Influence of moisture content and load duration in joints

STEP lecture C18
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Objectives
To develop an understanding of the influence of varying moisture content and the load duration effects in joints and to show how these effects are dealt with in EC5.

Prerequisites
A4 Wood as a building material
C4 Nailed joints I
C6 Bolted and dowelled joints I

Summary
This lecture provides background information on the influence of moisture content and load duration on the long-term load-carrying capacity and deformation behaviour of timber joints with mechanical fasteners. It covers joints made from timber or a combination of timber and wood-based materials. Information is given on research carried out in the field of creep deformations and the effect of cyclic moisture content variations. Furthermore the effect of load level on the long-term capacity of joints made with nails, toothed-plate and split-ring connectors is shown. Two examples are included, one showing the effect of load level on the long-term load-carrying capacity and another on the long-term deformation. Test results are compared with the design rules given in EC5.

Introduction
In the design of timber structures, the load-carrying capacity and the stiffness of joints are important parameters. During the calculation process several aspects of the load-carrying capacity and the stiffness of the joints have to be checked to control the safety and serviceability of the structure and its parts. During the lifetime of a structure, the joints will be loaded to a certain level with a permanent load, and to a generally higher level during shorter periods of time with variable loads like wind or snow.

Apart from loads, there is an additional type of action: the climatic environment in the form of temperature and relative humidity, since they influence the moisture content of the timber (see STEP lecture A4). A high moisture content in the timber has to be accounted for by means of modification factors for strength and stiffness. It has long been recognized that not only the absolute values of temperature and moisture content influence the behaviour. Also effects of variations in temperature and moisture content on timber under stress influence the long-term behaviour of both timber and timber joints (see for example Armstrong and Kingston, 1962 and Hearmon and Paton, 1964). Mechano-sorptive effects are the results of variations in temperature and moisture content on timber under stress.

There are, however, certain reasons why the influence of a changing moisture content has a greater effect on joints than it has on structural members. Joints are situated near the end grain of timber elements and the local stresses around fasteners are much higher than the stresses in ordinary components. The consequence is that moisture reaches highly stressed areas around the fastener easily. Diffusion takes place parallel to the grain from the end of the member, which is near the joint and perpendicular to the grain directly from the surface near the fastener. The diffusion coefficient is much greater parallel to the grain than perpendicular to the grain and thus moisture changes will have more effect on highly stressed areas near fasteners than on other parts of structural members, resulting in larger deformations and thus higher slip measurements.

Definition of creep

Creep is defined as the deformation increase under the effect of a constant load (see STEP lecture A19). As has been indicated before, the increase in deformation is highly affected by climatic changes in temperature and relative humidity of the air surrounding the structure.

For calculation purposes it is general practice to express the creep effects as a factor relative to instantaneous deformation although this is often difficult to determine in creep tests because of the time necessary to apply the load. A generally accepted method for the calculation of the long-term deformation is the application of a deformation factor k_{def}. In EC5 this deformation factor is defined as:

$$k_{def} = \frac{u_{fin} - u_{inst}}{u_{inst}} \qquad (1)$$

where k_{def} is the deformation factor, u_{inst} is the instantaneous deformation in *mm* and u_{fin} is the final deformation in *mm*.

If measurements of u_{inst} and u_{fin} are available, values of k_{def} can be calculated. The final deformation can then be calculated by multiplying the initial deformation by $(1+k_{def})$.

In the following section, attention will be paid to the effects of moisture changes on the deformation of joints with several types of fasteners and connectors.

Long-term effects in timber joints

Load duration effects in timber joints can be divided into two types. The first affects the long-term load-carrying capacity, while the second influences long-term deformation behaviour. The main factors influencing both the load-carrying capacity and the deformation are:

- the load level,
- the variations in moisture content and
- the type of fastener or connector.

In studies regarding the long-term load-carrying capacity of timber joints, the load level is generally defined as the ratio of the actual load to the average short-term load-carrying capacity of the joint. A ratio of 0,3 for example indicates that the load level is 30% of the average short term load-carrying capacity. For timber joints, the determination of the short-term load-carrying capacity is carried out according to EN 26891 "Timber structures - Joints made with mechanical fasteners. General principles for the determination of strength and deformation characteristics", where the loading procedure is prescribed as well as the time span in which failure occurs. The long-term load-carrying capacity of joints is mainly determined by loading specimens at load levels generally above 60% of the average short-term load-carrying capacity, and recording the time to failure. Since these tests are very time consuming, only a limited number of test results are available.

Figure 1 shows the results of several long-term tests with nails, toothed-plate and split-ring fasteners loaded at load levels between 30 and 90% (Vermeyden 1974, Kuipers and Kurstjens, 1986). The test results with load levels above 50% are from tests started in 1962. The lower load level tests were started in 1984. The test results available so far indicate that the long-term load-carrying capacity of joints is similar to the long-term load-carrying capacity of timber (Madsen and Barrett, 1976). For the design rules in EC5 this means that the modification factor k_{mod} for timber also applies to joints.

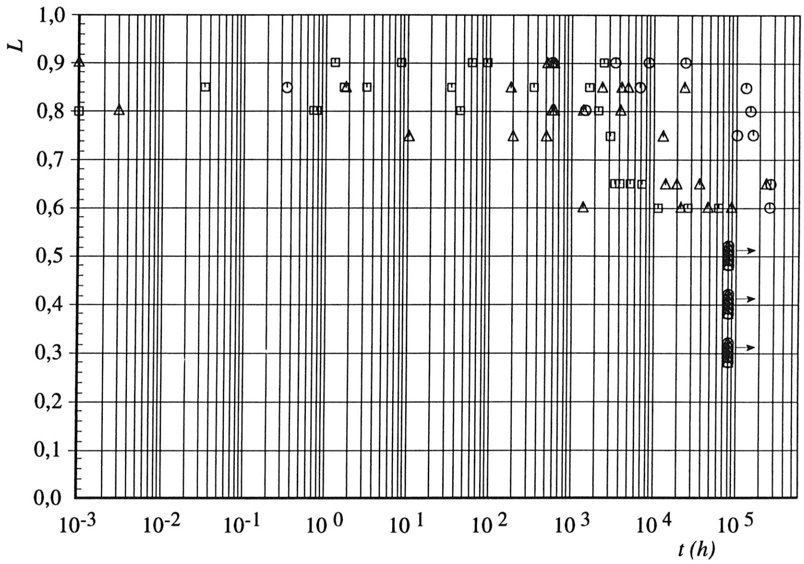


Figure 1 Time-to-failure test results of nailed, toothed-plate and split-ring joints.

No European test standards or RILEM recommendations are available for creep tests on joints. Therefore it is difficult to compare the results of different creep tests, mainly because the time span between the application of the load and the measurement of u_0 is often unknown. Results of creep tests with timber joints are very limited. The most important experimental studies found are Feldborg and Johansen (1986), Vermeyden (1974), Kuipers and Kurstjens (1986) and Van de Kuilen (1992). In the study by Feldborg and Johansen, carried out at the Danish Building Research Institute, the load level on the joints was 40% of the characteristic short-term load-carrying capacity F_k. Assuming a coefficient of variation of 15%, the load level 0,4 F_k is approximately 30% of the average short-term load-carrying capacity.

Four types of joints were analysed:

- Joints with punched metal plates;
- Steel-to-timber joints with ringed shank nails;
- Plywood-to-timber joints with square plain shank nails;
- Plywood-to-timber joints with ringed shank nails.

In the studies carried out by Vermeyden and Kuipers three types of joints were investigated, joints with round plain-shank nails, toothed-plate connectors and split-ring connectors. The study, started in 1962 with load levels of 60% and above, was extended in 1984 with load levels of 30%, 40% and 50% of the average short-term load-carrying capacity.

From both studies experimental creep data are available in varying climatic conditions which occur in practice. In the study by Feldborg and Johansen (1986) the moisture content was controlled and varied between 20% and 12% (20% at the beginning of the test), while in the second study the moisture content varied naturally between 10% and 18% (10% to 15% at the start of the tests, depending on the season). These moisture content levels are classified as service class 2 according to EC5.

The results of both these studies indicate that the effects of moisture content variations in joints is much more severe than it is in timber. An example of measured deformations over a period of 7 years is given in Figure 2 where the average deformation of five joints is shown. The joints were loaded at a level of 30% of the average short-term load-carrying capacity.

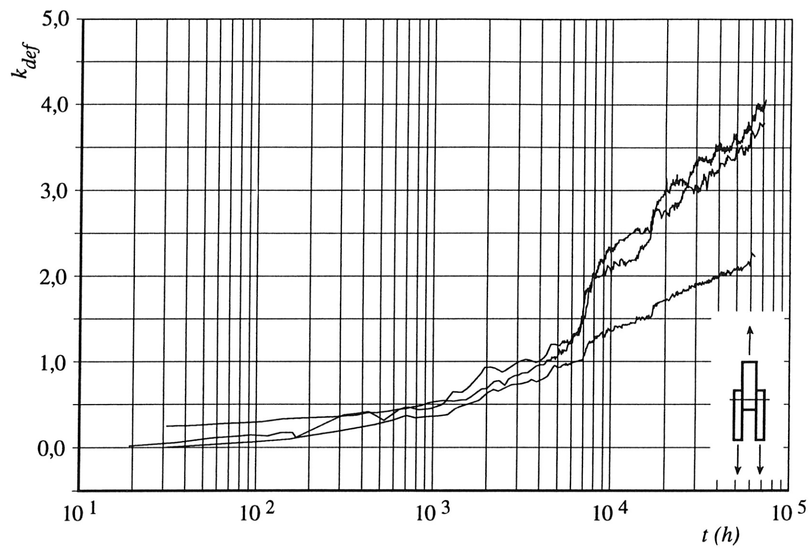


Figure 2 *Creep-curve for nailed, toothed-plate and split-ring joints at 30% load level in service class 2.*

The increases in creep factor at 4500, 7000 and 18000 hours are caused by rather sudden changes in relative humidity of the surrounding air. The magnitude of deformation increase depends on the type of joint. In Feldborg and Johansen (1986) it was concluded that the severity of the effects increased in the order: punched metal plates, steel-to-timber, plywood-to-timber with ringed shank nails and then plywood-to-timber with plain shank nails. From the study started by Vermeyden (1974) in 1962 which is still continuing, it can be concluded that joints with toothed-plate connectors show higher creep factors than joints with nails or split-ring connectors. Creep factors of joints vary widely but creep factors of up to 14 in varying climatic circumstances have recently been reported by Leicester (1992) at load levels between 20% and 31%. These high values indicate that large deformations can occur in the timber around a fastener without failure.

EC5: Part 1-1: 4.1

These values found in tests can be compared with the k_{def} values given EC5. It seems that the values given in EC5 underestimate the long-term deformations of joints. The reason for this difference may on the one hand be the very high load levels in many tests which are much higher than in most structures. On the other hand the same values for joints and for members are specified in EC5 for simplicity reasons, ignoring the fact that there is a different long-term deformation behaviour of joints and members under the same conditions.

Design of a joint according to Eurocode 5

In design calculations according to EC 5 a distinction has to be made between the verification of the Ultimate Limit State and the Serviceability Limit State. For the Ultimate Limit State the modification factor k_{mod} for the load with the shortest load duration has to be taken into account, while for the Serviceability Limit State for each load the contribution to the deformation has to be determined with the appropriate k_{def} value.

Loads

Besides the characteristic values G_k and Q_k the following load combinations are defined in EC 1: Part 1-1:

- Characteristic combination	:	$\psi_0 Q_k$
- Frequent combination	:	$\psi_1 Q_k$
- Quasi-permanent combination	:	$\psi_2 Q_k$

This means that for verification of the Serviceability Limit State the following load combination has to be used:

$$\sum_{j\geq 1} G_{d,j} + \sum_{i\geq 1} \psi_{2,i} Q_{d,i} \qquad (2)$$

in which $G_{d,j}$ is the design value of the permanent load, $Q_{d,i}$ is the design value of the variable load and $\psi_{2,i}$ is the combination value of the quasi-permanent load.

Long-term load carrying capacity

EC5: Part 1-1:6.2

The embedding strength is an important parameter in the determination of the load-carrying capacity of joints with dowel type fasteners (see STEP lecture C3). The design value of the embedding strength is determined by applying the modification factor k_{mod} depending on the load duration class. However, the yield moment of the fastener is independent of the load duration class. This means that the long-term load carrying capacity depends on the failure mode. If the failure mode mainly depends on the embedding strength, the reduction of the load carrying capacity under long-term loads is more severe than if the failure mode is also determined by yielding of the fasteners. It is possible that a different failure mode is governing under long-term loads than under short-term loads.

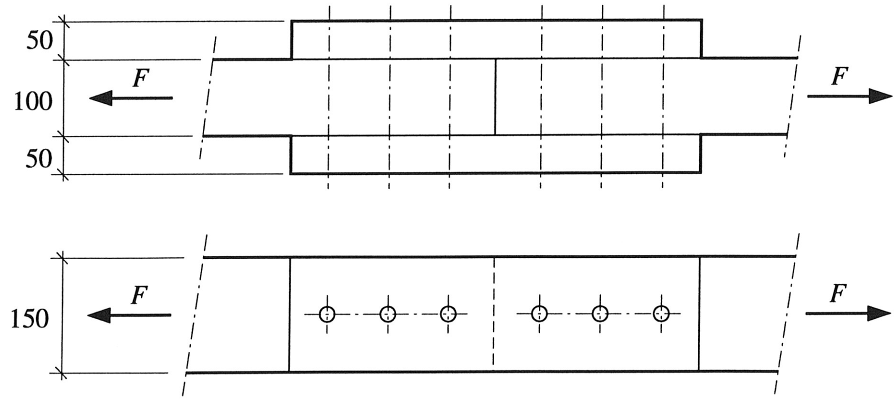
Generally, the design of joints (as well as of timber members) is governed by short-term loads, since the combination factor for quasi-permanent loads $\psi_{2,i}$ is low and the permanent load is low compared to the variable load. However, in the case of joints with particleboards or fibreboards the long-term load carrying capacity is much less, since the modification factor k_{mod} for fibreboards drops from 0,8 for short-term to 0,2 for permanent loads. These board types are much more sensitive to load duration than timber, glulam or plywood which have values of 0,9 for short-term and 0,6 for permanent loads.

Long-term deformation

For the determination of long term deformation the contribution to creep of each of the loads has to be determined with their respective k_{def} values. This means for a combination of a permanent load and one variable load the long-term deformation has to calculated as:

$$u_{fin} = u_{inst,G} \, (1 + k_{def,G}) + u_{inst,Q} \, (1 + k_{def,Q}) \qquad (3)$$

Example 1: Long-term load carrying capacity
Tensile joint in lower chord of a truss. Middle member $b \times h = 100 \times 150$ mm, side members $b \times h = 50 \times 150$ mm, Dowels $d = 20$ mm, $f_{u,k} = 600$ N/mm^2. Strength class C24 according to prEN 338 "Structural Timber - Strength classes".



Design values of permanent and variable load:
Permanent load: $G_d = 50$ kN (Tensile force, load duration permanent)
Variable load: $Q_d = 40$ kN (Tensile force, load duration short-term)

Combination value for quasi-permanent load: $\psi_2 = 0{,}3$
Design value for the tensile force for long-term loads:
$F_{t,d} = G_d + \psi_2\, Q_d = 50 + 0{,}3 \cdot 40 = 62$ kN

EC5: Part 1-1:3.1.7

Load duration class permanent/Service class 1: $k_{mod} = 0{,}6$

prEN 338: 1991

Characteristic values of the materials:
The characteristic value of the density is given in prEN 338. The characteristic values of the embedding strength and the yield moment are calculated according to EC5.
$\rho_k = 350$ kg/m^3

EC5: Part 1-1:6.5.1.2a

The characteristic value of the embedding strength is:

$$f_{h,0,k} = 0{,}082\ (1 - 0{,}01\ d)\ \rho_k = 0{,}0656 \cdot 350 = 23{,}0\ N/mm^2$$

EC5: Part 1-1:6.5.1.2e

The characteristic value of the yield moment is:

$$M_{y,k} = \frac{0{,}8\ f_{u,k}\ d^3}{6} = 640 \cdot 10^3\ Nmm$$

EC5: Part 1-1:6.2.11

The design value of the embedding strength is:

$$f_{h,d} = \frac{k_{mod}\ f_{h,k}}{\gamma_M} = 23{,}0 \cdot \frac{0{,}6}{1{,}3} = 10{,}6\ N/mm^2$$

EC5: Part 1-1:6.2.1n

The design value of the yield moment is:

$$M_{y,d} = \frac{M_{y,k}}{\gamma_M} = \frac{640 \cdot 10^3}{1{,}1} = 582 \cdot 10^3\ Nmm$$

EC5: Part 1-1: 6.2.1g-k

With the design values of the embedding strength and the yield moment a design load carrying capacity of 10,6 kN per dowel per shear plane is found. The governing failure mode is the embedding strength of the timber. With three dowels the design load carrying capacity of the joint becomes:

$R_d = 3 \cdot 2 \cdot 10{,}6 = 63{,}6\ kN$

EC5: Part 1-1: 2.3.2.1b

Verification of the strength:

$F_d < R_d$ or $62 < 63{,}6\ kN$.

For verification of the short term load carrying capacity the design value for the load is 90 *kN* and the short-term load carrying capacity is 95,4 *kN*.

Example 2: Long-term deformation

The long-term deformation u_{fin} in the joint of example 1 will be determined. The slip modulus is calcluated as:

EC5: Part 1-1:4.2 (1)

$$K_{ser} = \rho_k^{1,5}\ d\ /\ 20 = 350^{1,5} \cdot 20\ /\ 20 = 6550\ N/mm$$

According to equation (3):

$$u_{f,fin} = u_{f,inst,G}\ (1 + k_{def,G}) + u_{f,inst,Q}\ (1 + k_{def,Q})$$

The instantaneous deformation in the joint u_{inst} is calculated as:

$$u_{f,inst} = \frac{F_t}{K_{ser}} \qquad (4)$$

where F_t is the design value of the tensile force for serviceability limit state design. These values are lower than the design values for ultimate limit state design. The design values are:

Permanent load :$G_d = 37{,}0\ kN$ (Tensile force, load duration permanent)
Variable load :$Q_d = 26{,}7\ kN$ (Tensile force, load duration short-term)

The load per dowel per shear plane becomes:
Permanent load :$G_d = 6{,}17\ kN$
Variable load :$Q_d = 4{,}44\ kN$

EC5: Part 1-1: 4.1

With the deformation factor $k_{def} = 0{,}6$ for permanent loads and $k_{def} = 0{,}0$ for variable loads,the final deformation becomes:

$$u_{f,fin} = \frac{6170}{6550}\ (1 + 0{,}6) + \frac{4440}{6550}\ (1 + 0{,}0) = 2{,}2\ mm$$

Concluding summary

- The influence of long-term loading on the load-carrying capacity of timber joints appears to be in the same order of magnitude as for timber members.

- In most cases the design for short-term load-carrying capacity governs the design. In cases with a high ratio between permanent and variable loads, however, the long-term load-carrying capacity may be governing the design of a joint, especially if wood-based materials are used where the k_{mod} values are significantly lower than the values for timber.

- There is a large difference in deformation factors between test results and the k_{def} factors of EC5. It seems that the calculated final deformation in a joint according to the design rules of EC5 is too small. For simplicity reasons, EC5 gives identical k_{def} factors for members and joints.

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