Mechanical timber joints - General

STEP lecture C1
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Objectives
To give an overview of the types of mechanical fasteners used in timber structures. To define the geometry and the basic properties of these fasteners. To give general guidance and specific guidance on factors governing the design of the joints.

Prerequisites
A4 Wood as a building material
B2 Tension and compression
B4 Shear and torsion

Summary
This lecture describes the various types of mechanical fastener used in timber structures. The geometry and the application of the most commonly used fasteners are presented. Further, the behaviour of mechanical fasteners is examined to allow a proper selection depending on the aims of the designer. Then, general recommendations relating to the layout and the design of timber connections are given. They complement the EC5 rules for assessing reliable designs (see STEP lectures C2 to C16).

Introduction
The basis of design relates to the layout of the structure, the choice of the framing system, the proper design of the components and the ease of construction. For timber structures, the serviceability and the durability of the structure depend mainly on the design of the joints between the elements. For commonly used connections, a distinction is made between carpentry joints (see STEP lecture C12) and mechanical joints that can be made from several types of fastener.

For a given structure, the selection of fasteners is not only controlled by the loading and the load-carrying capacity conditions. It includes some construction considerations such as aesthetics, the cost-efficiency of the structure and the fabrication process. The erection method and the preference of the designer or the architect are also involved (Natterer et al., 1991). It is impossible to specify a set of rules from which the best connection can be designed for any structure. The main idea is that the simpler the joint and the fewer the fasteners, the better is the structural result.

In the first part, this lecture presents the different types of fastener. Obviously, it is not possible to present all types of fastener or connection devices in a single lecture. Therefore, only the most important and common fasteners are presented. The general geometry and structural applications are given. The second part deals with the classification of the fasteners according to their behaviour and their load-carrying capacity. Then, the final part mentions some calculations and details to be considered in the design of the joints.

Types of fastener
The traditional mechanical fasteners are divided into two groups depending on how they transfer the forces between the connected members.

The main group corresponds to the dowel type fasteners. Here, the load transfer involves both the bending behaviour of the dowel and the bearing and shear stresses in the timber along the shank of the dowel. Staples, nails, screws, bolts and dowels belong to this group. The second type includes fasteners such as split-rings, shear-plates, and punched metal plates in which the load transmission is primarily achieved by a large bearing area at the surface of the members. The load transmission is primarily achieved by a large bearing area at the surface of the members.

When dealing with larger structures, fasteners could be used with special steel hardware especially for the connection to the foundation or at the apex of the structure.

Apart from mechanical fasteners, a mention should be made of a new group relating to glued joints. They require specific quality control (Ozelton and Baird, 1976). This technique is mainly carried out using glued-in bolts for beam connections or large finger joints for frame corners (see STEP lectures C14 and D8).

Nails

Nails are the most commonly used fasteners mainly for structural components such as diaphragms, shear walls and trusses. They are manufactured in many sizes, shapes and materials (see Figure 1). Round wire nails are the most commonly used fasteners for timber. Improved nails with square cross-section or deformed shanks are also available. The sizes of nails are related to different standardised gauges in the European countries. The common sizes range from 2,75 to 8 *mm* in diameter and 40 to 200 *mm* in length.

For nailed joints, the main development results from the use of power-driving equipment using compressed air. For nail lengths up to 100 *mm*, it allows fast installation reducing the cost of the execution. The equipment should be set carefully to avoid over driving the nails especially in wood-based sheet material.

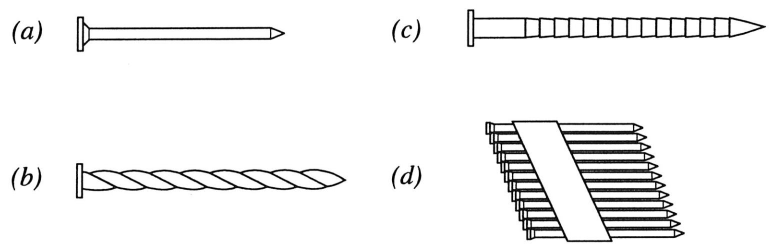

Figure 1 *Shapes of nails: (a) round wire nails, (b) helically threaded nails, (c) annular ringed shank nails, (d) machine driven nails.*

For the installation of nailed joints, predrilled holes may be necessary to avoid splitting or to enable nails to be driven into dense hardwood. For softwood species, this operation should be carried out for Douglas-fir and larch members. Then, the hole diameter has to be no greater than 80% of the nail diameter.

In timber structures, the nails have to be used primarily in single shear for connecting timber, steel or wood-based panels as side members. The designer has several possibilities for enhancing the load-carrying capacity of nailed joints. For a lateral load, larger lateral load-carrying capacity can be obtained using square nails. The other possibility is to insert steel sheets into the members. The nails are driven without predrilling for sheets up to *2 mm* in thickness. To increase both lateral and withdrawal load-carrying capacity, the common choice is to use special nails (helically threaded or annular ringed shank nails). They provide greater withdrawal strength and reduce the hazard of timber splitting.

Punched metal plates

As nailed plates, punched metal plates allow joints to be made between members in-plane. They are manufactured from galvanized steel plates of thickness ranging between 0,9 to 2,5 *mm*. The installation of the punched metal plates requires special equipment in a factory. They are mainly used for light-framed timber trusses for which the member thickness should be at least 35 *mm*.

Because of the out-of-plane flexibility of such trusses, care should be taken in handling to avoid damage to the joints during erection as recommended in prEN 1059 "Timber structures - Production requirements for fabricated trusses using punched metal plates". There exist many proprietary plates. The designer should refer to the manufacturer's specification which should be approved by a certification organisation.

Bolts and dowels

Bolts are commonly made from ordinary mild steel with hexagonal or square heads and nuts. The diameters range between 12 and 30 *mm*. For ease of installation, EC5 requires holes to be driven 1 *mm* larger than the bolt diameter although in practice larger tolerances may be required. This bolt hole clearance reduces the capacity of the bolted joints. For this reason and for appearance, dowels are taking the place of bolts. They are pieces of round steel rod fitting tightly into drilled holes.

As specified by the EC5 rules, both steel and timber properties affect the load-carrying capacity of bolted or dowelled joints. Using ordinary bolts as standardised for steel structures in EN 20898 "Mechanical properties of fasteners-part 1: bolts, screws and dowels", Table 1 defines the relevant properties. In addition, Table 2 gives the properties of the steel bar to be used in the design of dowels. Depending on the size of the connection or the method of erection, some dowels may be replaced by fitted bolts or end-threaded rods to hold the members together.

Bolt grade	4.6	4.8	5.6	5.8	6.8
f_y (N/mm^2)	240	320	300	400	480
$f_{u,k}$ (N/mm^2)	400	400	500	500	600

Table 1 Yield stress f_y and tensile strength $f_{u,k}$ for ordinary bolts.

Steel grade	Fe360	Fe430	Fe510
f_y (N/mm^2)	235	275	355
$f_{u,k}$ (N/mm^2)	360	430	510

Table 2 Values of f_y and $f_{u,k}$ for common steel bars.

Generally, bolts or dowels are used in double or multiple shear joints. To ensure the performance of the joints, a minimum thickness is required for timber elements: 30 *mm* for side members and 40 *mm* for internal members. All the tightened fasteners should be installed with a washer under any heads or nuts in contact with the timber.

Screws
The main type of screw used for structural applications is the coach screw. The common sizes range from 6 to 20 *mm* in diameter and 25 to 300 *mm* in length. As for bolts, the use of a washer is required. In large connections, they conveniently hold timber connectors in place or replace bolts when they are not suitable. Another use is to fix joist hangers or framing anchors in combination with nails. A limitation to their use results from the predrilling needed to install the coach screws.

Connectors
The use of timber connectors allows the transfer of heavy loads by increasing the bearing area in the timber. For truss connections, a nearly perfect pinned joint can easily be achieved using a single connector unit instead several dowel-type fasteners. Figure 2 shows the typical shapes of split-ring, shear-plate and toothed-plate connectors.

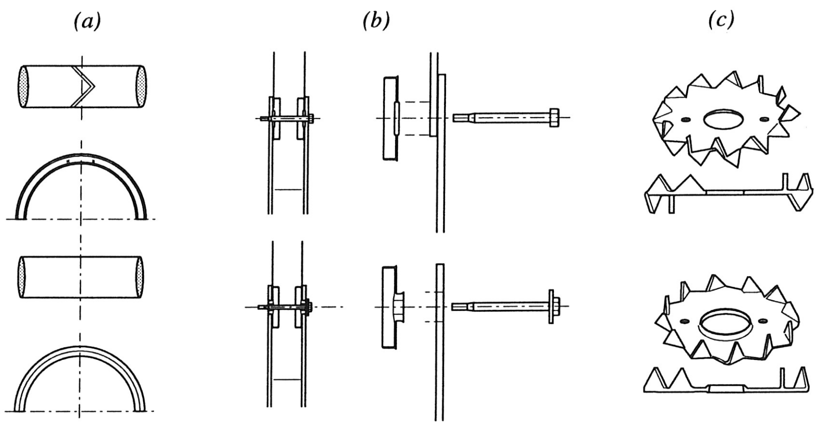

Figure 2 *Usual timber connectors: (a) split-rings, (b) shear-plates, (c) single and double sided toothed-plates.*

Split-rings and shear-plates are formed from aluminium cast alloy, cast iron or steel with diameters varying from 60 to 260 *mm*. Precision in grooving and boring is essential for the installation and performance of these types of connector. The second type is the toothed-plate connector which is made from cast iron or hot-dipped galvanized steel. Their diameters range from 38 to 165 *mm*. Larger connectors are available for connection of glued-laminated members. In structural timber, connectors with diameters up to 75 *mm* are installed. To limit the effects of the transverse moment, the joints are held together by fasteners installed with round or square washers of a size about half the diameter of the connectors used.

Split-rings and double sided toothed-plates are used in a similar way for timber to timber joints. They transfer the load directly between the surfaces of the members that are in contact. The assembly is generally done on site. On the other hand, shear-plates and single sided toothed-plates are suitable for steel to timber joints as well as timber to timber joints. They allow the prefabrication of the joints and only the bolts are installed on site. For these connectors, the load transfer is achieved by the bolt stressed in shear by the bearing area of the connector centre plates.

Behaviour of fasteners and structural joint modelling
The design procedure has to combine the global analysis of the structural timberwork and the local analysis of the connections. The key problem lies in joint behaviour that affects the distribution of the forces and the deformations of the structure. It can be determined from test results for the chosen joints according to

EN26891 "Joints made with mechanical fasteners - General principles for the determination of strength and deformation characteristics". Otherwise, the joint properties are assigned from the behaviour of a single fastener. Figure 3 shows the experimental behaviour of different fasteners where the load is defined per shear plane.

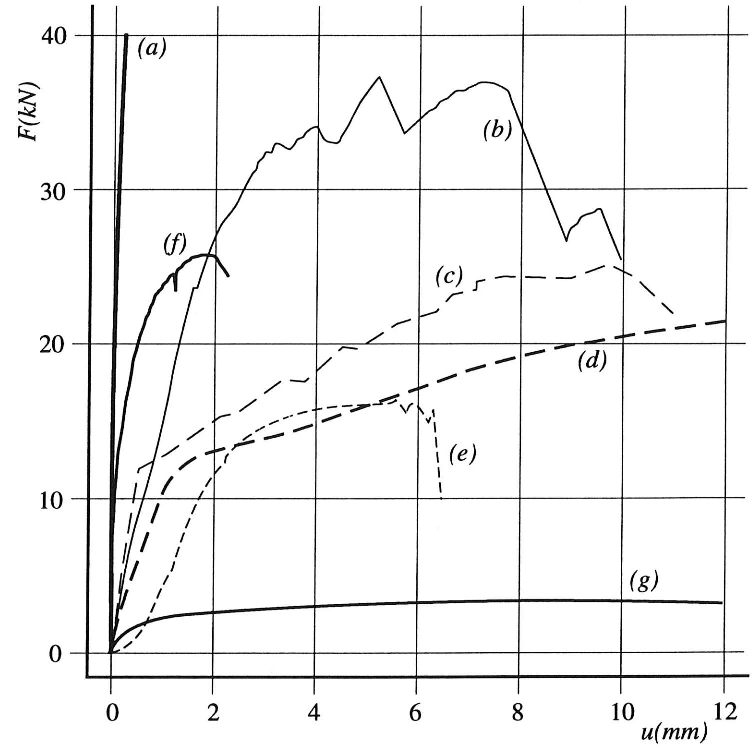

Figure 3 *Experimental load-slip curves for joints in tension parallel to the grain: (a) glued joints (12,5 10^3 mm^2), (b) split-ring (100 mm), (c) double sided toothed-plate (62 mm) (Hirashima, 1990), (d) dowel (14 mm), (e) bolt (14 mm), (f) punched plate (10^4 mm^2), (g) nail (4,4 mm).*

In contrast with rigid glued joints, mechanical fasteners exhibit large deformations that must be considered by the designer.

Apart from the stiffness of the joints, the overall behaviour depends on the stress concentrations in shear and in tension perpendicular to the grain. These induce a brittle behaviour for the split-ring connector and for shear-plates. The other fasteners exhibit an elasto-plastic behaviour resulting from the deformation of the fasteners as well as the crushing deformation of the timber.

Two important features should be mentioned from these curves:

- the initial slip for the bolted joints due to the oversized holes. This leads to brittle behaviour and a reduced load-carrying capacity for multiple fastener connections (see STEP lecture C15). An initial slip can also arise for shear-plate and single-sided toothed-plate connectors;
- the punched plates show a small plastic deformation capacity. It can induce a brittle failure depending on the geometric imperfections of the joints, within the fabrication tolerance.

Furthermore, the yielding of dowelled joints depends on the slenderness of the fastener as shown in Figure 4. Roughly, the slenderness can be defined for a double shear joint as the ratio between the thickness t_2 of the central timber member to the diameter d of the dowel (see STEP lecture C3).

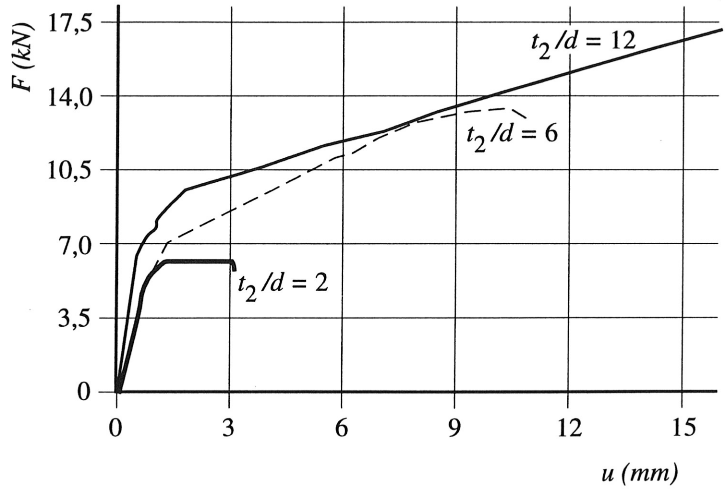

Figure 4 *Influence of the slenderness of the dowel on the load-slip behaviour of a timber to timber single joint in tension parallel to the grain.*

The direction of the transferred forces affects the behaviour of the joint. For a single fastener, this influence depends on the size of the fasteners compared with the thickness of the growth rings of the timber. From test results (Smith and Whale, 1986), the load-carrying capacity of fasteners with a diameter up to 8 *mm* is independent of the direction of load to grain. In the case of loads acting at an angle to the grain, tension stresses perpendicular to the grain reduce the ductility and the capacity of the joint.

To prevent brittle failure and splitting, the ductility of the joint can be enhanced by reinforcing the members in the joint area. Efficient reinforcement can be made with steel or wood-based panels glued on the internal sides of the connected members. Such designs could be suitable for resisting accidental actions such as seismic actions (see STEP lecture C17).

In order to model the joint for structural calculations, a joint classification can be conveniently based on the static ductility $D_S = u_u/u_y$ of the joint (Figure 5a).

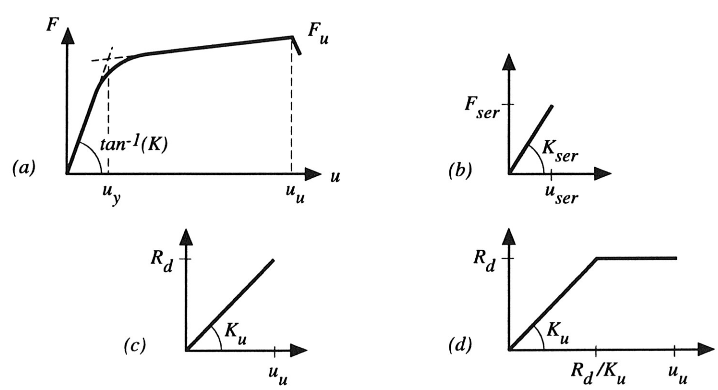

Figure 5 *Joint modelling: (a) definitions of the parameters, (b) model for serviceability limit states, (c) and (d) models for ultimate limit states.*

Following this classification (Table 3), design calculations can be achieved using the joint models defined for the serviceability and ultimate limit states.

Joint type and loading conditions	D_S	model at ultimate limit states
- axially loaded nails and screws, - glued-in bolts, - split-rings, shear-plates, - dowel-type fasteners with failure mode 1* or loaded at a grain direction greater than 60°,	$D_S \leq 3$	5c
- toothed-plates, - punched metal plates, - dowel-type fasteners with failure mode 2*,	$3 < D_S \leq 6$	5c
- nail plates, - dowel-type fasteners with failure mode 3*	$6 < D_S$	5d

Table 3 *Classification of joints based on the static ductility (*: see STEP lecture C3).*

Considering the choice of joint shape, mechanical fasteners provide the designer with a wide range of possibilities. The proper selection should include strength and stiffness criteria. As an example, a tension splice joint between glued laminated members (GL24) is considered. Following the design rules given in the STEP lectures C3 to C9, Table 4 presents some joints able to transfer the design load equal to $51 \cdot 10^3\ N$.

Fasteners	Number	A_j (10^3 mm^2)	R_d (10^3 N)	K_{ser} (10^3 N/mm)
split-rings d_c=100 mm	2	266	52,6	45,6
dowel d = 24 mm	2	242	51,2	35,6
dowel d = 14 mm	4	165	52,4	41,5
dowel d = 9 mm	8	136	53,7	53,3
nails d = 3,4 mm, l = 80 mm	2 x 38	240	52,9	59,9

Table 4 *Example of joints with similar load-carrying capacity (service class 1).*

The proper selection depends on the structural system and the loading conditions as well as the assumptions considered for the structural analysis. In this example, the first three joints correspond to pinned joints. For the two others, attention should be given to their rotational stiffness since it can induce overloading of the fasteners. Depending on the bending efficiency of these joints (see STEP lecture C16), it should be considered in the structural analysis in order to check the design of the joint itself and the design of the members. This example exhibits also large variations in timber joint size and stiffness for the same strength level. With many smaller fasteners, the translational stiffness is increased.

General joint design

To ensure the design performance of the joints as given in EC5, the correct location of the fasteners with respect to the end and the edge of the members is of utmost importance (Wilkinson and Rowlands, 1981). Despite this requirement, the design is not always controlled by the load-carrying capacity of the fasteners. It may depend on the joint shape that can induce supplementary stresses in the members. The main factors are now examined.

Swelling and shrinkage

Emphasis has to be put on the dimensional changes of the timber cross-section that can occur with variation of moisture content. In the area restrained by the fasteners, the moisture changes cause stresses perpendicular to the grain that can induce splitting (Figure 6a).

To avoid or limit splitting, the restrained area has to be limited. When possible, the fasteners should be put together in the appropriate part of the connected members (Figure 6b). The fasteners used to hold the joint components are installed in oval-shaped holes. In other cases such as moment-resisting joints in frames, the larger restrained dimension should be limited to one metre.

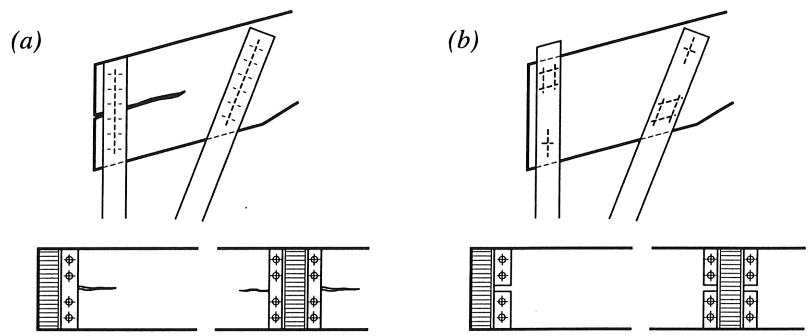

Figure 6 *Joint details: (a) splitting due to shrinkage, (b) correct joint with oval shaped holes.*

Eccentricities

In structural work, the joints and the members should be symmetrical and concentric wherever possible, especially in heavily loaded members. Nevertheless, eccentricities can result from several causes (Figure 7):

- the type of fasteners used,
- the installation of the designed joint,
- the layout of the structural system.

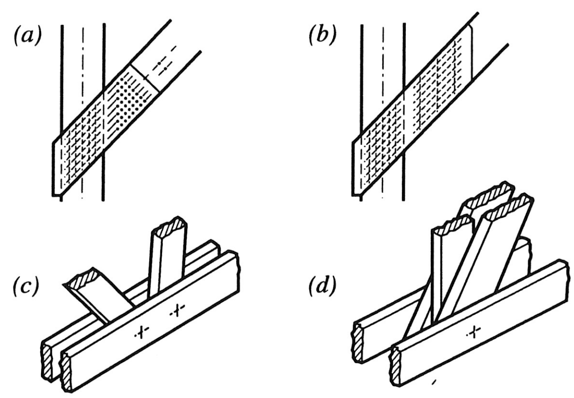

Figure 7 *Eccentricities in the structures due to the fasteners (a) or the members (c) and modified installations to avoid eccentricities (b),(d).*

For eccentric timber fasteners such as connectors, the influence of the secondary transverse moment is included in the calibration of the design strength. The installation of the required washers counteracts this type of eccentricity.

Often, the eccentricities can be avoided by providing a proper layout of the fasteners and members as shown in Figure 7b and 7d. Otherwise, the design has to consider the secondary forces (moment, shear and tension) induced on the fasteners and the members.

Group action

When using a closely packed fastener pattern or many fasteners in line, the load-carrying capacity of the joint may be controlled by the tearing strength of the member (Figure 8). This block shear failure for a group of fasteners involves shear along one plane and tension on a perpendicular plane.

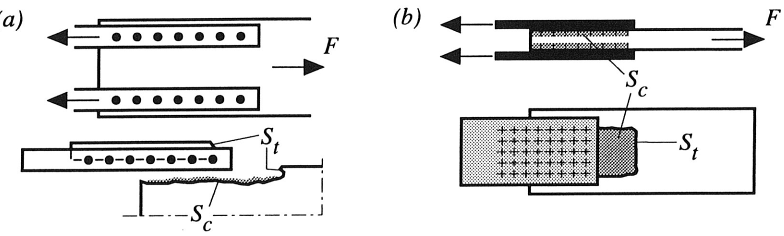

Figure 8 *Block shear failure in joint: (a) tension failure of the net area S_t, (b) shear failure of the net area S_c.*

The failure mode is sequential with a fracture on one of the resisting areas, S, followed by yielding and failure on the area perpendicular to the fracture plane. For a brittle material such as timber, the strengths on both planes must not be added. Then, the strength of the member is checked considering the net section S_t in tension or S_c in shear and the design strength of the material. The design block shear strength corresponds to the larger value.

Combination of fasteners

For the transfer of a given force, the design of joint with a combination of various fasteners can sometimes be achieved especially in trussed structures. To avoid overloading caused by large stiffness differences or by oversized holes, gluing or bolts shall not be combined with other mechanical fasteners.

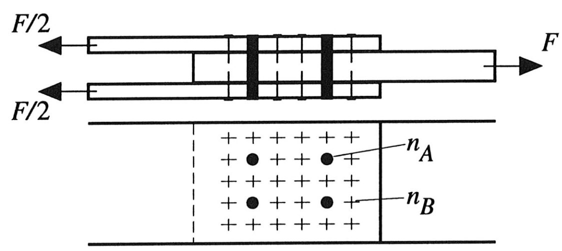

Figure 9 *Joint made with a combination of fasteners: n_A dowels and n_B nails.*

Conservatively, the design of a joint is made with the assumption of an elastic behaviour of the fasteners. The distribution of the design load F_d is based on the slip modulus of the fasteners.

For lateral load on two types of fastener (see Figure 9), equilibrium condition and compatibility of deformation are expressed as follows:

$$F = \sum_{i=1}^{n} F_i = n_A F_A + n_B F_B \qquad (1)$$

$$u = \frac{F_A}{K_{u,A}} = \frac{F_B}{K_{u,B}} \qquad (2)$$

with $K_{u,A}$ and $K_{u,B}$, the slip modulus at ultimate limit state for fasteners A and B.

The ultimate design load $F_{A,d}$ and $F_{B,d}$ on a fastener is :

$$F_{A,d} = \frac{K_{u,A}}{n_A K_{u,A} + n_B K_{u,B}} F_d \qquad F_{B,d} = \frac{K_{u,B}}{n_A K_{u,A} + n_B K_{u,B}} F_d \qquad (3)$$

Other factors

Another challenge for the designer is to fulfill the fire resistance specifications. At present, the trend is to hide the joints in the members. At the same time, this gives aesthetic solutions.

With the design of the joints, the aim of the designer must be the limitation of stresses perpendicular to the grain. This is interesting work as it requires the examination of the path of the forces in the timber structure and the joint area. When the force acts at an angle to the grain, the joint must be located so as to reduce tension perpendicular to the grain.

Lastly, some consideration is given to corrosion when designing connections in aggressive or exposed conditions. As a starting point, the design should avoid water being trapped in the joint area. For exposed connections, a covering provides an efficient protection from the sun and water (see STEP lecture A14). In severe conditions, corrosion is resisted by rustproofing of steel components or using corrosive-resistant metals. The designer should also consider the compatibility of the metal with timber treatment. As example, caution should be taken for the installation of components made from aluminium or steel into timber treated with preservatives containing copper.

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