}$. Compared to Equation (8), the design stress values for shear and compression perpendicular to the grain are multiplied by 2. The equation is clearly based on Norris.

Norris Equation (11) is compared with Hankinson's Equation (9) in Figure 9. As can be seen Norris results in lower capacity values.

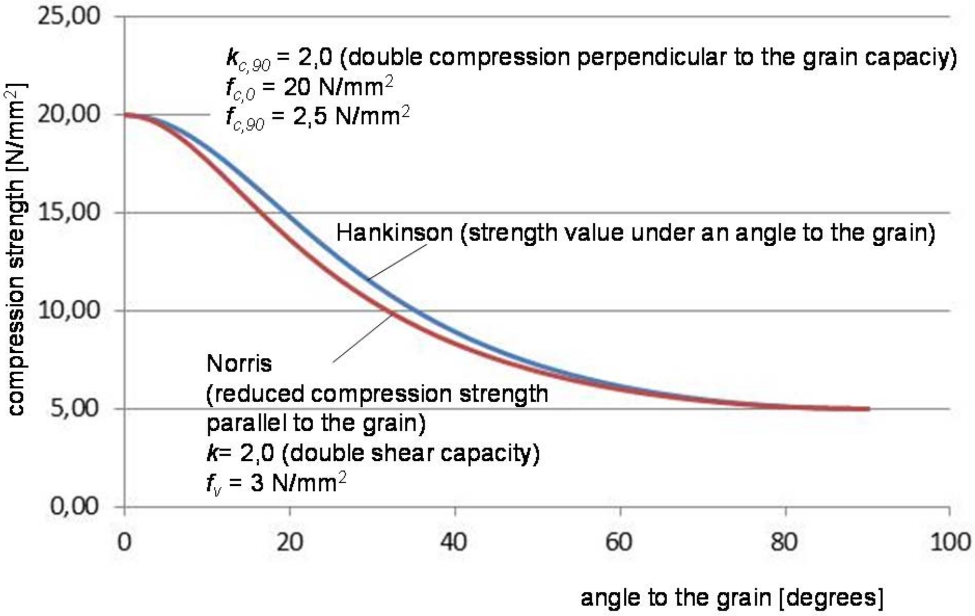


Figure 9: Comparison between Hankinson (equation (9)) and Norris (equation 11)).

Dutch National Annex to Eurocode 5

For the Dutch National Annex to Eurocode 5 a simple, straight forward approach is chosen based on design rules in previous national standards.

Given that the geometrical requirements discussed later are satisfied, the design rules are expressed by Equations (12), (13) and (14), illustrated by the single step joint of Figure 10.

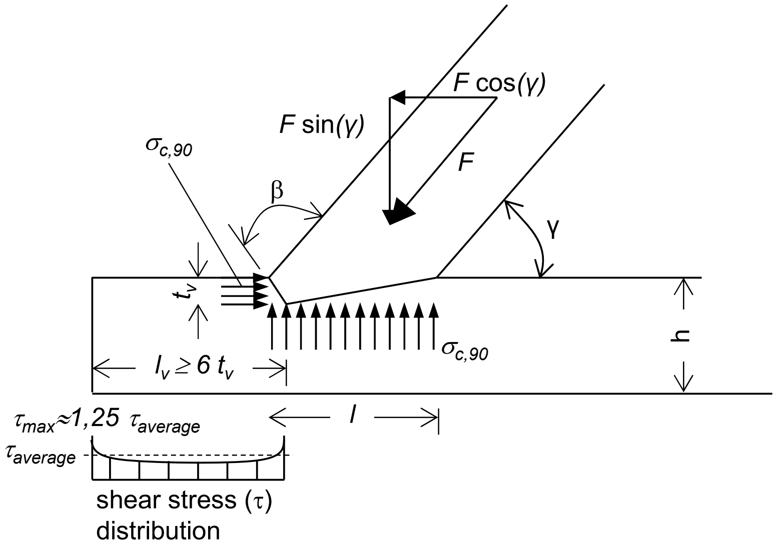


Figure 10 Background for the design rules in the Dutch National Annex to Eurocode 5.

Equation (12) and Equation (13) assume the compressive stresses are equally distributed across the vertical and horizontal projections of the contact surfaces as illustrated in Figure 10. The equations do not take into account the reduced strength in the contact surface, between the components, due to the angle between the force and the fibre direction.

$$\frac{F_d \cos\gamma}{bt} \leq f_{c,0,d} \tag{12}$$

$$\frac{F_d \sin\gamma}{bl} \leq f_{c,90,d} \tag{13}$$

For shear, Equation (14), a reduction is assumed.

$$\frac{F_d \cos\gamma}{bl_v} \leq 0{,}8 f_{v,d} \tag{14}$$

4.2 Swiss Standard Scia 265 [8]

The Swiss standard takes into account the fibre direction and uses a slightly modified version of Hankinson, Equation (1). The modification is also slightly different from the version in Eurocode, Equation (9). The Swiss version is shown as Equation (15)

$$f_{c,\propto,d} = \frac{0{,}8 f_{c,0,d}}{\frac{0{,}8 f_{c,0,d}}{f_{c,90,d}} sin^2(\propto) + cos^2(\propto)} \tag{15}$$

For single step joint the value $\alpha = 0.5\gamma$ can be used in Equation (16) when the design stresses in the fibre direction are checked.

$$\frac{F_d \cos\gamma}{bt} \leq f_{c,\alpha,d} \tag{16}$$

For shear, Equation (17), a reduction is assumed. For Brettschichtholz K = 0.8, and for solid wood k = 0.6

$$\frac{F_d \cos\gamma}{bl_v} \leq k f_{v,d} \tag{17}$$

Geometry of Joints

Single Step joint

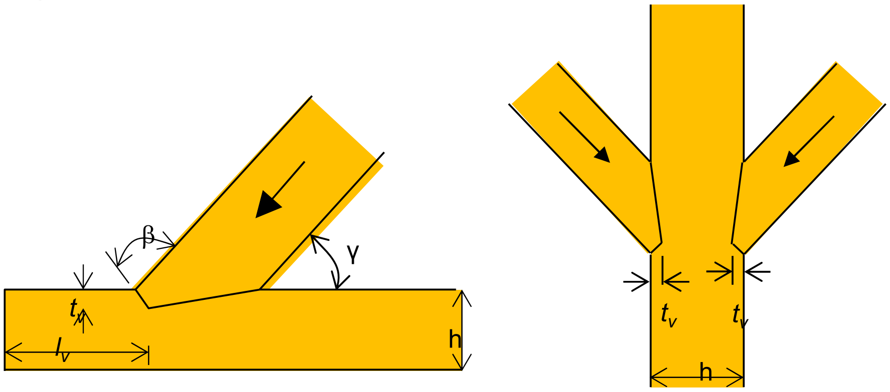


Figure 11 a) Single Step joint, b) Two-sided single step joints

The most important parameters characterising the geometry of the step joint are; γ – the angle between the strut and the cord, t_v – the depth of the notch in the cord, β – the angle between the front notch and the centre line of the strut and l_v – the length from the bottom of the notch to the end of the cord.

In all the standards, there is a relation between the maximum notch depth and the angle γ as shown in Figure 12.

	Germany, Switzerland and Italy [1,2,8,9]			Netherlands [3,4,5,6]		Norway [7]		
γ	≤50	50≥ γ ≤60	≥60	≤50	≥50	≤45	45≥ γ ≤60	≥60
t_v	≤ h/4	Interpolation	≤ h/6	≤ h/4	≤ h/5	≤ h/4	≤ h/5	≤ h/6

Figure 12 Relations between the angle γ and t_v (indicated in figure 10)

For two-sided single step joints, $t_v \leq h/6$.
According to [18], the relations in Figure 12 are based on research and practice. The book had references to 20 other books from the same period, but no research papers.
If the components in the joint have the same material quality, the recommended angle β of the frontal area to optimize the joint is half the angle between the strut and the cord. Then the angle between force and grain is minimised and equal (γ/2) for both the surfaces. If the components have different material quality, a different angle could be optimal. The different assessed standards have different rules for β as illustrated in Figure 13. The Norwegian, [7] and Swiss, [8] standards have a set value

$$\beta = 90° - \frac{\gamma}{2}$$

The Netherland standards, [3-6] say

$$90° - \frac{\gamma}{2} \leq \beta \leq 90°$$

In the German standard, [1,2] and a Danish textbook, [18], from 1949 it is described a method where the two planes in the notch have an angel of 90°; this lead to an even smaller angle β. This is the smallest value the angle β can be before the step joint will start behaving like a wedge and increase the possibility to introduce tension perpendicular to the grain along l_v. The Italian standard doesn't have rules for β.

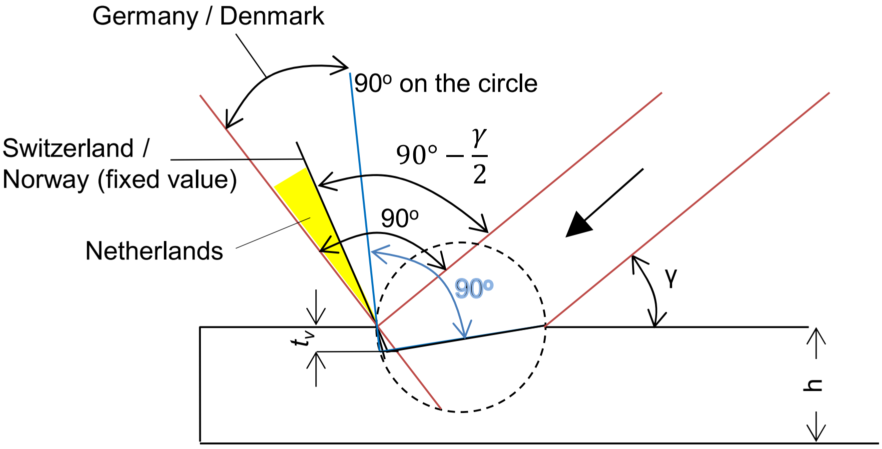


Figure 13 Design rules for β

The minimum length l_v is given in the Swiss and Norwegian standards as 150 mm and in the German standard as 200 mm. The maximum length is given as $8t_v$ in the German standard. The maximum length is probably due to the elastic shear stresses in long connections leading to a "hammock shape" where the stress levels in both ends of the connection are high compared to medium shear stress, Figure 10.

When designing step joints that only have loads in the plane, bolts are used to secure the connection. Such bolts are not designed to carry loads. If it is necessary to design for loads out of the plane, bridle joints (Figure 2, 12B) or oblique tenon joints (Figure 2, 12C) can be chosen.

Double step joint

The double step joint is also one of the most important joints stated in the standards and is covered in almost all the standards, [3-9] and is shown as Figure 14.

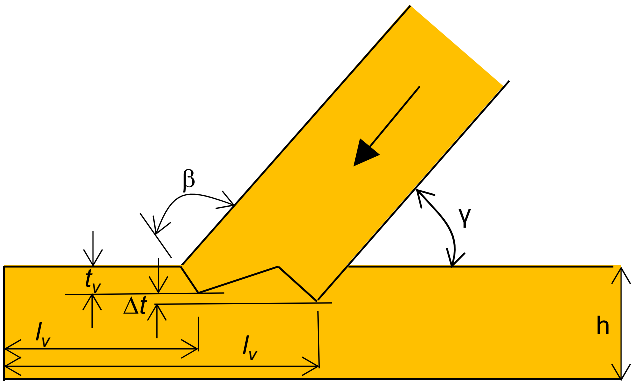


Figure 14 Double step joint

In the double step joint the force is transferred through two surfaces. Thus the force will not be moved to the front of the strut as in the single step joint. The point where the shear force starts to be transferred is moved and therefore the strut can be closer to the end of the cord compared to a single step joint. The depth of the two notches has to be different to avoid a triangle to be cut along the fibre direction in the cord (l_{v2}- l_{v1}), thus the difference Δt. This kind of connection is difficult to produce precise and should not be used if it isn't necessary, [18].

A summary of the different geometric rules in the standards are shown in Figure 15.

	Netherlands, [3]	Switzerland, [8]	Italy,[9]	Norway, [7]
γ	$< 50°$			$< 45°$
t_v		$\leq h/6$ and $\leq h/4 - \Delta t$	$\leq 0{,}8(t_v + \Delta t)$	$\geq h/4$
Δt	$\geq$ 15 mm	$\geq$ 10 mm	$\geq$ 10 mm	$\geq$ 15 mm and $\leq$ 20 mm
l_{v1}	$\geq 6\, t_v$	$\geq$ 150 mm		

Figure 15 Geometric rules for double step joint

Other step joints

The heel step joint and the heel joint shown in Figure 16 are described in the standards from the Netherlands, [3-6] and Germany, [1]. The heel joint is shown in the Swiss standard, [8].

In the Netherlands standards there is a restriction that $90° \leq \Upsilon \leq 110°$. In the German standard, the heel step joint has the same design rules as single step joint concerning γ and t_v. The length l_v has to be less than 8 t_v and larger than 200 mm.

To avoid cracks along the fibre direction in the strut, it is important that there is a distance between the strut and the cord in the heel step joint (not shown on Figure 16).

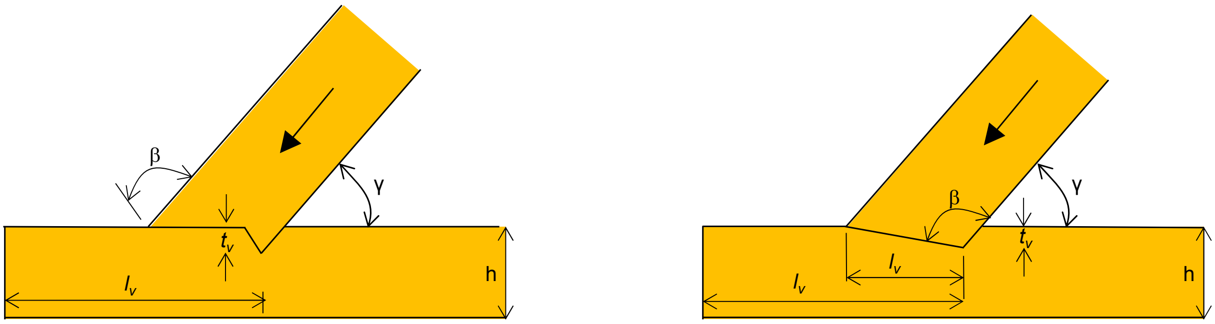


Figure 16 Heel step joint and heel joint

Tap joints

The tap joints are shown in the German standard, [1,2].

Dowel joints

Dowel joints as shown in Figure 17 can be used to transfer shear forces between two elements. The dowels can be square shaped hardwood. When transferring shear forces, eccentric forces appear on the dowels. Thus it is necessary with bolts along the stippled lines to keep the connection together.

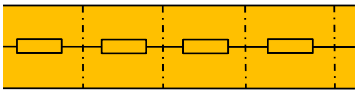


Figure 17 Dowel joints

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