Multiple fastener joints

STEP lecture C15
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Objective

To develop an understanding of the combined action of several fasteners in line within a timber joint and its effect on the connection strength.

Prerequisite

C3 Joints with dowel-type fasteners - Theory

Summary

An idealised elastic solution of the interaction of multiple fasteners in timber joints is given. The main parameters influencing the load-bearing capacity of multiple fastener joints are plastic fastener behaviour, creep, manufacturing inaccuracies and variations in load-slip behaviour of single fasteners. The rules for multiple fastener joints for different types of fasteners according to EC5 are presented.

Introduction

Mechanical timber joints generally contain more than one fastener. Even if the load on the joint is acting at the centroid of the connection, the load distribution between the fasteners is non-uniform. The ultimate load of a multiple fastener joint equals the sum of the single fastener loads at failure. If the single fastener loads at failure show large differences and some of those fasteners are loaded well below their own failure load, the ultimate load of the multiple fastener joint is smaller than the sum of the ultimate loads of the single fasteners. This fact is the reason for reducing the load-carrying capacity per fastener in multiple fastener joints for certain fastener types. Principally, the different influences on the load distribution in multiple fastener joints apply both to joints with only one type of fastener as well as to joints containing different types of fasteners.

Elastic solution

Lantos (1969) developed a model to calculate the load distribution in timber joints at an allowable load level assuming the same linear-elastic load-slip behaviour without initial slip for every single fastener and assuming that normal stresses are uniformly distributed over the cross-sections of the connected members. The validity of his analysis is limited to the range within which the behaviour of the fasteners can be considered elastic and to loads acting parallel to the grain of the timber members. Cramer (1968) took a similar approach, taking into account the non-uniform distribution of the normal stresses over the cross-section and their influence on the extensional stiffness of the members. Because the elastic solution of Lantos forms the basis for the reduction of the load-carrying capacity of multiple fastener joints in EC5, the solution for joints with constant fastener spacing is given. A more general solution can be found in Wilkinson (1986).

In Figure 1, a two-member joint is shown. The load transfer between member 1 (M_1) and member 2 (M_2) occurs in discrete steps at the fastener locations. Each step represents the load transferred by the respective fastener. Considering the part of the joint between fastener i and i + 1 in the deformed position, member 1 is loaded by the total joint load minus the loads transferred by fasteners 1 to i, resulting in an extension $u_{1,i}$ of the original length s. Accordingly, member 2 is elongated from s

to $s + u_{2,i}$. In addition, the loads transferred by fasteners i and $i + 1$, respectively, cause fastener slip values of $u_{f,i}$ and $u_{f,i+1}$.

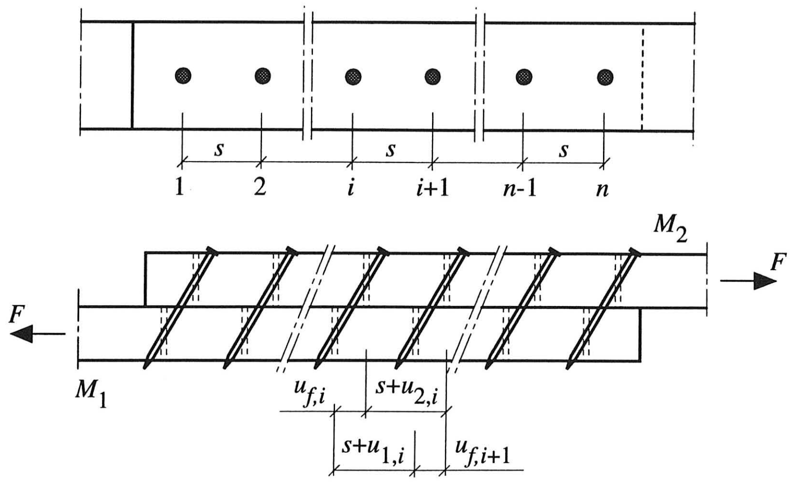

Figure 1 *View of undeformed connection (top) and section showing deformed position (bottom) M_1: Member 1; M_2: Member 2.*

Comparing the elongated member lengths plus the respective fastener slip values yields:

$$u_{f,i} + s + u_{2,i} = s + u_{1,i} + u_{f,i+1} \tag{1}$$

Replacing the fastener slip by

$$u_f = \frac{F_f}{K} \tag{2}$$

where F_f is the load transferred by the fastener and K is the slip modulus, and replacing the elongation of the member between two fasteners by

$$u = \frac{F_m\, s}{E\, A} \tag{3}$$

where F_m represents the load transferred by the member between two fasteners, yields the load on the most stressed fastener at the end of the fastener row for connections where the connected members have the same axial stiffness EA:

$$F_1 = \frac{F}{2}\left(1 - m_1 + (m_1 - m_2)\,\frac{m_1^n + 1}{m_1^n - m_2^n}\right) \tag{4}$$

with

$$m_1 = \frac{\omega + \sqrt{\omega^2 - 4}}{2} \tag{5}$$

$$m_2 = \frac{\omega - \sqrt{\omega^2 - 4}}{2} \tag{6}$$

$$\omega = 2 + \frac{2\, K\, s}{E\, A} \tag{7}$$

The complete derivation of Equation (4) for different member stiffnesses is also given by Lantos (1969). Figure 2 shows an example of the load distribution in a joint containing ten fasteners based on the Lantos solution. The load concentration at the beginning and the end of the fastener row is clearly visible.

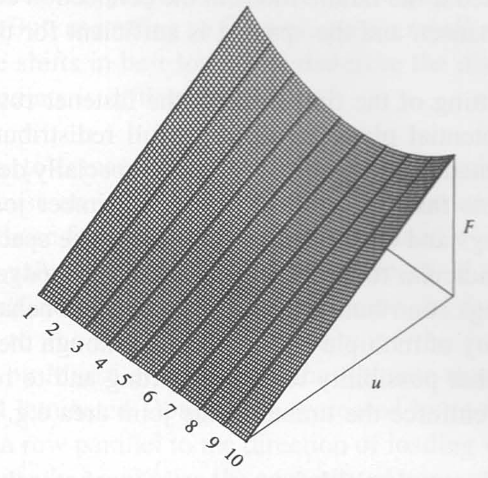

Figure 2 Load distribution between single fasteners according to Lantos. F is the load and u is the deformation.

The idea behind this elastic solution is that the most stressed single fastener should not be loaded above its allowable load level. Since the allowable load is reached first in the fasteners at the beginning or the end of the row, these then control the magnitude of the allowable load for the joint. The factors influencing the difference in fastener loads according to the elastic solution are the longitudinal stiffnesses of the connected members, the number of fasteners in a row, the fastener spacing and the slip modulus.

Main factors

Apart from the effect of the difference in longitudinal deformation in the connected members, there exist several other factors significantly influencing the load distribution between the fasteners in a timber connection.

Plastic deformations and creep

Isyumov (1967) took a more general approach to calculate load distribution between fasteners arranged parallel to loading. He considered nonlinear load-slip behaviour of the fasteners resulting in a redistribution of loads between the fasteners at higher load levels. When the most stressed fastener at the end of the row begins to deform plastically, its stiffness decreases compared to the stiffness of the other fasteners in the joint. Since stiffer components attract more load in a parallel system, the fastener loads in the middle of the row consequently will increase. This effect counteracts the effect described by Lantos and leads to higher ultimate loads compared with connections behaving elastically until failure.

The same is true for the influence of time dependent deformations in the connection. Creep reduces the initial stiffness of the fasteners thereby causing a fastener load redistribution. The magnitude of creep deformations generally increases with the load level. Therefore, the first and last fastener in the row are expected to show larger creep deformations leading to more balanced loads in the connection.

The ultimate load of timber joints with dowel-type fasteners according to EC5 is based on the work of Johansen (1949). He assumed rigid-plastic behaviour for the fasteners as well as for the wood surrounding the fasteners (see STEP lecture C3). Consequently, the load-slip behaviour of dowel-type joints is assumed to be plastic at ultimate load level. However, considerable plastic deformations can only be expected if the failure mode in the connection corresponds to one of those described by Johansen and the spacing is sufficient for this purpose.

If splitting of the timber along the fastener rows occurs at load levels well below the potential plastic capacity, a full redistribution of the load within the joint is prevented. Consequently, splitting especially decreases the load-bearing capacity of multiple fastener joints. Splitting in timber joints can be avoided by appropriate spacings and end distances. The larger the spacing, the smaller the tension stresses perpendicular to the grain caused by the wedge effect of the fasteners. Thus, large spacings contribute to a plastic connection behaviour and consequently increase the capacity of multiple fastener joints although the elastic model predicts the contrary. A further possibility to avoid splitting and to reach a plastic connection behaviour is to reinforce the timber in the joint area e.g. through glued-on plywood.

Significant plastic deformations in mechanical timber connections can be expected for connections with nails and other dowel-type fasteners with a comparatively small diameter as well as for toothed-plate connections. The plastic deformation at failure in toothed-plate connections is the reason why the toothed-plate and the bolt are considered to share the load, whereas for split-ring connector joints, which generally fail in a brittle manner, a load sharing between split-ring and bolt is neglected in the design. Creep deformations, however, occur in all mechanical timber connections.

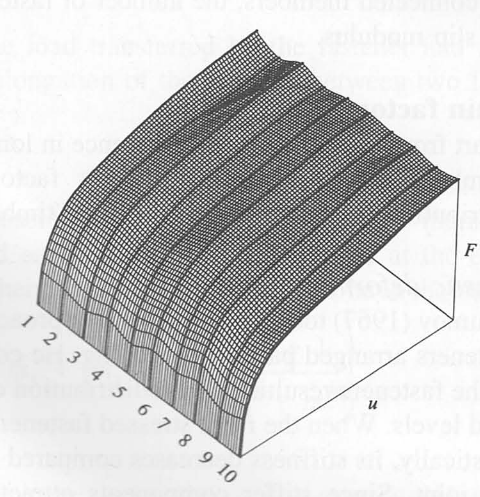

Figure 3 *Load distribution between fasteners showing plastic behaviour. F is the load and u is the deformation.*

Fabrication tolerances

If pre-drilled connections with for example bolts or split-ring connectors are used, fabrication tolerances like misalignment of the bolt holes, lack of straightness of the bolt holes and variations in the hole diameter and initial position of the bolts in the holes further increase the variability in load distribution between fasteners. Dannenberg and Sexsmith (1976) as well as Isyumov (1967) emphasised the importance of fabrication tolerances for the load distribution and the ultimate load of bolted joints and connections with split-rings or toothed-plates. According to

Wilkinson (1986), fabrication tolerances and different shapes of the load-slip curves within a joint cause most of the non-uniformity of the load distribution, while the influence of the different extensions of the connected members seems negligible.

In the elastic range, Cramer found fairly good agreement between his theory and tests with carefully prepared specimens, avoiding misalignment of the bolts and the bolt holes. But, according to Cramer, even a small misalignment of bolt holes may cause large shifts in bolt loads and therefore the distribution of bolt loads in field-fabricated joints is difficult to predict.

Fabrication tolerances, due for example to misaligned bolt holes or split ring grooves, cause an initial slip for some of the fasteners in the joint. When the joint is loaded, those fasteners only start to carry load when the fastener slip exceeds the initial slip values (e.g. bolt No. 4 in Figure 4). If the failure mode is by splitting before significant plastic deformations occur, the fasteners with initial slip will not contribute to the load-bearing capacity of the joint at all. According to tests performed by Massé et al. (1989), the ultimate mean load per bolt of joints made from glued laminated Douglas fir decreased by more than 50% when the number of bolts in a row parallel to the direction of loading was increased from one to four. Those test results emphasise the necessity of appropriate spacings and end distances securing plastic joint behaviour and a redistribution of loads especially for joints with fabrication tolerances. Fabrication tolerances can be avoided by precisely manufacturing timber joints using computer controlled equipment.

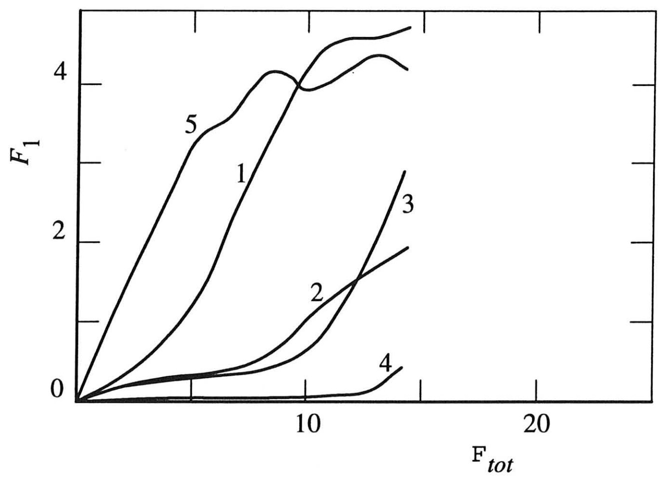

Figure 4 *Example of a load distribution in a bolted joint according to Wilkinson (1986). F_1 is the single fastener laod and F_{tot} is the total joint load.*

Variation in load-slip behaviour between single fasteners

Apart from fabrication tolerances which affect load distribution in pre-drilled connections to a large extent, variable material properties within the wood and between the fasteners cause variations in load-slip behaviour in a joint. Knots, splits, pitch pockets, local slope of grain or density variations in the timber also cause variations of load-slip behaviour also in non-predrilled connections, for example with nails. Figure 5 shows an example of the load distribution in a nailed connection where the high density in knots causes particularly high fastener loads in fasteners No. 4 and 8.

Although this variation of load-slip behaviour does not influence the mean value of the ultimate load of multiple fastener joints, the more important characteristic value of the ultimate load depends on this variation.

Considering the extreme case of identical load-slip curves within a multiple fastener connection, a large variation in the ultimate load of the *connection* will result. This variation corresponds to the variation of single fastener joints, independent of the number of fasteners. A large value for the variation of ultimate loads means a low value of the 5-percentile as the characteristic ultimate load.

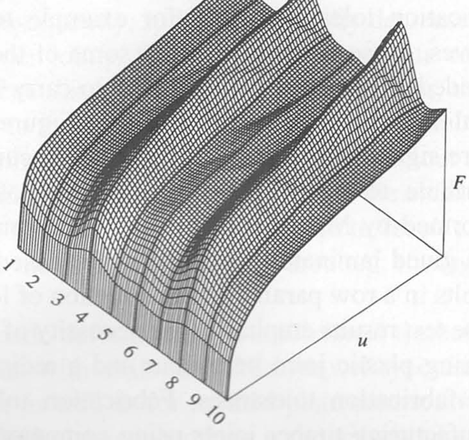

Figure 5 *Example of load distribution in a nailed connection. F is the load and u is the deformation.*

Considering the other extreme - the load-slip curves of the fasteners within a connection show the same variation as the load-slip curves of different single fastener connections - the variation in the ultimate loads of the multiple fastener connection would decrease with increasing number of fasteners. This is because with many fasteners in one connection the probability of having fasteners with both low and high ultimate loads increases. In this case the characteristic value of the ultimate load of the *connection* would increase with increasing number of fasteners. In reality, the load-slip curves of the single fasteners within a connection are neither identical nor statistically independent. The correlation between the load-slip curves consequently represents a parameter influencing the ultimate load of multiple fastener joints.

However, these considerations are only correct, if the failure of the joint occurs after significant plastic deformations. If the joint fails in a brittle manner - e.g. by splitting of the wood - the equalisation of forces between the fasteners is prevented. In this case, the favourable effect of plastic deformations on the ultimate load cannot be used. Therefore, fastener spacing as well as end and edge distances should be sufficiently large. The potential load-bearing capacity of a connection can only be utilised, if splitting is avoided and plastic deformations are possible. The combined positive effects of plastic deformations and variations in load-slip behaviour are the reasons for the fact that the characteristic load-carrying capacity of nailed joints according to EC5 is independent of the number of nails in the joint.

Influence of number of fasteners

The design procedures for different types of multiple fastener joints according to EC5 follow. The design procedure is based on the assumption of ideal plasticity and a subsequent downgrading for the effect of number of fasteners.

Nailed and stapled joints

Any influence of the number of fasteners on the load-carrying capacity of nailed or stapled connections may be ignored.

Bolted and dowelled joints

EC5: Part 1-1: 6.5.1.2 (3)

For more than six bolts or dowels in line with the load direction, the load-carrying capacity of the extra bolts or dowels, respectively, should be reduced by 1/3, i.e. for n bolts the effective number n_{ef} is:

$$n_{ef} = 6 + 2\,(n - 6)\,/\,3 \tag{8}$$

Screwed joints

EC5: Part 1-1: 6.7.1

For screws with a diameter less than 8 *mm* the rules for nailed joints apply, that means any influence of the number of fasteners on the load-carrying capacity may be neglected. For larger diameter screws, the respective rule for bolted and dowelled connections applies.

EC5: Part 1-1: 6.8

Toothed-plate connector joints

In connector joints, the load sharing between fasteners of the same type as well as between different fasteners has to be considered. Since the failure mode of toothed-plate connector joints in general is plastic, a complete load sharing between toothed-plate and bolt is assumed. The capacity of the connection is the sum of the capacity of the toothed-plate and the bolt. If the connection contains several toothed-plates, a decrease in load-carrying capacity per toothed-plate/bolt similar to the rule for bolted and dowelled connections will be inserted in EC5. Until a definitive rule is introduced, the effective number of connectors for more than two connectors in a line can be assumed as (Brüninghoff et al., 1989):

$$n_{ef} = 2 + (1 - n\,/\,20)\,(n - 2) \tag{9}$$

Ring and shear-plate connector joints

The failure mode of ring and shear-plate connector joints in tension is often brittle, the failure being initiated by a shear failure of the wood in front of the connector. Because the shear block failure often occurs at small displacements where the bolt carries hardly any load yet, the capacity of the bolt is neglected when designing ring and shear-plate connector joints. For several connectors in a joint a decrease in load-carrying capacity per ring or shear-plate will be introduced in EC5. Until this rule is agreed upon, Equation (9) may also be used for ring and shear-plate connector joints.

Concluding summary

- The characteristic load-carrying capacity of a multiple fastener joint is frequently less than the sum of the individual fastener capacities.

- The most important factors influencing the characteristic load-carrying capacity of multiple fastener joints are plastic deformations in the connection, creep, fabrication tolerances and variations in load-slip behaviour between single fasteners.

- Plastic deformations and creep tend to equalise the loads between the single fasteners and are therefore beneficial for the load-carrying capacity of a multiple fastener joint.

- Fabrication tolerances in pre-drilled connections may severely decrease the load-carrying capacity, unless significant plastic deformations take place before the failure load is reached. Computer controlled high precision manufacturing largely reduces fabrication tolerances in pre-drilled connections.

- Variations in load-slip behaviour within the joint increase the *characteristic* load-carrying capacity of multiple fastener joints.

- The uneven load distribution in the elastic range due to different longitudinal deformations of the connected members hardly influences the ultimate loads of multiple fastener joints.

- EC5 includes a decrease in load-carrying capacity with increasing number of fasteners arranged in line with the load direction for bolts, dowels, large diameter screws and connector joints. The design of connections with slender dowel-type fasteners is not affected by the number of fasteners.

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Notation

F_1 is the load on the first or last fastener in the row
F is the load acting on the joint
n is the number of fasteners in a row parallel to the load F
K is the slip modulus
s is the fastener spacing
E is the member modulus of elasticity
A is the cross-sectional area of the connected member