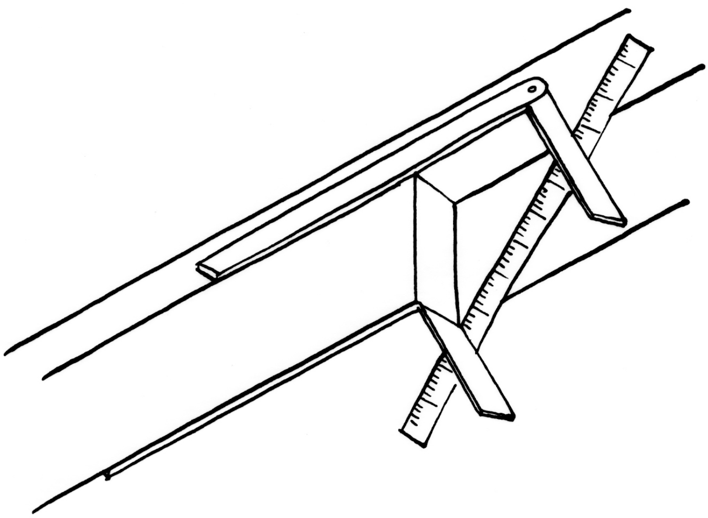
Lapped Scarf Joints for Repairs of Historical Structures

result of applied research - design method



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METHOD

Lapped Scarf Joints for Repairs of Historical Structures

Project Name: DF12P01OVV004
"Design and Assessment of Carpentry Joints of Historical Structures"

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This method is intended for the administrators of historical buildings, designers and workers, and organizations performing repairs of timber members and structures of historical buildings in order to ensure high quality of the preparation and execution of works for the preservation, long-term sustainability, high reliability, and safety of wooden structures.

Opponents:
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N_{met} – METHOD CERTIFIED

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Lapped Scarf Joints for Repairs of Historical Structures

Methods for designing and performing carpentry joints (hereinafter the "methods")

The methods were developed and published within the implementation of the project NAKI DF12P01OVV004 "Design and Assessment of Carpentry Joints of Historical Structures", funded by the Ministry of Culture of the Czech Republic pursuant to Agreement No. 4/2012/OVV. The project was executed from 2012 to 2015. The project executors were the Faculty of Civil Engineering of the Czech Technical University in Prague (FCE CTU), the Institute of Theoretical and Applied Mechanics AS CR, v. v. i. (ITAM) and the Faculty of Forestry and Wood Technology of Mendel University in Brno (MENDELU). The coordinating project executor was doc. Ing. Petr Fajman, CSc. who focused mainly on the assessment of the static load bearing capacity of the joints based on the results of the project.
Apart from the coordinating executor, the methods were also developed especially by Ing. Jiří Kunecký, Ph.D. (method editor, experiments, numerical models, stiffness determination), Ing. Hana Hasníková (experiments), doc. Ing. Petr Kuklík, CSc. (standardisation, relationship of methods to standards), Ing. Michal Kloiber, Ph.D. (timber diagnostics, material properties), Ing. Václav Sebera, Ph.D. (material properties, numerical models) and Ing. Jan Tippner, Ph.D. (material properties, wooden fasteners). The authors have years of experience in experimental testing of structures, advanced methods of structural mechanics and long-term behaviour of timber in structures. The results of the project were consulted in the course of its implementation in a working group, established for this purpose and comprising experts - structural engineers and carpenters, engaged in traditional techniques. In addition, the results were also presented and consulted in the European scale through the programme "COST FP1101 Assessment, Reinforcement and Monitoring of Timber Structures" financed by the European Union. Partial results of the research were published in prestigious international journals (Construction and Building Materials, Materials and Structures, etc.).

Abstract

This paper presents a description of the repair of timber structures using a prosthesis scarf joint designed for the replacement of damaged parts of beams. This new scarf joint makes use of the strutting effect of inclined contact faces where the forces are transmitted through wooden coupling elements - wooden dowels or keys. The scarf can be modified in four variants according to the relevant stress and is suitable for historically valuable timber structures. It meets both functional and aesthetic requirements. The designer - structural engineer will learn in the methods the load bearing capacity or stiffness of the beam with the designed joint, its recommended dimensions and detailed geometry. The contractor will appreciate the description of the execution and maintenance of the joint.

Keywords: carpentry joints, scarf joint, replacement, load bearing capacity, stiffness, joint execution

Acknowledgments

The authors of the methods would like to thank to the carpenters Petr Růžička, David Stejskal and Martin Šnajdr for their help in developing the technology of the joint execution. They are also grateful to structural engineers Ing. Otakar Hrdlička, Ing. Jan Vinař and Ing. Vít Mlázovský for their advice on the practical functioning of the joint. The authors thank also to the employees of ITAM AS CR, who participated in the experiments, especially Ing. Jan Bayer, Bc. Jan Chlád, Ing. Ondřej Vála, Ing. Pavel Zíma, Petr Alexander, Miroslav Slížek and Jaroslav Hodrment. Last but not least, they would like to thank Anna Arciszewska-Kędzior for her cooperation in the experiments and development of numerical models, Ing. Jaromír Milch for his experimental work, Jaroslav Buzek for his cooperation in the preparation of graphic materials for the methods.
The methods were developed with the support of the project of the Ministry of Culture NAKI DF12P01OVVOO4 "Design and Assessment of Carpentry Joints of Historical Structures".

CONTENTS

1 INTRODUCTION

1.1 Approach and Objective

Restoration of historical architectural sights is based on the requirement of preserving the original character of the building for future generations. Selected sights shall be preserved in a condition that our descendant can appreciate it in its most authentic form. Each preserved element of the structure or a part thereof carries historical information of immeasurable value - e.g. regarding the material, manufacturing technology, construction, etc. Therefore, there is an effort to repair historical buildings in such a manner that a visitor does not notice the repairs that would disturb the overall impression of the building, preserve the original building to the maximum extent and carry out repairs with maximum thoughtfulness [7], [15].

The timber structures in historical buildings, unless they are exposed to increased humidity, attacked by wood destroying insects, rot or overloaded, remain in a very good condition even after centuries, particularly with regard to the mechanical properties of the original (old) timber. In unfavourable conditions, however, wood degrades quickly, and the damaged parts must be removed and replaced. The defects are mainly detected in areas of contact between the beams and walls at the beam head. These areas provide an environment where the water could accumulate, culminating in high humidity which in turn may trigger wood degradation. In order to preserve as much of the original material as possible only the damaged or attacked parts of a structural member can be replaced. The reason is not only the monument protection but also purely practical and economic issues. Metal coupling elements are today normally used for these repairs (connection of old and new wood). Although metal elements were used in the past for carpentry joints, today, repairs with the use of bolts in a valuable roof structure or in an interior ceiling beam may seem inappropriate.

These methods focus on the use of a **carpenter scarf joint which makes use of only wooden coupling elements.** This joint provides sufficient mechanical stiffness and load bearing capacity, it is less noticeable, preserves the aesthetic character of the original structure and eliminates the disadvantages of the contact between wood and metal (e.g. chemical corrosion, mechanics of heterogeneous materials, condensation of moisture around coupling elements, etc.).

The guidelines assume the knowledge of the fields of structural mechanics and repairs of historical timber structures. The design section (see subsection 2.2) is intended for structural engineers and designers, while the practical section (section 0) is intended especially for carpenters and specialists performing construction supervision. It is advisable and recommended that the craftsmanship section is read and understood by all users of the methods, as they can meet with the practical consequences related to the use of the joint. It is substantial to read subchapter 1.4 for the joint design to understand the philosophy of the method.

1.2 Background

The technical standards in the Czech Republic became applicable in the 1930s, at the time when the use of classic carpentry joints was in decline and when joints with the use of industrially produced metal coupling elements started to be used. Therefore, traditional carpentry joints did not have to be dealt with in the developed standards. Today, the situation has changed. The basic document for designing timber structures is Eurocode 5 (EC5, [21]), where, however, the designing of carpentry joints is not addressed in a comprehensive manner. The transmission of forces in these joints takes place through the pressure and friction on the contact surfaces of the connected parts. Joints subjected to bending, such as a bent scarf joint, however, cannot be properly designed, because their mechanical behaviour (acting forces, stiffness) is unknown. This drawback is dealt with by giving a detailed description of how the scarf joint functions. It provides a clearer, more descriptive and, in terms of the protection of historical buildings, more thoughtful processes of the design and manufacture of carpentry joints for the repairs of historical timber structures.

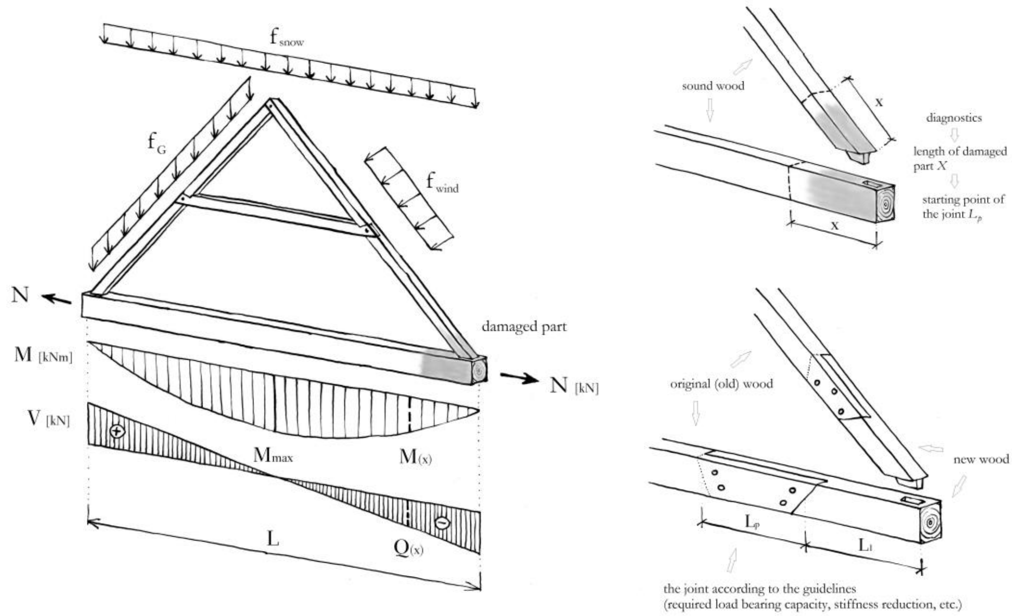


Fig. 1 Truss with damaged elements and the course of repair

1.3 Developing the Methods

Fig. 1 shows the course of the repair of a damaged structural member and the execution of a suitable carpentry joint. The damaged part at the end of the beam needs to be replaced. To determine where the wood in the member is not damaged the diagnostics of the material properties of wood is used [4]. This place is the starting point of the joint L_1. The structural engineer calculates the internal forces which are generated as a result of external loading (dead weight, wind, snow). The resulting combination of the bending moment M and the normal force N is then compared with the charts of the load bearing capacity in the methods (see below) and the joint length L_p is determined according to the recommended dimensions. The assessment of the serviceability limit state with respect to the stiffness of the scarfed beam is determined by the deflection w, which is calculated according to the formulas below for each type of joint (see e.g. section 2.2.2.1) as a function of the deflection of the entire beam without the joint w_0. The actual repair is then carried out by a professional company that performs the work in accordance with the practical section of the method.

1.4 Assumptions and Validity of the Method

1.4.1 Subject Specification

This method focuses specifically on an oblique face scarf joint, which is not formally covered by the existing standards and offers a range of uses in the conservation of monuments. It is an optimized lengthening joint ranking among the most common and suitable ones to be used for thoughtful repair of historical structures. Since the terminology in carpentry is not clearly estabilished, the terms used throughout the document are defined in the glossary (see Appendix C).

This subsection also mentions **some other carpentry joints** which are either trivial in terms of design, or are designed in such manner that they do not require any deeper explanation. The designs of those carpentry joints can be seen in the figures below, as well as could be found in literature [2], [8], [18], [22], [23], [50].

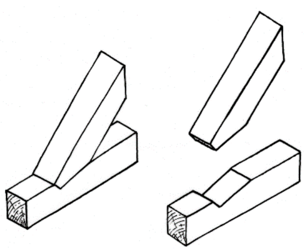


Fig. 2 Oblique step joint [23]

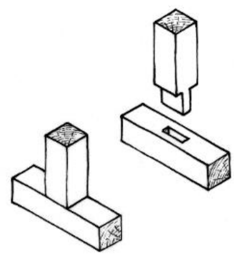


Fig. 3 Mortise and tenon [2]

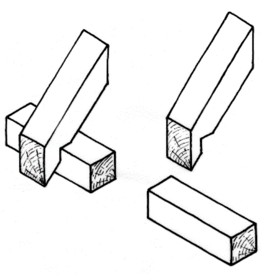


Fig. 4 Bird's-mouth joint [2]

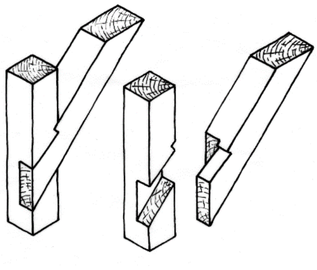


Fig. 5 Dovetail lap joint [2], [50]

1.4.2 Process of Developing the Methods and Validity of Results

The oblique face scarf joint was studied in detail experimentally as well as using mathematical and numerical models. The results are valid within the specified ranges of the joint parameter. **If the joint in non-compliant with the ranges of load bearing capacity or stiffness, its use must be consulted with the authors of the methods, or the responsibility for the design must be taken. In this case, however, it is not possible to refer to these methods.**

The experimental testing involved three-point bending of beams of different configurations (different sizes, number of coupling elements, geometry, type of wood). Material tests of individual test samples were performed separately and the humidity of test samples was monitored. The load bearing capacity of wooden dowels and keys used in the calculation criteria is also based on the experimental tests. The joint geometry was designed based on a mechanical analysis (including the application of numerical methods) and a series of tests (first with oblique faces, then with the use of coupling elements). The use of wooden coupling elements is not described in EC5; the minimum spacing (a_1 - a_4) is only provided for steel coupling elements [21]. However, they are partially accounted for in the basic design of the geometry of the carpentry joint (generally, they are preserved, in parameter $a_{3,t}$ distance *6d* is used instead of *7d* and in $a_{4,t}$ *3d* is used instead of *4d*). The numerical models, calculations and experiments carried out show that a lower inclination of the faces of the scarf joint (≤**40**°) is more convenient in bending from the structural point of view. From the practical point of view, lower inclination excessively increases the length of the cut and, naturally, the length of the joint itself. A medium inclination of **45**° was selected to satisfy both requirements. The inclination of **60**° is only suitable for combined compressive and bending stress (e.g. rafters, inclined supports).

The structural model dealing with the load bearing capacity and the numerical model specifying the stiffness were verified using the experimental results [51], [52] and, subsequently, the models were applied to create diagrams of load bearing capacity, or to derive formulas for deflection (stiffness). **The method itself does not introduce any design safety; it shows the results corresponding to the end of the linear area of the joint behaviour in the experiments and models.**

THE DESIGN SAFETY IS A TASK OF THE STRUCTURAL ENGINEER PREPARING THE DESIGN.

The structural engineer should take into account the exposure (humidity, temperature effects), the quality of both the original and new timber, the expected quality of craftsmanship, the impact of long-term loading, etc. These influences are described in EC5 [20] through coefficients k_{mod}, k_{def}, γ_M.

The stiffness of the joints is approximated so that its results show a maximum error of 10%, especially in case of extreme dimensions ($L/h = 15 \div 50$).

For the sake of completeness, the **failure criteria** are stated with regard to which the model of the load bearing capacity was calculated. This model was verified by experiments. The material properties were considered in their characteristic values.

- The timber was considered with the limit tensile and compression strength parallel to the grain;$f_{0,max} = 40$ MPa.
- The load bearing capacity of the system of dowel/hole drilled in parallel to the grain was determined according to experiments at $F_{dowel,0,max} = 12.5d^2 - 54d$ [N], where *d* is the diameter of the dowel in millimetres. For definition of the dowel see glossary Appendix C.
- The load bearing capacity of the system of dowel/hole drilled in perpendicular to the fibre was considered as $F_{dowel,90,max} = F_{dowel,0,max} \frac{f_{h,90}}{f_{h,0}}$ [N], where $f_{h,0}$ is the embedment strength in the direction parallel to the grain a $f_{h,90}$ is the embedment strength in the direction perpendicular to the grain determined according to [21] for a particular geometry of the joint.
- The load bearing capacity in the direction perpendicular to the grain which was experimentally experienced as a limiting condition for the formation of a crack in the face, was considered as $F_{face,90,max} = nd\frac{b}{4}f_{t,90,max}$ [N], where *nd* is the distance of the dowel from the face of the joint in the direction parallel with the grain (*n* is the number of diameters, *d* is the dowel diameter, e.g. *6d*; the dowel joints had this value of *6d*, key joints of *6d* and *9d* corresponding to the lengths of the joint of *3h* and *5h*), $\frac{b}{4}$ is a half of the section divided by two because of the usual presence of drying cracks extending up to half of the lap and $f_{t,90,max}$ is the experimental tensile strength perpendicular to the grain according to [14].
- The load bearing capacity of the key was determined experimentally using the keys of recommended dimensions with the final value of 10 kN, which corresponds to the end of the linear part of the force-deflection diagram. If more keys are considered, the effective number of keys is $n_{ef} = 0{,}8 \cdot n^{0{,}9}$ (relation based on EC5 [21]). For definition of the key see glossary Appendix C.
- The diagrams of load bearing capacity are computed for dowel diameter $d = \frac{h}{10}$.
- Stiffness is approximated within the limits $10 < \frac{L}{h} < 50$, where *L* is the length of the beam and *h* is its height. Inaccuracies in the definition of the length may occur in the case of beams supported at several points, where *L* can be regarded either as the entire length of the beam or the span of its fields. In such cases, the method does not provide any clear valid formulas, as it is not possible in principle.

1.5 Advantages and Disadvantages of Carpentry Scarf Joint

Advantages

- The joint can be made on site using standard carpenter equipment.
- The joint is highly durable, assuming that the conditions and maintenance are in compliance with (see section 4).
- The scarf joint has a relatively high load bearing capacity.
- The use of the joint cultivates and promotes the craft of carpentry.
- The joint is compatible, from the aesthetic point of view, with most of historical timber structures.

Disadvantages

- The requirement for mastering carpentry - this applies particularly to the company performing the work.
- Careful execution and low tolerances are required.
- Necessary checks and maintenance of joints.

2 DESIGN OF CARPENTRY SCARF JOINTS

2.1 Description of Mechanical Behaviour of Joints

2.1.1 General Principles

- The main principle of joint is the engagement of oblique (or also undercut) faces into the mechanical action. The faces transfer the shear force V, thereby reducing the force applied on the dowel V_{kz} in the direction perpendicular to the grain.
- The force acting through the strutting of the faces turns the direction of its action from forces perpendicular to the grain to forces that are parallel with the grain; this higher timber load bearing capacity can be utilized in this direction.

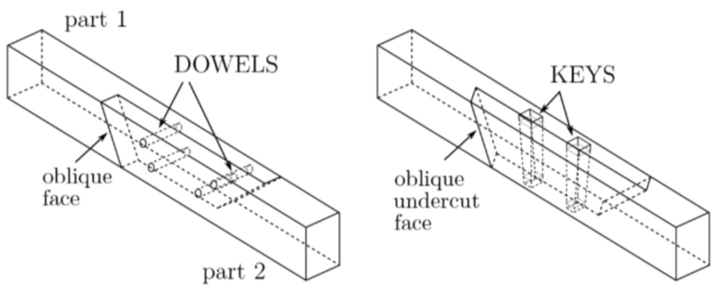


Fig. 6 Scarf joint with four dowels and scarf joint with two keys

- The mutual displacement of the oblique faces is prevented by friction; the angle of inclination determines the distribution of forces on the face. The face angle of 45° proved to be very useful both in practical and functional terms. The only exception to this rule are faces with 60° inclination suitable for compressed members - mostly rafters, collar beams, etc.
- Wooden coupling elements of stiffness similar to the connected material allow more uniform distribution of stress around the dowels compared with steel coupling elements. This prevents deformation and subsequent damage. Some wooden coupling elements, e.g. keys, have stiffness that high that they transmit majority of forces in the joint and can thus replace steel studs in terms of the load bearing capacity. Nevertheless, they do not tear the surrounding wood because of the large area in which they act.
- A joint can be subjected to combined load. While the shear force V is neglected because its size does not affect the load bearing capacity of the joint much, the combination of the stress applied by the normal force N (tension/compression) and the bending moment M is decisive.
- In case of **combined stress, both the load bearing capacity and the stiffness of the joint vary.** The effect on the joint load bearing capacity is shown in the load bearing capacity diagrams *M-N* (see Fig. 8). In the case of a combination of compression and the bending moment the joint stiffness increases. In the case of bending and tension, however, the **rigidity is decreased by about 25%** due

to the reduced frictional force on the faces as a result of the expansion of the joints to the sides. This fact is highlighted separately for each joint.

- Keys always work as the main (load-bearing) coupling means. Dowels work as either the main coupling elements, or as securing elements. The distinction between these two functions lies especially in the stiffness of individual members - e.g. an oak key always carries higher force because it is much stiffer than a dowel. The function the coupling elements is indicated for each joint.
- The joint is fitted with a relatively low number of coupling elements ($n \leq 4$), since appropriate stiffness and load bearing capacity of the joint must be ensured in order to avoid the condition where the load bearing capacity depends only on the reduced cross-section of the original member. An example is a joint with many dowels, which may be too stiff to provide another condition for failure than reduced cross-section - the oblique faces are not engaged in the transmission of forces and the dowels will not shear off.

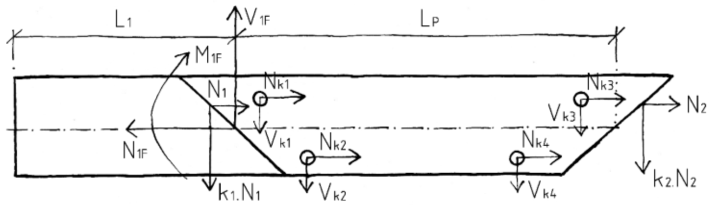
2.1.2 Joint Structural Model

The oblique face scarf joint resists the loading by the engagement of the faces and the load bearing capacity of the keys and dowels (see Fig. 7). If there is a member in the xz plane, the load acts mainly in this plane. In the case a member is without a joint, then the only forces present are normal forces (N_x), shear forces (V_z) and bending moments (M_s). However, in the case of a scarf joint, the situation is more complicated and the forces generated in individual parts cause other internal forces - the torque moment (M_x) and bending moment (M_z). In many structures (joists, rafters), these influences are eliminated by supports preventing a shift sideways and twisting (decking on joists, lathing on rafters). In addition, the torque moment (Mx) and bending moment (Mz) are negligible in massive elements (tie beams). Furthermore, opening and twisting motions could be prevented in a joint by providing undercut faces, studs and wooden dowels with wedges, which limit movement at the end of the joint.

Loading generates the following forces in the joint:

- Forces acting at the abutment of faces - a force perpendicular to the face which exerts frictional force acting in parallel with the faces. This force acts against the sliding of faces and increases the scarf joint load bearing capacity. The forces can be transformed into forces acting in parallel with the axis of the member - x-direction (N_i) and perpendicular to it - z-direction (V_i).
- Forces in dowels - acting in two directions parallel with the axis of the member (N_{ki}) and perpendicular to it (V_{ki}).
- Forces in keys - the prevailing force is parallel with the axis of the member (N_{bi}); there can also act a perpendicular force arising from friction ($V_{bj}=\mu N_{bi}$). There is also the moment M_{bi} that acts in the xz plane, bending the key in the height.

The second part of the scarf joint is subjected to equal and oppositely oriented forces according to the principle of action and reaction.



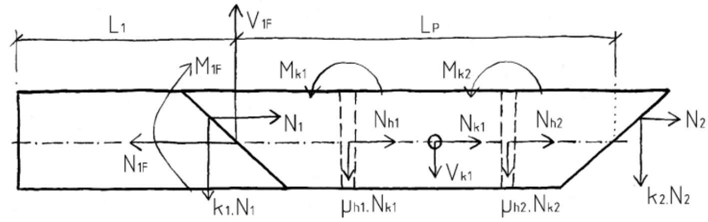


Fig. 7 Forces acting in the joint with four dowels 4D (top) and in the joint with two keys and one dowel 2K+1D (bottom).

In terms of strength characteristics, the weakest point on the faces is the tension or compression acting perpendicularly to the fibres (in the direction of the force V_i). In the case of dowels, there is shear perpendicular to the grain, or deformation of the dowel; in the case of keys, there is shear parallel or perpendicular to the grain. The manufacturing processes of the coupling elements differ in that the dowels have to be split, while the keys may feature desirable growth imperfections, particularly knots, which improve the shear properties parallel with the grain.

The ratio of the stiffness of individual components (member, friction, dowel, key) determines which criterion is the crucial one. The dowel stiffness depends mainly on its diameter. If the joint has very stiff dowels, the forces are concentrated in them and their load bearing capacity will be decisive (the beam may be split in parallel with the grain at the dowels). In case of joints with smaller dowels, the face is subjected to a higher stress and its load bearing capacity is decisive. If the principles described in this method are observed, the stress is divided evenly between the dowels, or keys, and the faces. See more on the mechanics of the scarf joint in [37], [38], [39], [40], [41].

2.2 Joint Design

2.2.1 General Design Principles

The replacement of the original member should be made of the same kind of wood. Moisture and other physical and mechanical properties of timber should be compatible with the original structure.

The joint is designed for the ultimate limit state and serviceability limit state, i.e. the maximum deflection. The table, hereinafter referred to as the so-called "joint card" (see for instance section 2.2.2.1), specifies design diagrams and equations for the calculation of deflection for each joint. The notation of the joint geometry corresponds to the common practice - section width *b*, section height *h*, length of beam *L*.

2.2.1.1 Important and Indispensable Design Principles:

- ! The values of the load bearing capacity are calculated for the **end of the linear section of the joint loading working diagram**. **It is never designed to this limit**, but it is necessary to apply adequate **safety determined by the structural engineer**.
- ! The structure is simplified to a planar one - the moments bending the structure perpendicular to the longitudinal vertical plane have little effect on the distribution of forces in the scarf joint.
- ! Twisting of the section at the point of the scarf joint is neglected.
- ! When repairing timber ceiling structures, the second limit condition must be verified along with the load bearing capacity. Its compliance ensures that the structure is flexible.
- ! **The scarf joint stiffness changes in combined stress. The details are described separately for each joint.**
- ! The minimum number of the coupling elements is **three**.
- ! The **dowel diameter** shall be $\boldsymbol{\frac{h}{10}}$, could be higher for specific purposes (e.g. negligible bending moment and high tension can allow the designer to increase the diameter and bearing capacity consequently).
- ! **The minimum distance of the end of the joint from the edge of the beam is *2h*.**
- ! In the event that the beam is to be **scarfed at several places, their minimum distance is *6h*.**
- ! **The joints are only designed for sections of** $\boldsymbol{\frac{2}{3} < \frac{b}{h} < 1}$ **.**
- ! All distances are given on the **centreline of the beam, not on the edges of the cross-section**. The points L_1 or $L_1 + L_P$ are the centres of the face rotation.
- ! **The joint should not be made in the middle of the beam** and its end shall never exceed the half of the length of the beam. In these places, the use of the joint is extremely inappropriate due to the high bending moment. The closer to the centre of the beam, the longer the scarf joint should be.
- ! **The joint may never be loaded directly at the point of the joint** (e.g. by a support or column), but always at least at the distance of *one height* of the beam from the ends of the faces on both sides.
- ! The **joint orientation** must ALWAYS be such that the faces are angled in the direction of the letter V (\=/) for the positive bending moment according to the convention. One should always try to "narrow" the imaginary letter V, not to "break" it apart. In the opposite direction of the bending moment (see the design diagram below), the joint has a significantly lower resistance to bending.

2.2.1.2 Design of the Ultimate Limit State

The structural engineer determines, based on the external loading of the structure, the normal force *N* and the bending moment *M* acting in the middle of the scarf joint. (to the point where undamaged wood starts according to the diagnostic examination, namely the value L_1, a half of the designed length of the scarf joint L_P is added). If the length of the scarf joint L_p is unknown, the default joint length of *5h* should be selected (where *h* is the height of the original beam). These values are compared with the *M-N* diagram (see Fig. 8), whose **inner section represents a safe area for the design based on the values without considering safety!** Linear interpolation between the dimensions is possible to obtain information for different sections. The method considers standard cross-sections occurring in structures. The calculated values for a specific designed beam compared with the values of the diagram will show the final design safety. The structural engineer shall determine the safety limit depending on the quality of the timber, level of craftsmanship, environmental conditions, etc. As some viscoelastic effects may occur at the ultimate limit loading of the timber, it is not recommended to apply this limit, particularly due to possible long-term increased deflection. The **diagrams of key joints** are calculated for the lengths of the scarf joints L_P in the range from *3h* to *5h;* integer limits are preferable in case of interpolation (scaling of sections). The minimum recommended length of the joints is *3.3h*, or *3.7h*, see the GEOMETRY section in the joint cards.

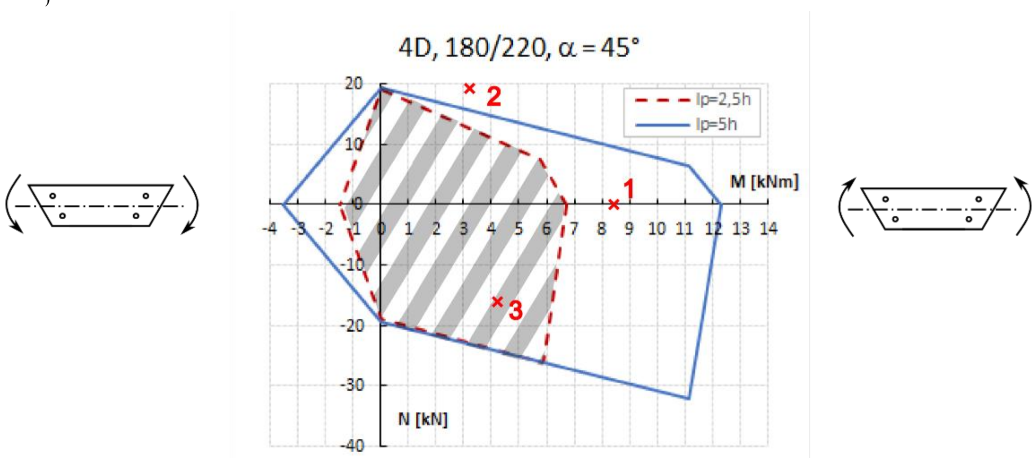


Fig. 8 Examples of the use of the design diagram, M-N; point 1 corresponds to a ceiling beam with the prevailing loading by the bending moment (compliant joint with the length L_p higher than 2.5h), point 2 represents a member loaded mainly by tension and it is outside the design diagrams (the scarf joint would fail), point 3 indicates combined loading of a member occurring for instance at rafters (a joint of a minimum length of 2.5h with adequate safety may be used). The left part of the chart with a negative bending moment shows bending of the joint to the wrong side.

2.2.1.3 Design of the Serviceability Limit State

There is a formula for the calculation of stiffness *k* from the beam parameters for each of the following types of joints. There is also a formula for the calculation of the increased deflection of a member with a joint *w* compared with an undamaged beam w_0. Since the values are based on laboratory measurement and linear models, they are instantaneous and the creep is not considered. The calculation of stiffness is shown in Fig. 9. The minimum distance from the edge of the beam (*2h*) is ideal for the joint, because it is then loaded with the lowest moment. The stiffness ratios are valid for $10 < \frac{L}{h} < 50$, where *L* is the length of the beam and *h* is its height. Beams having higher or lower slenderness cannot be approximated by the ratio and the method does not address it, nevertheless, they are almost absent in practice. Very stiff beams ($\frac{L}{h} \leq 15$) show the greatest approximation error - that is 20%. The joint card (see, for instance, section 2.2.2) always lists the stiffness of a scarfed member *k* and then its deflection *w*. The stiffness corresponds to experimental values, the formulas were derived from models of experiments in three-point pure bending.

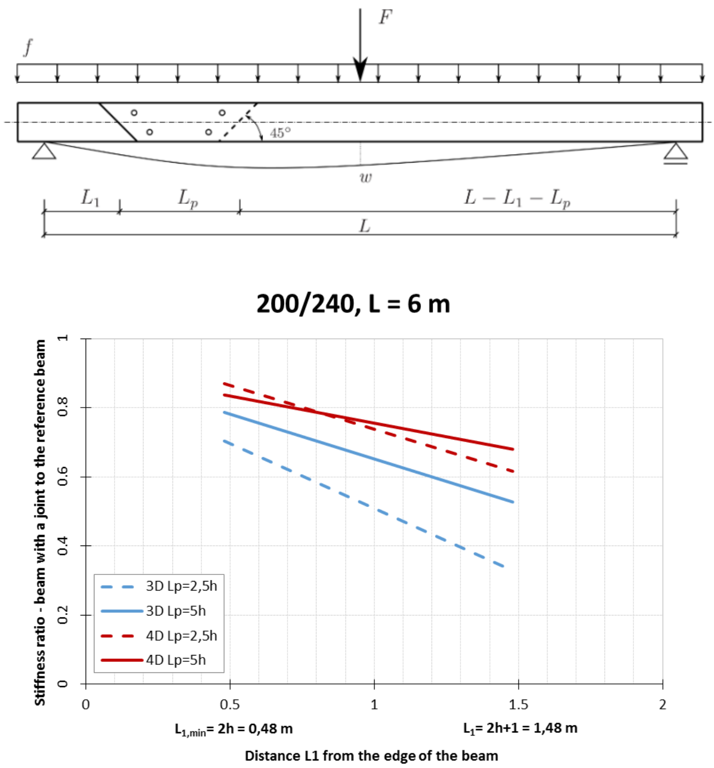


Fig. 9 Dimensions of structure and beam deflection (above), dependence of beam stiffness with a joint shifting along the beam centreline (bottom)

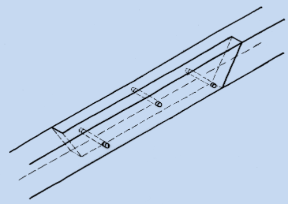
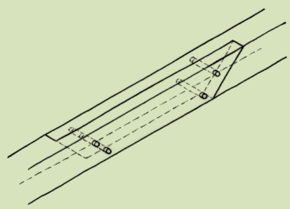
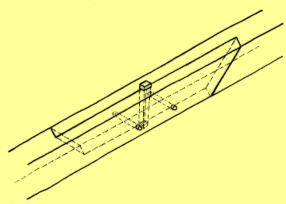
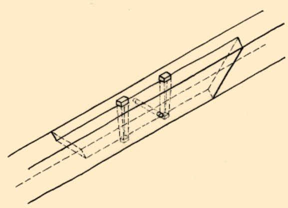
2.2.1.4 Joint dimensions, minimum and maximum recommended length

The joint cards provide general dimensions of joints (DRAWING, GEOMETRY). They can be increased or decreased as needed, while maintaining the above ratio of dimensions. The geometry is generally determined by the multiples of the section height *h*. Then the minimum and maximum recommended dimensions of the joint are specified, which depend on a suitable distance of the coupling elements and other practical results obtained during the experimental testing of the joint. They are always calculated and drawn for the size of a relevant section specified in the load bearing capacity diagrams.

When designing a joint longer than *5h,* it is not suitable to extrapolate the load bearing capacity or stiffness, because the results beyond this limit cannot be guaranteed. Nevertheless, you can consult a specific possible use with the authors of this method (see Annex D for contacts).

2.2.2 Overview of Joints and Their Suitable Use

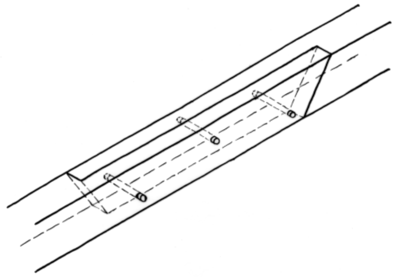
The following section discusses in detail **four alternatives of a designed extension scarf joint**. They are determined according to the number and type of the coupling elements. There is a recommended appropriate use of each joint in a structure that corresponds to the type of stress the joint is designed for.

Name of joint and basic data	Suitable type of stress	Figure	Use in the structure
Three-dowel • number of dowels $n = 3$ • angle of faces 60° • the bearing members are dowels and faces • in specified cases, a suitable alternative with undercut faces	BEND + COMPRESSION		rafters
Four-dowel • number of dowels $n = 4$ • face angle of 45°, in case of rafter bending and compression a 60° alternative • the bearing members are dowels and faces • in specified cases, a suitable alternative with undercut faces	Prevailing BEND + TENSION, COMPRESSION		rafters (version of 60°), joists (version of 45°)
One-key • one key, number of dowels $n = 2$ • angle of faces 45° • the bearing parts are the key and faces • always undercut faces	Prevailing BEND + TENSION		joists
Two-key • two keys, number of dowels $n = 1$ • angle of faces 45° • the bearing parts are the keys and faces • always undercut faces	Prevailing BEND + TENSION		joists

2.2.2.1 Three-Dowel Joint with Oblique Faces

(hereinafter referred to as “three-dowel” or “3D”)
Alternative with only oblique (A) or oblique undercut (B) faces

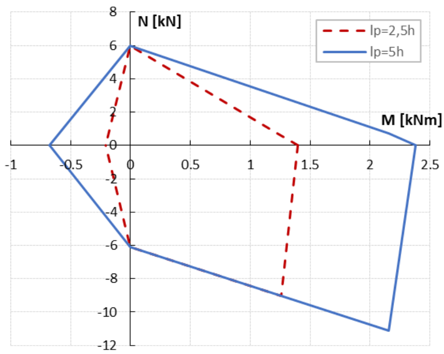
FUNCTION



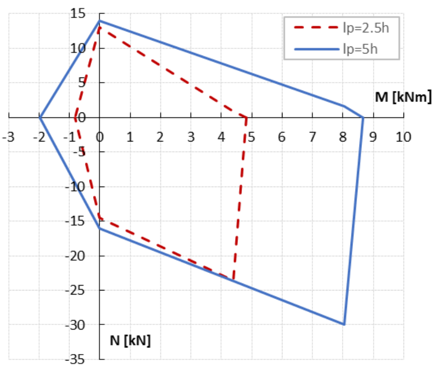
- transmits **suitably only the combination of compression and bending** and therefore is only suitable for small loading, e.g. rafters
- only in the alternative with 60° faces
- suitable for smaller sections
- three load-bearing dowels
- in the case of the section twisting, twisting of new or old wood, or changes in shape due to shrinkage, it is desirable to apple alternative B with undercut faces (see DRAWING, GEOMETRY - alternative B).

LOAD BEARING CAPACITY

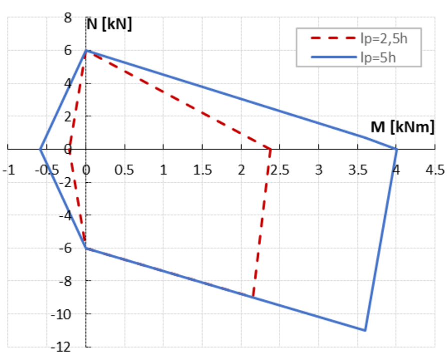
3D, 140/160, α = 60°



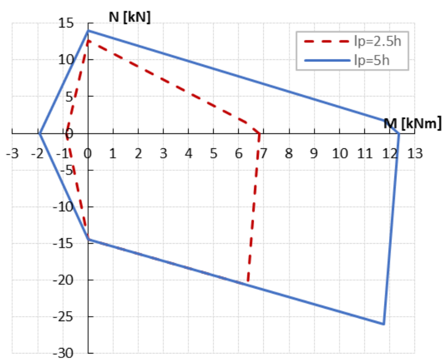
3D, 180/220, α = 60°



3D, 140/160, α = 45°



3D, 180/220, α = 45°



STIFFNESS

Stiffness of a member with a scarf joint and corresponding deflections

$$L_1 < \frac{L}{12}, L_p = 2.5h: \quad k = 367Eb\frac{h^{2.4}}{l^{2.4}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 10.9\frac{h^{0.6}}{L^{0.6}}$$

$$L_1 > \frac{L}{12}, L_p = 2.5h: \quad k = 100Eb\left(3.67 - 11.73\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.4}}{L^{2.4}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(3.67 - 11.73\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.6}}{L^{0.6}}$$

$$L_1 < \frac{L}{12}, L_p = 5h: \quad k = 410Eb\frac{h^{2.4}}{l^{2.4}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 9.8\frac{h^{0.6}}{L^{0.6}}$$

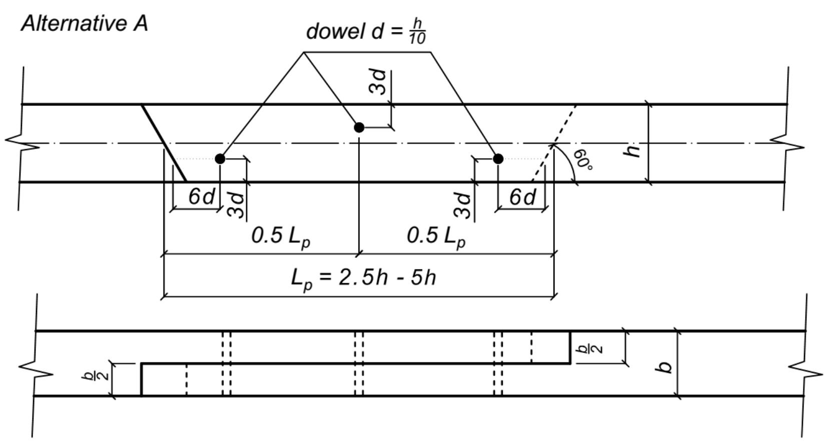
$$L_1 > \frac{L}{12}, L_p = 5h: \quad k = 100Eb\left(4.1 - 8.1\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.4}}{L^{2.4}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(4.1 - 8.1\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.6}}{L^{0.6}}$$

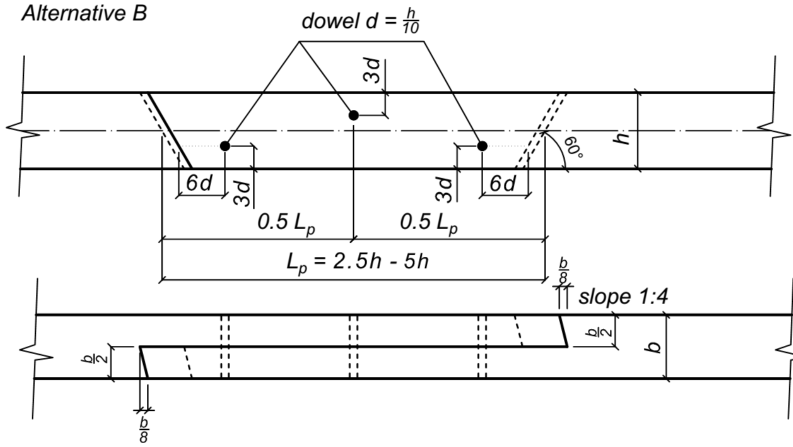
b is the section width [m], *h* is the section height [m], *L* is the member length [m], L_1 is the distance of the face in the axis from the end of the beam [m] and *E* is the average value of the modulus of elasticity [GPa] according to [24]; *w* is the deflection of the beam with a joint, w_0 is the initial deflection of the beam without a joint.

This stiffness is calculated for pure bending. In the case of combined loading, compression and bending the stiffness remains or slightly increase; **in the case of tension and bending, on the other hand, the stiffness is about a quarter lower, therefore the deflection is up to a quarter higher** compared to the aforementioned relations.

DRAWING, GEOMETRY

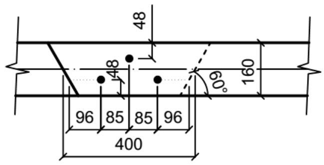


Alternative B

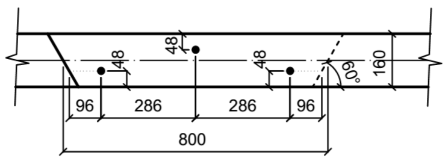


RECOMMENDED DIMENSIONS

$b/h = 140/160$
$L_p = 2.5h$
$d = 16$ mm
$a_1 = \min 5d = 80$ mm < 85 mm



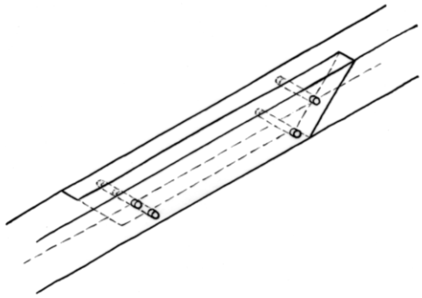
$b/h = 140/160$
$L_p = 5h$
$d = 16$ mm



2.2.2.2 Four-Dowel Joint with Oblique Faces

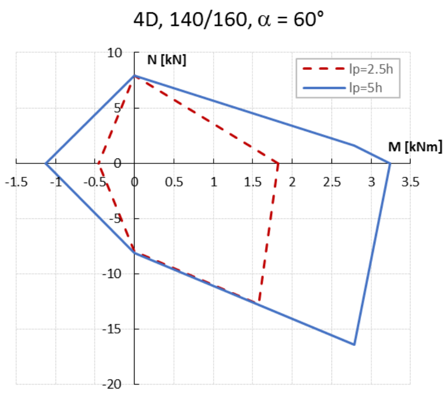
(hereinafter referred to as "four-dowel" or "4D")
Alternative with only oblique (A) or oblique undercut (B) faces

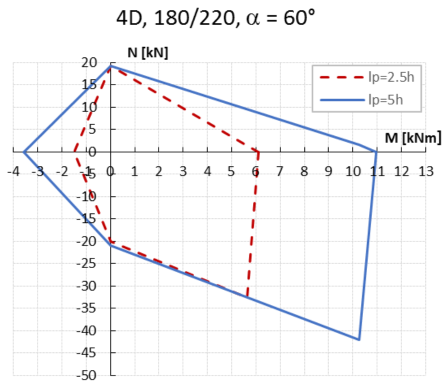
FUNCTION

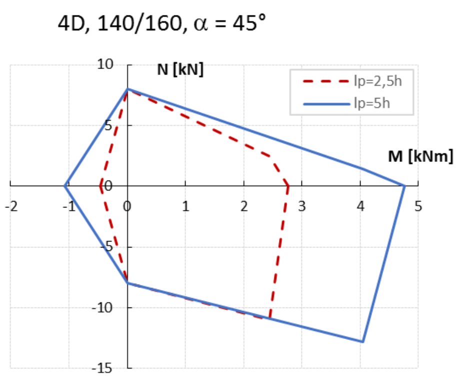


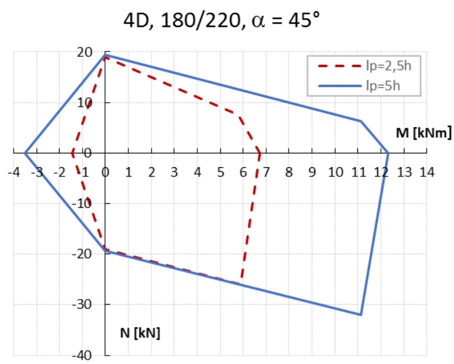
- suitable for sections of all sizes
- all four dowels are load bearing
- transmits **suitably the combination of compression and bending** as well as **tension and bending** and therefore has universal use
- in the alternative with the angle of faces of 45° (bending, tension + bending) and 60° (compression + bending)
- in the case of the section twisting, twisting of new or old wood, or changes in shape due to shrinkage, it is desirable to apple alternative B with undercut faces (see DRAWING, GEOMETRY - alternative B). **It is always necessary in the case of tie beams.**

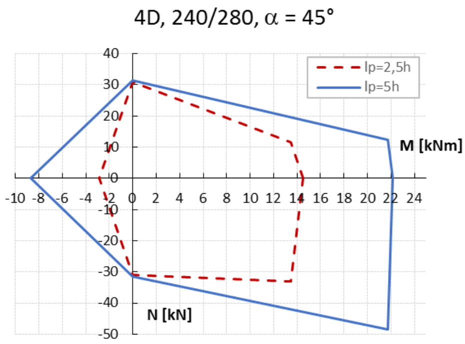
LOADING CAPACITY









	
STIFFNESS	Stiffness of a member with a scarf joint and corresponding deflections

$$L_1 < \frac{L}{12}, L_p = 2.5h: \quad k = 870Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.6\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 > \frac{L}{12}, L_p = 2.5h: \quad k = 100Eb\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0\frac{40}{\left(8.7-16\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 < \frac{L}{12}, L_p = 5h: \quad k = 830Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.8\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 > \frac{L}{12}, L_p = 5h: \quad k = 100Eb\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

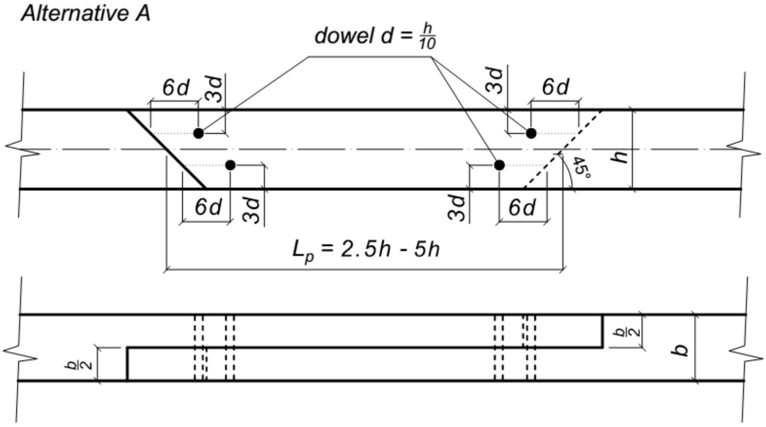
$$w = w_0\frac{40}{\left(8.3-9.4\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

b is the section width [m], *h* is the section height [m], *L* is the member length [m], L_1 is the distance of the face in the axis from the end of the beam [m] and *E* is the average value of the modulus of elasticity [GPa] according to [24]; *w* is the deflection of the beam with a joint, w_0 is the initial deflection of the beam without a joint.

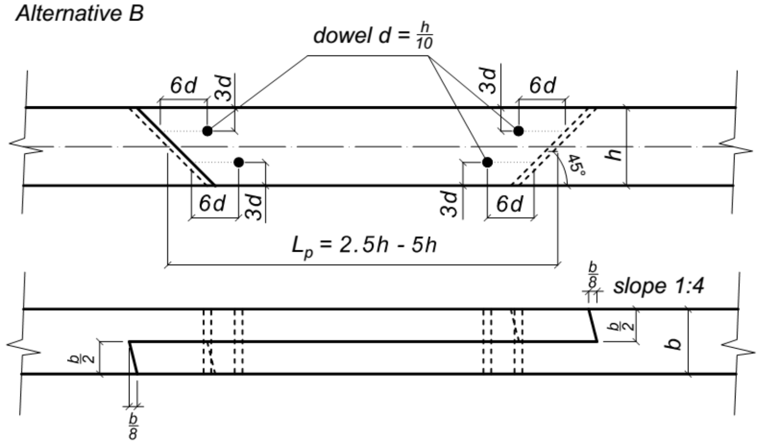
This stiffness is calculated for pure bending. In the case of combined loading, compression and bending the stiffness remains or slightly increase; **in the case of tension and bending, on the other hand, the stiffness is about a quarter lower, therefore the deflection is up to a quarter higher** compared to the aforementioned relations.

DRAWING, GEOMETRY

Alternative A

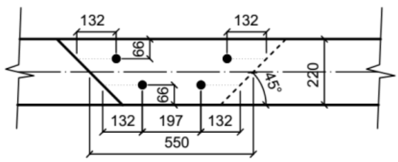


Alternative B

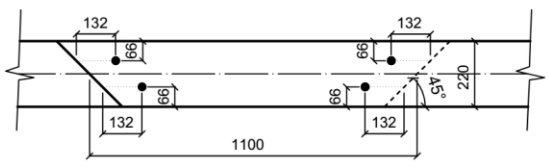


RECOMMENDED DIMENSIONS

$b/h = 180/220$
$L_p = 2.5h$
$d = 22$ mm
$a_1 = \min 5d = 110$ mm < 197 mm



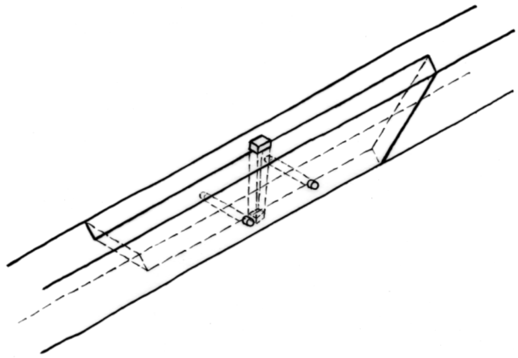
$b/h = 180/220$
$L_p = 5h$
$d = 22$ mm



2.2.2.3 Single-key joint with oblique undercut faces secured with two dowels

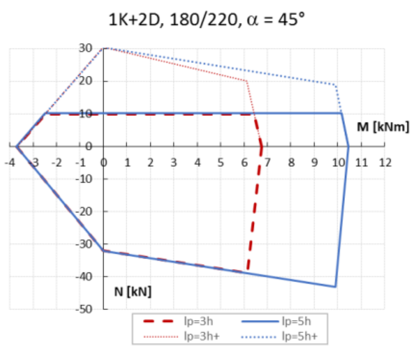
(hereinafter referred to as the "single-key" or "1K+2D")

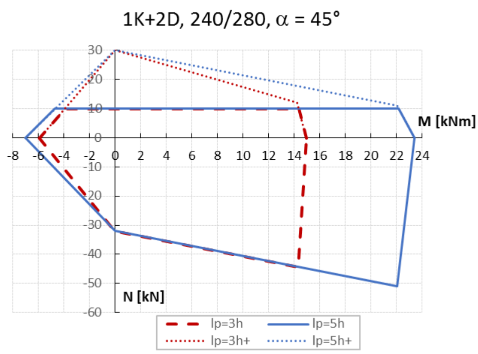
FUNCTION



- **both oblique and undercut faces are always required that prevent the rotation of the key**
- it transmits **desirably all the above types of loading (tension, compression, bending)**
- available only in the alternative with 45° faces
- suitable only for larger sections because of the size of the key
- the key is the main load-bearing element that with its high stiffness and load bearing capacity transfers the vast majority of forces in the joint
- in beams of a width up to $b \leq 220\ mm$, it is desirable to use keys with the base dimensions of 40 × 40 mm; in the case of larger sections, the alternative with the dimensions of 50 × 50 mm shall be used (see the DRAWING, GEOMETRY)

LOAD BEARING CAPACITY





Note: When loaded in pure tension, the joints containing the keys could become unstable, the keys tend to rotate (roll off) and open pushing the two halves of the lap joint apart. In the graphs there are two linestyles: the straight thick line shows the basic configuration of the joint described in the method under consideration. The dotted line shows the potential load bearing capacity in tension if the rotation of the key is prevented by the introduction of transversal fasteners for the two laps of the scarf joint.

STIFFNESS

Stiffness of a member with a scarf joint and corresponding deflections

$$L_1 < \frac{L}{12}, L_p = 2.5h: \quad k = 870Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.6\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 > \frac{L}{12}, L_p = 2.5h: \quad k = 100Eb\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 < \frac{L}{12}, L_p = 5h: \quad k = 830Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.8\frac{h^{0.4}}{L^{0.4}}$$

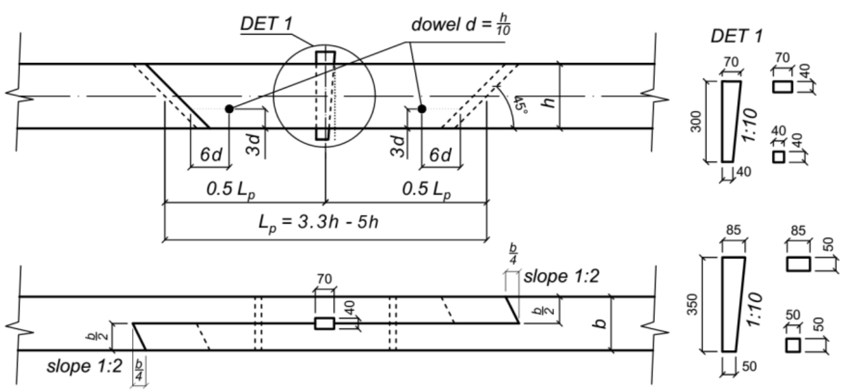
$$L_1 > \frac{L}{12}, L_p = 5h: \quad k = 100Eb\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

b is the section width [m], h is the section height [m], L is the member length [m], L_1 is the distance of the face in the axis from the end of the beam [m] and E is the average value of the modulus of elasticity [GPa] according to [24]; w is the deflection of the beam with a joint, w_0 is the initial deflection of the beam without a joint.

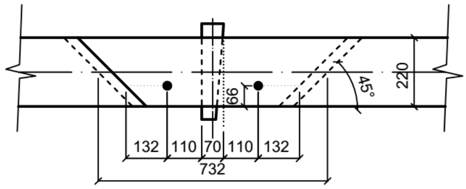
This stiffness is calculated for pure bending. In the case of combined loading, compression and bending the stiffness remains or slightly increase; **in the case of tension and bending, on the other hand, the stiffness is about a quarter lower, therefore the deflection is up to a quarter higher** compared to the aforementioned relations.

DRAWING, GEOMETRY

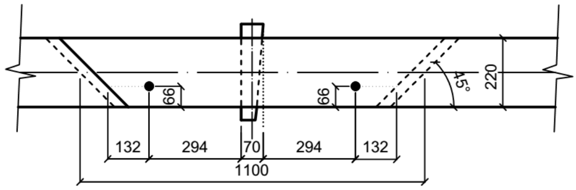


RECOMMENDED DIMENSIONS

b/h = 180/220
$L_p = 3.3h$
d = 22 mm
a_1= *min 5d = 110 mm*



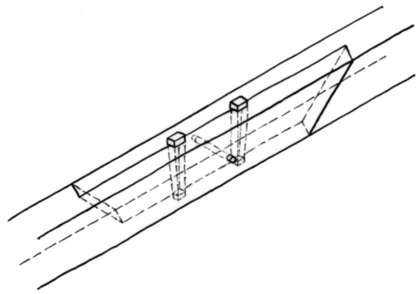
b/h = 180/220
$L_p = 5h$
d = 22 mm



2.2.2.4 Two-key joint with oblique undercut faces secured with one dowel

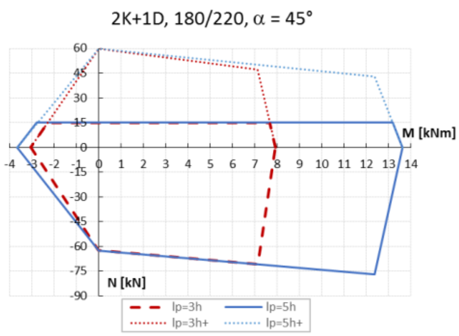
(hereinafter referred to as the "two-key" or "2K+1D")

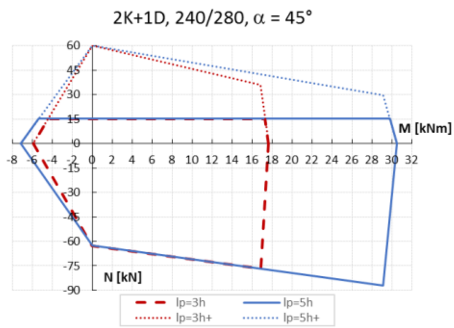
FUNCTION



- **both oblique and undercut faces are always required to prevent the rotation of the keys**
- it transmits **desirably all the above types of loading**
- available only in the alternative with 45° faces
- suitable only for larger sections because of the size of the key
- the keys, with their high stiffness and load bearing capacity, are the main load-bearing elements and transfer the majority of the forces present in the joint
- in beams of a width up to $b \leq 220\ mm$, it is desirable to use keys with the base dimensions of 40 × 40 mm; in the case of larger sections, the alternative with the dimensions of 50 × 50 mm shall be used (see the DRAWING, GEOMETRY)

LOAD BEARING CAPACITY





Note: When loaded in pure tension, the joints containing the keys could become unstable, the keys tend to rotate (roll off) and open pushing the two halves of the lap joint apart. In the graphs there are two linestyles: the straight thick line shows the basic configuration of the joint described in the method under consideration. The dotted line shows the potential load bearing capacity in tension if the rotation of the key is prevented by the introduction of transversal fasteners for the two laps of the scarf joint.

STIFFNESS

Stiffness of a member with a scarf joint and corresponding deflections

$$L_1 < \frac{L}{12}, L_p = 2.5h: \quad k = 870Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.6\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 > \frac{L}{12}, L_p = 2.5h: \quad k = 100Eb\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

$$L_1 < \frac{L}{12}, L_p = 5h: \quad k = 830Eb\frac{h^{2.6}}{l^{2.6}} \text{ [MNm}^{-1}\text{]}; \quad w = w_0 4.8\frac{h^{0.4}}{L^{0.4}}$$

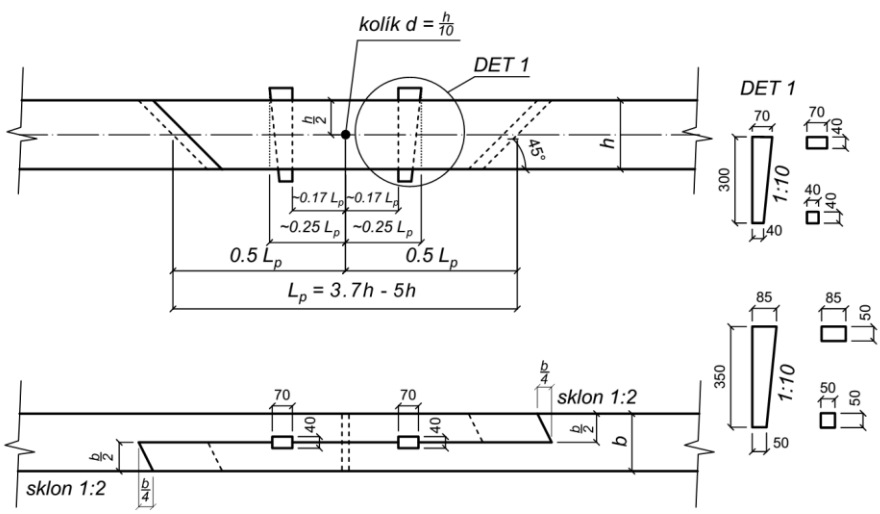
$$L_1 > \frac{L}{12}, L_p = 5h: \quad k = 100Eb\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} \text{ [MNm}^{-1}\text{]};$$

$$w = w_0 \frac{40}{\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)}\frac{h^{0.4}}{L^{0.4}}$$

b is the section width [m], *h* is the section height [m], *L* is the member length [m], L_1 is the distance of the face in the axis from the end of the beam [m] and *E* is the average value of the modulus of elasticity [GPa] according to [24]; *w* is the deflection of the beam with a joint, w_0 is the initial deflection of the beam without a joint.

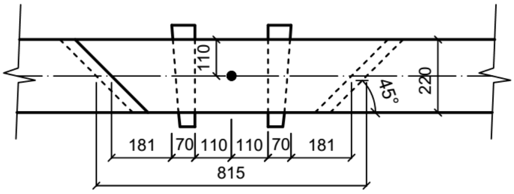
This stiffness is calculated for pure bending. In the case of combined loading, compression and bending the stiffness remains or slightly increase; **in the case of tension and bending, on the other hand, the stiffness is about a quarter lower, therefore the deflection is up to a quarter higher** compared to the aforementioned relations.

DRAWING, GEOMETRY

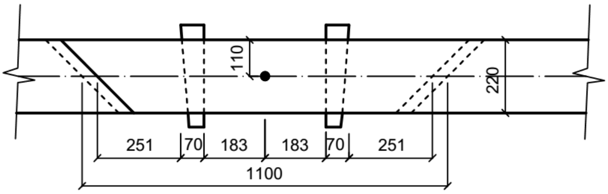


RECOMMENDED DIMENSIONS

b/h = 180/220
$L_p = 3.7h$
$d = 22$ mm
$a_1 = \min 5d = 110$ mm



b/h = 180/220
$L_p = 5h$
$d = 22$ mm



3 PROCESS OF JOINT EXECUTION

The properties of the joint are limited by the level of skill of the carpenter implementing the design of the joint into reality. This limitation is vital during the production of the test samples and affects the mechanical behaviour of joints. The methods are described in this section, taking into account the experience of the authors and carpenters. The process of joint execution along with the output of the process and the conditions **required** for proper functioning of the joint, are summarized in section 3.7.

In practice, there are two methods for manufacturing the log prosthesis: a) by **hewing** of logs, b) by **machine processing**. The appropriate technology is determined by many factors - the level of craftsmanship knowledge on the part of the contractor, availability of suitable material, financial demands, etc. It is recommended to ensure the compatibility of the damaged member with the prosthesis where the methods of their processing should match. Hewn beams thus should be repaired using hewn replacements and vice versa. The manufacture of squared beams by hewing used to be the most common method of timber processing up until the first half of the 14th century. Initially, logs were mostly processed on the ground (low labour). Later, they started being processed on trestles (high labour), which consisted of three subsequent steps – notching, rough hewing and fine hewing flattening. Both processes also differ in the fact, with some exceptions, that in the case of low labour the carpenter moves backwards, while in the case of high labour he moves ahead with the axe. Individual steps of the process of hewing can be determined and the type and form of the instrument used identified. The same applies to the execution of joints. Trace analysis can describe the work of a carpenter who had to cope with individual characteristics of each processed log. See more about trace analysis in [1], [3], [16]. Construction timber and wood processing in sawmills came only with the industrial revolution thanks to the development of transport and the growing number of driven saws.

The recommended manufacture of a carpentry joint involves the determination of the **required dimensions and quality of the material** of the member to be repaired, manufacture of **wooden coupling elements** (dowels, keys), the actual **manufacture of the scarf joint** and the final **joint assembly**. The entire chapter is structured according to this sequence.

3.1 Determination of Material Dimensions

3.1.1 Hewn Beam

Determining the section and shape of the original hand-hewn beam:

1. The method of beam processing should be taken into account (sharp squared, with wane, non-convergent – convergent).
2. The section must be measured at both ends of the beam and on the edge of the designed joint with regard to the convergence (Fig. 10).
3. If there are wanes on the beam, the wane determines the required minimum diameter of

the log preventing the drying of the beam. It is essential to perform the measurement at the point of the joint and determine the direction of the smaller end of the log - convergence (Fig. 11).

4. The determination of non-rectangular sections can be complemented with an angular measurement using a bevel gauge.
5. When hewing, the size of the wanes on the edges must be taken into account (Fig. 12). In addition, the section measurement should also take into account the beam deformation caused by drying cracks; 1 or 2 control measurements are recommended and allowance for drying must be added to the measured section (Fig. 13).
6. If the section is twisted, it is necessary to consider the allowance for the compensation of the twisting (Fig. 14).
7. Please remember, that bark and sapwood will also have to be removed from the log.

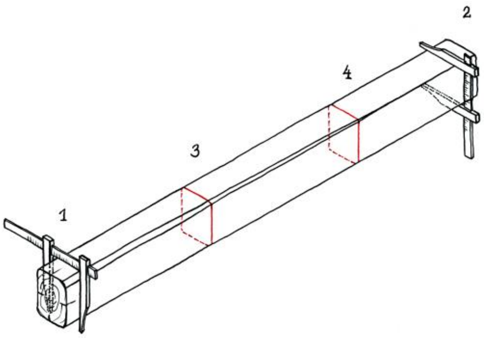


Fig. 10 Measuring the original beam section at four places

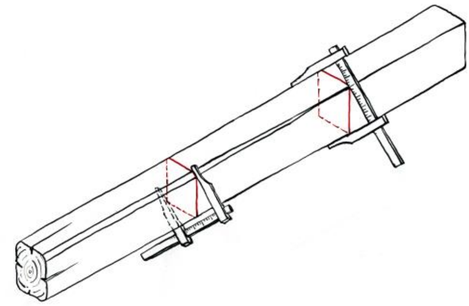


Fig. 11 Measuring the minimum diameter of the log at wanes

Fig. 12 a) Centric sharp-squared section, b) centric section with wanes, c) eccentric section with wanes on one side of the member

3.1.2 Machine Processed Beam

The process of section determination is easier than in the case of a hewn beam:

1. Simple section measurement, preferably in the location selected for the extension joint, should take into account the deformation of the beam caused by drying cracks is

sufficient (Fig. 13).

2. If there are wanes on the beam, this fact should be accounted for when determining the dimensions of timber, from which the beam will be made.
3. If the section is twisted, it is necessary to consider the allowance for the compensation of the twisting (Fig. 14).
4. When ordering fresh wood for the prosthesis, the dimensions must be determined considering appropriate allowances for drying (applies also to the original hand-hewn beam) [25].

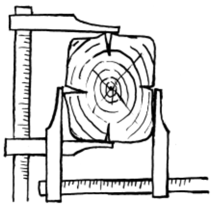


Fig. 13 Taking into account deformation when measuring the section

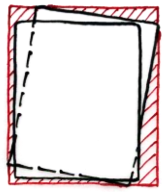


Fig. 14 Taking into account twisting when measuring the section

3.2 Selecting Timber

The material should be selected very carefully. It is advisable to select the timber in the woods, in a sawmill or warehouse. When selecting the material, defects and their range are checked according to the relevant standards (see [25], [26], [27], [28], [29], [30]), but more specifically for following properties:

- the regularity of the structure and width of rings (without reaction changes) – the proportion and distribution of late wood of the prosthesis should ideally correspond with the originally used type of wood,
- knots (number, size, health, location and connection of knots) – in bending stress the knots in the tensile field reduce the strength of wood,
- abnormal colouring indicating possible attack by fungus or rot, or damage by insects is not allowed,
- twisted grains are allowed, due to the widening of the longitudinal gap of the extension joint, only to a limited extent,
- wood should be harvested after the growing season,
- the wood moisture when making the joint should not exceed 20% abs. (if possible, the material should be prepared in advance to achieve the required quality).

3.3 Manufacture of Coupling Elements

Dowels

The dowels are made from split straight grain oak heartwood without defects. The dowel dimensions depend on the joint geometry; the diameter *d* should be ideally a tenth of the section height *h/10*. The moisture of the dowels during processing and fitting in the joints should be 8% abs., which corresponds to the equilibrium moisture content of wood stored for a long time in the workshop conditions, i.e. at air temperature of 18 – 20 °C. Although there are several ways for manufacturing the dowels, the methods proposed only considers drifting, as it ensures good contact between the dowel and the joined wood. In the case of non-round sections of coupling units (e.g. wooden pegs), the contact and insertion of the stud into the wood of the beam cannot be defined, which can result, for instance, in a larger deflection of the beam. The functionality of wooden nails (see glossary in Appendix C) is not guaranteed.

Fig. 15 Process of dowel manufacture

The process of the manual manufacture of dowels is shown in Fig. 15 , including drifting through a steel calibration tool. The calibration tool must be pre-set and tested for the given drill bit diameter. It is advisable to have a few holes next to each other with decreasing diameters and drift the dowels through, starting from the largest to the smallest hole. The hole sizes shall differ only little, based on practical experience (fractions of a millimetre). Before drifting, the dowels may be machined to a rough diameter on a lathe.

Keys

The keys are made of durable hardwood (oak), which should not be easily cleavable. The key is adjusted *in-situ* to the desired size using a plane. The key dimensions depend on the size of the cross-section, the pitch of the wedge is 1:10, please find more in section 2.2.2.3 or 2.2.2.4 in DRAWING, GEOMETRY. The wood of the key should be dried to 8% abs. (i.e. below the level of moisture of the scarf joint itself). This measure ensures that the wedge key does not get loose; on the contrary, it is tightened as it swells after being placed along with wood of higher humidity through water absorption. The keys must be by about 2 mm narrower in the longitudinal direction of the scarf joint so that the shrinking of the new section and the swelling of the key cannot push away the longitudinal joint.

3.4 Execution of the Scarf Joint

Recommendation

! When making the joints, it is strongly recommended to use **high-quality and well-sharpened** tools.

! The carpentry company should have **sufficient qualification** (number of references and quality of delivery, or a special training may be taken - see Annex C).

! General principles for performance (wood without defects at the place of joint, precise fitting of contact surfaces, etc.) are defined by standard ČSN 73 2810 [32].

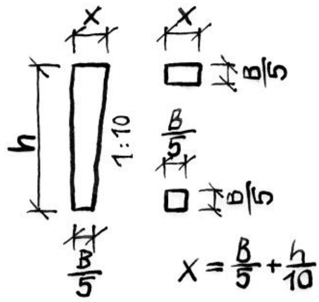


Fig. 16 Approximate general dimensions of an oak key

Selecting Appropriate Place of Scarf Joint

The location for the scarf joint is selected depending on the extent of damage of the original material, which is determined during the designated construction-technical survey, and the structural analysis of the place. It is recommended to:

! maintain a sufficient length of the full section of the prosthesis measured from the head – min. twice the member height - *2h*,

! maintain sufficient distance of the scarf joint from other joints – min. six times the member height - *6h*,

! the scarf joint on the repaired member must be compact - i.e. always placed so that a half of the beam section with the largest drying crack is cut off,

! undesirable knots in the place of the scarf joint should be eliminated (around faces and the section subjected to tension).

Determination of Plane of Joint Longitudinal Cut

Because most of the original beams tend to be irregular (hewing, deformation by twisting), the longitudinal cut cannot be made perpendicular to any of the surfaces. The cut plane must be determined separately and the face is therefore made roughly at first with an allowance of several centimetres.

The plane of the longitudinal cut is determined gradually:

1. The beam section is divided into two equal halves; the dividing line should be drawn with respect to the position of the ideal centre of possible beam twisting.

a. *Exact method* (if the original beam is significantly twisted, Fig. 17):
   - the inclination in the middle of the designed scarf joint is determined using a spirit level,
   - diagonals are marked on the cut off face and the axis of the cut is plotted in the middle in the measured angle,
   - the position of the second dividing point at the distance of the rough length of the scarf joint on the top surface of the beam is determined by halving the width of the member at the measured point, to which the distance between the attached spirit level and the face of the beam is added (or subtracted from).

b. *Estimate* (the original beam is little twisted or nearly straight, Fig. 18)
   - measuring a half of the scarf joint on a cut off face,
   - plotting the rough length of the scarf joint on the top surface of the beam; the centre of the top surface is measured again at this distance (Fig. 19).

c. *Gradual vertical method* (the original beam is twisted)
   - diagonals are marked on the cut off face and the axis of the cut is plotted vertically in the middle using a spirit level,
   - it is proceeded gradually along the length of the scarf joint by subsequent processing (roughing, cutting off) or cutting by a saw with secured verticality of the blade.

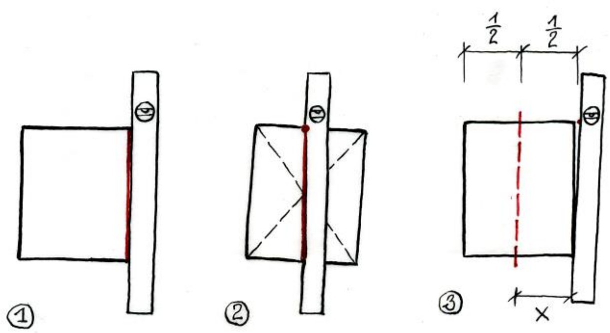


Fig. 17 Exact method of beam section measurement; 1 - determining the inclination in the middle of beam, 2 - plotting the axis of the cut on the cut off face, 3 - location of the point of the second division point at the end of the scarf joint

2. The result of the previous step is shown in Fig. 19. A remote dividing point on the top surface is transferred to the bottom surface of the beam using an angular spirit level. It has to be checked how the bottom point divides the bottom surface of the beam. In case of an irregular section or twisting of beam, the bottom point may not correspond with the half of the bottom surface; then the smaller part of the beam shall be cut off. If this is not the case, it is necessary to shift both end points (top and bottom) towards the cut off part (Fig. 20).
3. The connection of the points of the top and bottom surfaces with lines using a chalk line with clay (i.e. snapping line or reel) or a batten (Fig. 21).
4. Marking the length of the scarf joint and the inclined face for longitudinal cut in the lines.

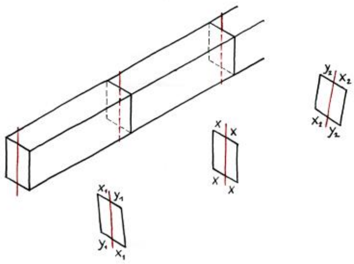


Fig. 18 Dividing the beam section into two equal halves taking into account possible twisting

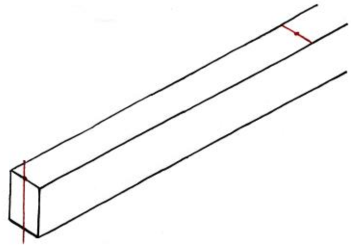


Fig. 19 Plotting the rough length of the scarf joint and marking the end point of the top surface

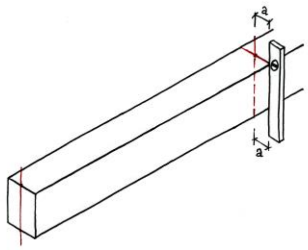


Fig. 20 Transferring the end point using a spirit level

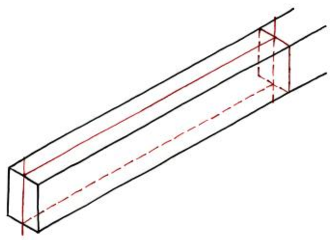


Fig. 21 Connecting points on the surfaces using a chalk line

Execution of Joint Longitudinal Cut

Possible methods of execution:

- manual execution of the longitudinal cut using a two-man saw (Fig. 23),
- roughing by a saw and hewing and finishing by a chisel axe,
- cutting using a carpentry chainsaw (Fig. 22), or circular saw drawn on a plane guide table, which is limited by the cut thickness.

Marking the Oblique Face Cut of the Joint

1. A half of the joint to be removed is roughly cut off in the perpendicular direction (without the length required for the oblique face, Fig. 24).
2. The longitudinal axis of the beam is plotted on the surface of the member.
3. A perpendicular is erected at the point of the assumed centre of the scarf joint.
4. A half of the joint is measured from the intersections of the perpendicular and the top and bottom beam surfaces on both sides of the joint length - a shorter part on one side (x, bottom edge) and a longer part on the other side ($y = x + h$, top edge) of the joint (Fig. 24).
5. The side lines of the cross undercutting are plotted - i.e. unsdercutting of the scarf joint face, using an angular template, a carpenter's square or bevel gauge on the top and bottom surfaces of the beam (Fig. 25).

6. When connecting the lines on the side beam surface, the joint oblique faces are marked (Fig. 26).

Fig. 22 Cutting a longitudinal scarf joint by a carpentry chainsaw

Fig. 23 Manual cutting of the longitudinal scarf joint by a two-man saw (left)

! The figures show a more complex example of a key joint, where the oblique face must always be undercut. In the case of dowel joints, it may be only oblique.

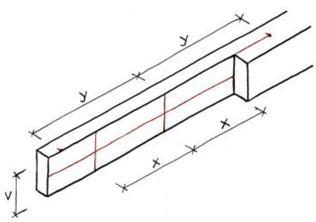


Fig. 24 Measuring the scarf joint length

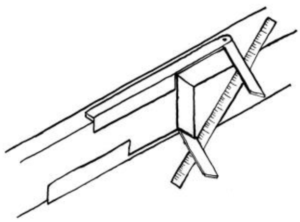


Fig. 25 Plotting the lines of the cross cut of the joint faces

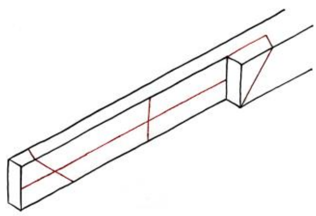


Fig. 26 Plotting the lines of the oblique undercut face

Execution of Oblique Face Cut of the Joint

The finishing cut of the oblique face is done by a handsaw. The use of machines would not allow for adequate control of the angle of undercutting.

Execution of Grooves for Wedge Keys

1. First, a wedge key is made with the skew of 1:10 (see section 3.3).

2. On the surface made in this way, the location of the key seat – is measured and the keys are marked by tracing (Fig. 27).
3. The taper of the wedge is positioned in the direction of the gravity force.
4. It is recommended to make a groove in the inner surface by a small hand-held circular saw (in this case the circular saw ensures the perpendicularity and depth of the cut) or a hand saw (Fig. 29). The cuts are made with joinery precision, i.e. to the half of the line – a part of the line is cut off, while the other part remains visible for checking. Along with the accurate side cuts, auxiliary cuts inside the groove can be made to facilitate proper cleaning of the bottom of the groove. The recommended tools for making the groove are a chisel (rough) and a narrow chisel axe.

The key is tried and a possible adjustment of the taper (slope) of the key is made by planing (Fig. 28). Tried keys are marked to avoid any confusion of the finished parts.

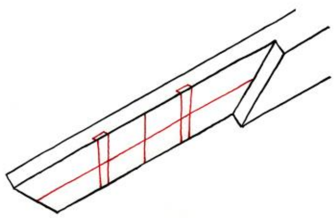


Fig. 27 Measuring grooves for keys

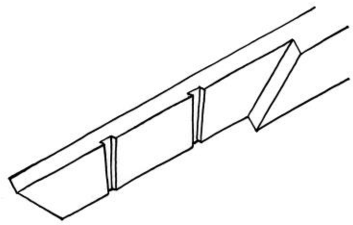


Fig. 28 Scarf joint after cleaning the grooves for keys

Fig. 29 Preparation of a groove for a key using a hand saw

Fig. 30 Marking the oblique face according to already prepared counterpart

3.5 Measurement and Manufacture of Longitudinal Scarf Join on Prosthesis

This methodology follows the same principals as those of the above section pertaining to "old" wood. Alternatively, the oblique face can be measured after the joint assembly with a provisionally cut face and marking according to the finished counterpart (Fig. 30). Unlike the above case (scarf joint on old wood) no grooves for fitting the keys are made.

3.6 Joint Assembly

Preparation Prior to Assembly of Extension Beam

1. The inner surface of the scarf joint must be adjusted prior to assembly. This is done to adjust any bulging from seasonal changes or stress released from cutting off half of the beam section. Therefore, it is slightly undercut along the longitudinal axis in approximately one third of the height of the joint above and below the axis to the depth of about 3 mm so that the contact surfaces remain only on its edges in a width of one sixth (Fig. 31) – it is recommended to use a plane or a chisel axe.
2. The sharp edges of the groove edges of the key are slightly bevelled by a chisel to prevent their splitting off when driving the wedge key in or removing it.
3. Prior the assembly, the parts of the scarf joint are put together to ensure that the gap between the oblique faces is small enough to be cut through after assembly. If the gap is bigger than 5 mm, the face of the other part of the joint must be cut off or chiselled (Fig. 32).

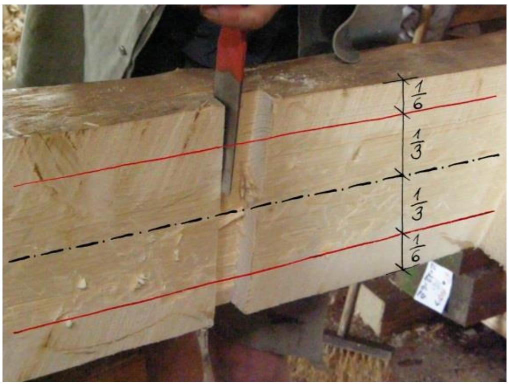


Fig. 31 Undercutting two-thirds of the inner central part of the joint, contact surfaces remain only along the edges of the joint

Fig. 32 Cutting off the excess length of the scarf joint

Assembly of Joint Faces

1. The joint is assembled into the desired position and secured by fasteners (ideally by locksmith clamps, less firm carpentry clamps), the tolerance in the contact along the longitudinal joint being **max. 1 mm**.
2. The faces of the scarf joint are pushed together (Fig. 33a), e.g. by tightening with straps and strikes of the mallet on the free end of the prosthesis.
3. The contact front gaps are cut by a handsaw (Fig. 33b) and the front faces of the joint are tightened until they fit completely together (Fig. 33c; this traditional procedure was

published already in 1743 [19]).
4. When cutting through the gaps, care should be taken to avoid cutting the neck of the joint thus reducing the half-section of the joint member.
5. Both faces must be in contact in **at least two-thirds of their surfaces;** in the remaining one third, the contact surfaces should not be more than 1 mm away.

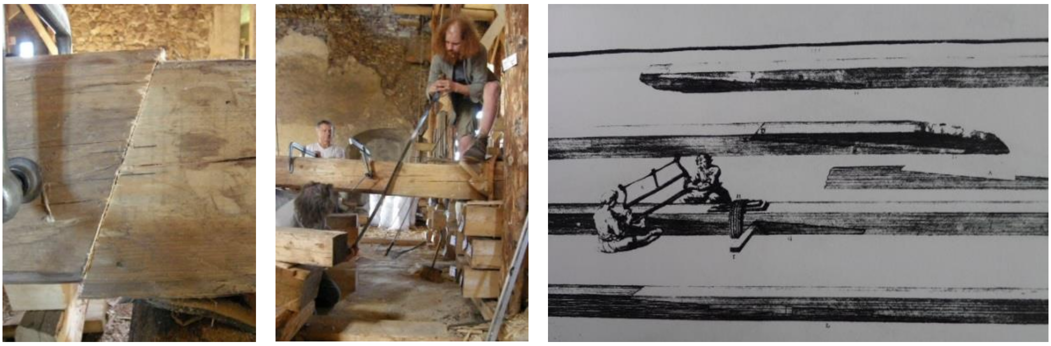


Fig. 33 a) Putting the joint faces together, b) cutting through by a handsaw c) cutting through the joint faces [19]

Fitting the Keys

The keys are fitted after a preliminary accurate assembly of the faces (including a spatial inspection of the preliminary assembly of the joint).
1. The front faces of the key groove are marked on the prosthesis according to the old member.
2. The plotted lines on the joint are connected.
3. The joint is disassembled and grooves are cut into the prosthesis with an offset of about 0.5 to 1 mm (depending on the hardness of the timber used) against the direction of the joint assembly – in this manner the joint faces are activated by fitting the keys (Fig. 34a).
4. The keys are also tried out in the grooves before the assembly (Fig. 34b). The keys are tried out by inserting them in the grooves and the shape of the opposing grooves is checked.
5. The grooves on the scarf joint of the prosthesis can be made with the joint assembled, using a holesaw (Fig. 34c).

Assembly of Extension Beam

1. The joint is assembled and secured in the correct position by clamps and the faces are fitted together.
2. The alignment of the grooves and the fitting of the keys in the grooves is checked.
3. The contact of the sides of the key grooves may be adjusted by a chisel axe and the flatness of the groove is checked by an edge of a square or a steel ruler.
4. The keys are then driven in so that the joint is tightly fit, but allowing future disassembly.
5. Holes for the dowels are drilled using an auger bit (care should be taken to avoid tearing

out wood fibres when removing the bit).

6. The outer ends of the holes for the dowels are slightly conically expanded by about 2 mm using a semi-circular chisel (only in the longitudinal direction of the joint in order to secure the wedge).

Fig. 34 a) Cutting grooves for keys with offset allowing shoring of faces when tightening keys (highlighted in colour, top left), b) check of the key fitting in groove (right), c) formation of groove for key on the assembled joint (bottom left)

Final Joint Assembly

The joint must not be left disassembled for long as the drying cracks cause the deformation of the oblique faces, which then cannot be fitted well. Depending on the situation on site, the joint is either assembled before the final assembly of the structure (trouble-free alternative), or within the structure assembly. The holes for dowels are used as the fitting points. After driving in the dowels - in the direction from the face of the prosthesis into the beam - their protruding ends are roughly cut off (Fig. 35). In order to secure the position of the dowel, it is split and wedged with a hard wedge, and adhesive is applied so that the dowel extends along with the grain of the scarf joint. The protruding ends are removed and finished with a chisel, chisel axe or soft handsaw (Fig. 36). Finally, the outer surface of the beam is carefully removed at the point of the fitting of the joint faces to make the surface uniform.

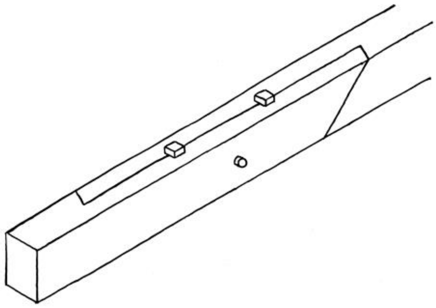


Fig. 35 Coarsely cut off coupling elements after joint assembly

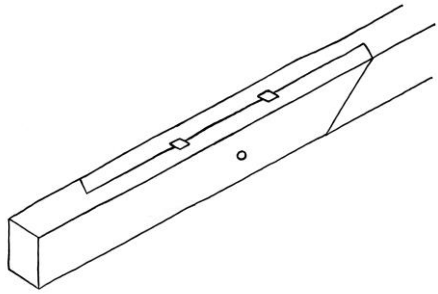


Fig. 36 Scarf joint after assembly and finishing

3.7 Mandatory Requirements Necessary for Proper Joint Performance

1. Quality wood is required of at least class C24 according to [24].
2. Both faces must be in contact in **at least two-thirds of their surfaces;** in the remaining one third, the contact surfaces should not be more than 1 mm away.
3. The manufacturer must consider the **changes in moisture, swelling and shrinking of wood** so that the resulting joint is geometrically congruent with the design drawing.
4. The dowels must be made of quality oak wood and must be perfectly round, ensuring good contact with the wood in the drilled holes.
5. The keys must have the geometry and orientation of the grain, as described in 3.3 and 2.2.2.
6. No clearance between the coupling elements and the surrounding wood is allowed.
7. A coupling element may never be placed in drying cracks or to a point where a crack may spread as a result of wood drying.
8. The faces, dowels and keys are fitted in places free of reactionary modifications, imperfections, knots or damages.
9. The width of the longitudinal gap between the scarf joint and the prosthesis can be up to 3 mm locally.
10. The angle tolerance is $\pm$ 3°.
11. The elements must be secured against ejection or knocking out by wedges.

List of tools:

Axes (carpenter's axe, broad axe), foxtail saw, two-men saw, drawknife, drill and auger bits, chisel axe, chisels, mallet, square, bevel gauge, alpha square, spirit level with an angular ring, measure, chalk line with clay, plane, clamps, templates, punch tool (calibration iron tool for dowels), tensioning belts, mallets, calliper, half-round chisel.

4 MAINTENANCE AND INSPECTION OF JOINT BEHAVIOUR

Joints require proper environmental conditions; in particular the level of moisture should be controlled. In the event that the joint is exposed to leaking, swelling or fungus infestation it may result in reduced joint integrity (opening), or impaired mechanical properties of the coupling elements or the timber itself. This must be accounted for as it is a prerequisite for the proper functioning of the joint. Another aspect is the insect attack, which should also be monitored. In case of an attack near the load-bearing coupling elements, for instance, a failure of the joint cannot be excluded.

Visual inspection of the structure must be carried out when **handing over the structure**. After **one year of use**, the condition of the structure should be examined and the maintenance of joints performed. Along with that, the user should periodically check the condition of the structure approximately **every three years**. The contractor should inform the user of this obligation during the delivery of the timber structure during its handover to the customer. A report of the condition of the structure must be drawn up during the inspection.

The **visual inspection** of the joint should consist of the following checks of the joint condition:

- when handing over the building, check whether the joint is made **with the inclination of the faces in the right direction** (the faces must form the letter V for the positive moment)
- check whether it is protected against ingress of **water and excessive moisture**,
- check that the joint is **not damaged in any way**, for example, attacked by insects or rot,
- check that the **distance between the faces is not increasing** due to uneven distribution of forces in the structure (in case of a loss of contact at the faces, the joint is "hanging" only on the dowels, without engaging the oblique faces and the shear force is transferred directly to the dowels, which results in lower load bearing capacity of the joint),
- check whether in a top view, the joint does not show **sheared off dowel(s)** (when viewed perpendicularly to the longitudinal axis of the scarf joint, the axes of the dowels can be seen in order to ensure that they are in a straight line),
- check the joint for apparent **extension of the drying cracks on the faces of the joint**,
- check the joint for **rotation or twisting of the key** due to the displacement of the faces,
- check the joint for **bulging (buckling) of its sides** due to the twisting of the joint,
- check the joint **visually for significant deflection of the beam**.

The **joint maintenance** should include all the items listed for the visual inspection, as well as tightening of the wooden keys with light blows in the direction of the point of the wedge (narrowing), never in the opposite direction! Nevertheless, the keys should already be tightly snug in the wood and not be moved by such action. However, if a key is loose (e.g. due to drying), it needs to be tightened by tapping it over a piece of wood or with a mallet that would not damage the dowel head (not directly by a metal tool). Joints with dowels require no maintenance.

Any failures of the joint discovered during an inspection must be immediately consulted with a structural engineer.

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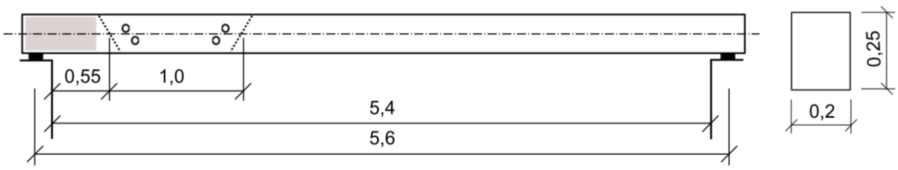
ANNEXES

A. EXAMPLES OF THE METHOD APPLICATION

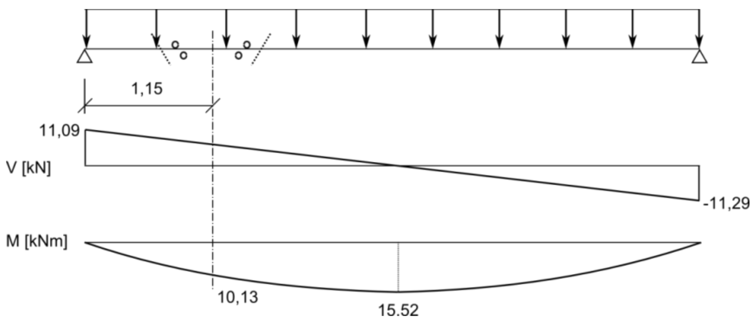
A.1 Design of the Scarf Joint on Joist

Design an extension scarf joint on a damaged joist, which is loaded according to the assignment. The results of the diagnostic methods show that the sound part of the beam suitable for joint begins at a distance of 0.55 m from the wall on which it is supported.
The quality of the original member, according to the analysis, corresponds to timber of class C24.



Design loading (considered according EN 1991-1-1, safety factors according to National Annex ČSN EN 1990 ed. 2)

permanent	$g_k = 1.3\ \mathrm{kNm^{-1}}$		
	$\gamma_G = 1.2$	$\rightarrow$	$g_d = 1.56\ \mathrm{kNm^{-1}}$
variable	$q_k = 1.6\ \mathrm{kNm^{-1}}$		
	$\gamma_Q = 1.5$	$\rightarrow$	$q_d = 2.4\ \mathrm{kNm^{-1}}$
Total	$f_d = g_d + q_d = 1.56 + 2.4 = 3.96\ \mathrm{kNm^{-1}}$		



Sectional characteristics

$$W_y = \frac{bh^2}{6} = \frac{0.2 \cdot 0.25^2}{6} = 2.08 \cdot 10^{-3}\ \mathrm{m^3}$$

$$I_y = \frac{bh^3}{12} = \frac{0.2 \cdot 0.25^3}{12} = 2.6 \cdot 10^{-4}\ \mathrm{m^4}$$

Material properties (according to EN 338, coefficients according to EN 1995-1-1, i.e. EC 5)

$\gamma_M = 1.3$ $\quad k_{mod} = 0.8$ $\quad k_{def} = 0.6$ $\quad E_{mean} = 11 \text{ GPa}$

$f_{m,k} = 24 \text{ MPa}$ $\quad f_{m,d} = k_{mod}\frac{f_{m,k}}{\gamma_M} = 0.8\frac{24}{1.3} = 14.77 \text{ MPa}$

$f_{v,k} = 4.0 \text{ MPa}$ $\quad f_{v,d} = k_{mod}\frac{f_{v,k}}{\gamma_M} = 0.8\frac{4.0}{1.3} = 2.46 \text{ MPa}$

1. **Assessment of beam without joint**

   Ultimate limit state - ULS (load bearing capacity)

   - **Bending** (the joist is secured along the entire length against the loss of transverse and torsional stability)

     $\sigma_{m,d} \le f_{m,d}$ $\quad\rightarrow\quad$ $\sigma_{m,d} = \frac{M_d}{W_y} = \frac{15.52 \cdot 10^3}{2.08 \cdot 10^{-3}} = 7.45 \text{ MPa}$

     $7.45 \text{ MPa} \le 14.77 \text{ MPa}$

     cross-section SATISFACTORY

   - **Shear** (the relation for $\tau_{v,d}$ applies to the rectangular cross section, $k_{cr} = 0.67$)

     $\tau_{v,d} \le f_{v,d}$ $\quad\rightarrow\quad$ $\tau_{v,d} = \frac{3V_d}{2A} = \frac{3V_d}{2k_{cr}bh} = \frac{3 \cdot 11.09 \cdot 10^{-3}}{2 \cdot 0.76 \cdot 0.2 \cdot 0.25} = 0.44 \text{ MPa}$

     $0.44\text{MPa} \le 2.46 \text{ MPa}$

     cross-section SATISFACTORY

   Serviceability limit state – SLS (deflection)

   - **Maximum deflection** (limit values for simple beam according to EN 1995-1-1)

     $$w_{lim,inst} = \frac{\mathrm{L}}{300} = \frac{5.6}{300} = 0.019 \text{ m}$$

     $$w_{inst,g} = \frac{5}{384}\frac{\mathrm{g_k L^4}}{\mathrm{EI}} = \frac{5}{384} \cdot \frac{1.3 \cdot 10^3 \cdot 5.6^4}{11 \cdot 10^9 \cdot 2.6 \cdot 10^{-4}} = 0.0058 \text{ m}$$

     $$w_{inst,q} = \frac{5}{384}\frac{\mathrm{q_k L^4}}{\mathrm{EI}} = \frac{5}{384} \cdot \frac{1.6 \cdot 10^3 \cdot 5.7^4}{11 \cdot 10^9 \cdot 2.6 \cdot 10^{-4}} = 0.0072 \text{ m}$$

     $$w_{inst} = w_{inst,g} + w_{inst,q} = 0.0058 + 0.0072 = 0.013 \text{ m}$$

     $0.013 \text{ m} < 0.019 \text{ m}$ cross-section SATISFACTORY

     $$w_{lim,fin} = \frac{L}{250} = \frac{5.6}{250} = 0.022 \text{ m}$$

     $$w_{fin} = w_{inst,g}(1 + k_{def}) + w_{inst,q}(1 + \psi_{2.1}k_{def}) = 0.0058 \cdot 1.6 + 0.0072 \cdot 1 = 0.016 \text{ m}$$

     $0.018 \text{ m} < 0.022 \text{ m}$ cross-section SATISFACTORY

- **Bending stiffness of beam**

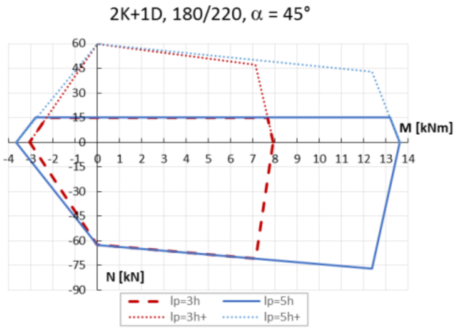
$$k = \frac{48EI}{L^3} = \frac{48 \cdot 11 \cdot 10^9 \cdot 2.6 \cdot 10^{-4}}{5.6^3} = 783 \text{ kNm}^{-1}$$

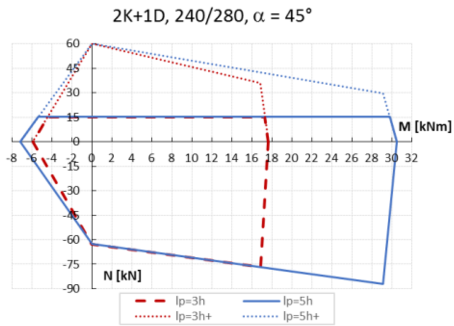
2. Assessment of beam with joint

Selected joint – **2K+1D** (scarf joint with 2 keys and 1 dowel), $L_p = 4h = 1$ m,
$M_{SP} = M(x = 1{,}15 \text{ m}) = 10{,}36$ kNm

ULS

$M_{max,k}$ for the cross-section 200/250 - the values from the load bearing capacity diagram of *M-N* are interpolated for profiles 180/220 and 240/280





					200/250 interpolation	
180/220	2.5h →	8.0 kNm	4h →	11.3 kNm	acc. to ***b***	**15.97 kNm**
	5h →	13.5 kNm				
240/280	2.5h →	17.5 kNm	4h →	25.3 kNm	acc. to ***h***	**18.30 kNm**
	5h →	30.5 kNm				

safety

The characteristic value of the moment $M_{max,k}$ for the interpolation according to h is considered (dimension with a greater influence on the load bearing capacity).

$$\frac{M_{max,k}}{M_{SP}} = \frac{18.3}{10.13} = \mathbf{1.81}$$

When compared with the design value $M_{max,d}$ obtained with use of k_{mod}= 0.8 and γ_M=1.3, the result of the safety calculation is sufficient.

$$M_{max,d} = k_{mod} \frac{M_{max,k}}{\gamma_M} = 0.8 \frac{18.3}{1.3} = 11.26 \text{ kNm}$$

SLS

- **Maximum deflection of beam with joint**

  the joint card lists relations for the joint parameters $L_1 = 0.55$ m, $\frac{L}{12} = 0.47$ m, $L_p = 4h = 1$ m, $b = 0.2$ m, $h = 0.25$ m

  $$L_1 > \frac{L}{12}, L_p = 2.5h : w = w_0 \frac{40}{\left(8.7-16\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)} \frac{h^{0.4}}{L^{0.4}} = 0.016 \cdot 1.363 = 0.0218 \text{ m}$$

  $$L_1 > \frac{L}{12}, L_p = 5h : \quad w = w_0 \frac{40}{\left(8.3 - 9.4\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)} \frac{h^{0.4}}{L^{0.4}} = 0.016 \cdot 1.4134 = 0.0226 \text{ m}$$

  the results are interpolated (joint length *4h)* → $w = 0.0223$ m , i.e. $w \approx w_{lim,fin}$

  deflection SATISFACTORY

- **Bending stiffness of beam with joint** (NB: after the conversion of units from tabulated $\mathrm{MNm^{-1}}$ to $\mathrm{kNm^{-1}}$)

  $$L_1 > \frac{L}{12}, L_p = 2.5h : k = 100Eb\left(8.7 - 16\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} = 574 \text{ kNm}^{-1}$$

  $$L_1 > \frac{L}{12}, L_p = 5h : k = 100Eb\left(8.3 - 9.4\left(\frac{L_1}{L} - \frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}} = 554 \text{ kNm}^{-1}$$

Conclusion

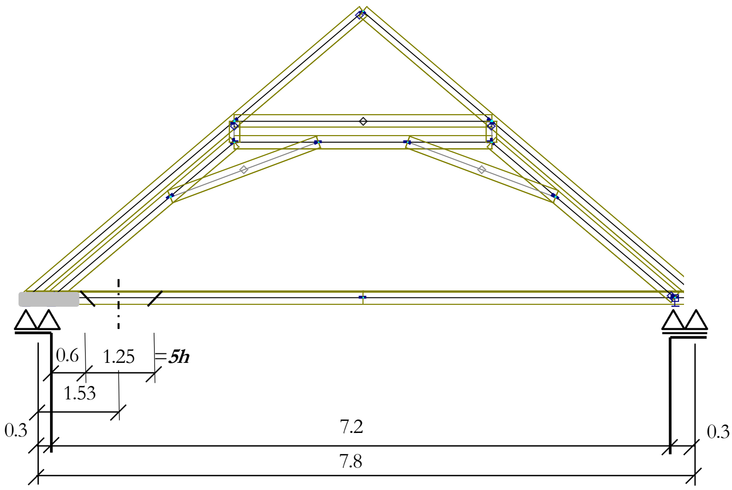
The scarf joint selected for the repair of the beam **can** be used considering the design safety of 1.81.

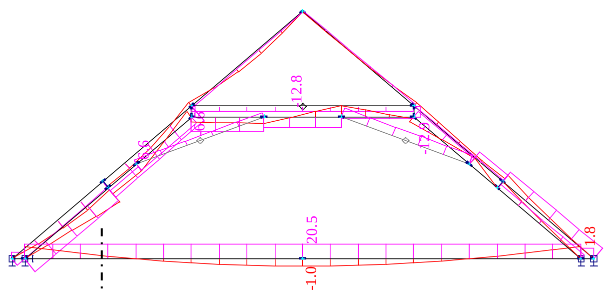
If higher safety is required for the design of the load bearing capacity, the length of the scarf joint L_p can be increased upto *5h.* This change leads after interpolation in the design graphs to $M_{max,k}$= 22.0 kNm and resulting safety 2.17.

The values of the final deflection of the beam with the joint correspond to the limit values, which are commonly used for new structures. As seen from the calculation of the resultant deflections, only one of the approximation formulas may often be used for approximate calculation. Differences are apparent only at a higher value of L_1 (see Fig. 9).

A.2 Design of Scarf Joint on Tie Beam

Design an extension scarf joint on a damaged tie beam of a truncated principal roof. The tie beam has a rectangular section of 200×250 mm. Normal loading is considered, internal forces and deformations are determined using FEM software, see the figures below. The beam damage reaches a distance of 0.6 m from the face of the vertical wall. The quality of the original member corresponds to timber of class C20.





$$M_d = M(x = 1.53) = 0.2\ \text{kNm}$$
$$N_d = N(x = 1.53) = 20.5\ \text{kN}$$

$$M_{max} = M(x = 3.9) = 1.0\ \text{kNm}$$
$$N_{max} = N(x = 3.9) = 20.5\ \text{kNm}$$

Sectional characteristics

$$A = bh = 0.2 \cdot 0.25 = 0.05\ \text{m}^2$$
$$W_y = \frac{bh^2}{6} = \frac{0.2 \cdot 0.25^2}{6} = 2.08 \cdot 10^{-3}\ \text{m}^3$$
$$I_y = \frac{bh^3}{12} = \frac{0.2 \cdot 0.25^3}{12} = 2.6 \cdot 10^{-4}\ \text{m}^4$$

Material properties (according to EN 338, coefficients according to EN 1995-1-1)

$\gamma_M = 1.3$ $\quad k_{mod} = 0.8$ $\quad k_{def} = 0.6$

$f_{m,k} = 20\ \text{MPa}$ $\quad f_{m,d} = k_{mod}\frac{f_{m,k}}{\gamma_M} = 0.8\frac{20}{1.3} = 12.3\ \text{MPa}$

$f_{t,0,k} = 12$ MPa $\quad f_{t,0,d} = k_{mod}\frac{f_{t,0,k}}{\gamma_M} = 0.8\frac{12}{1.3} = 7.38$ MPa

$E_{mean} = 9.5$ GPa

1. **Assessment of beam without joint**

   ULS

   - **Bend - at the point of greatest moment**

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1 \qquad \rightarrow \qquad \sigma_{m,d} = \frac{M_d}{W_y} = \frac{1.0 \cdot 10^3}{2.08 \cdot 10^{-3}} = 0.48 \text{ MPa}$$

$$\sigma_{t,0,d} = \frac{N_d}{A} = \frac{20.5 \cdot 10^3}{0.05} = 0.41 \text{ MPa}$$

$$\frac{0.41}{7.38} + \frac{0.48}{12.3} = 0.09 \qquad \rightarrow \qquad 0.09 < 1$$

cross-section SATISFACTORY

SLS

- **Maximum deflection** (limit values according to EN 1995-1-1)

$$w_{lim,inst} = \frac{L}{350} = \frac{7.8}{350} = 0.022 \text{ m}$$

→ from FEM calculation the maximum deflection is determined $w = 0.003$ m

→ cross-section SATISFACTORY

- **Beam bending stiffness**

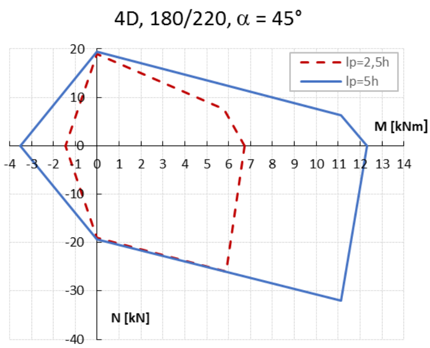
$$k = \frac{48EI}{L^3} = \frac{48 \cdot 9.5 \cdot 10^9 \cdot 2.6 \cdot 10^{-4}}{7.8^3} = 250 \text{ kNm}^{-1}$$

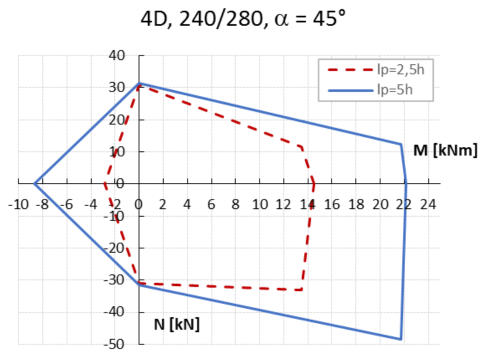
2. **Assessment of beam with joint**

   Selected joint - **4D** (with 4 dowels), $L_p = 5h = 1.25$ m, $M_{SP} = M(x = 1.53 \text{ m}) = 0.2$ kNm, $N_d = N(x = 1.53) = 20.5$ kN

ULS

$M_{max,k}$ and $N_{max,k}$ for the cross-section 200/250 - the values from the load bearing capacity diagram of *M-N* are interpolated for profiles 180/220 and 240/280 determined by the limit for $L_p = 5h$





	$M_{max,k}$ [kNm]	$N_{max,k}$ [kN]	safety	$M_{max,d}$ [kNm]	$N_{max,d}$ [kN]
180/220	1	18			
240/280	1	30			
200/250	**1**	**24**	**1.5**	**0.67**	**16.0**
			2	**0.5**	**12.0**

Note: Safety value of 2 corresponds to k_{mod}=0.6 and γ_M=1.3.

SLS

- **Maximum deflection of beam with joint**

  This joint card lists data L_1= 0.6 m, $\frac{L}{12} = 0.65$ m, $L_p = 5h = 1.25$ m, $b = 0.2$ m, $h = 0.25$ m.

  The member is drawn with a small bending moment; therefore, the deflection must be increased by a quarter (see the joint card).

$$L_1 < \frac{L}{12}, L_p = 5\text{h} : \quad w = w_0 4.8 \frac{h^{0.4}}{L^{0.4}} = 0.003 \cdot 1.212 \cdot 1.25 = 0.005 \text{ mm} < w_{lim,inst}$$

deflection SATISFACTORY

- **Bending stiffness of beam with joint** (again decreased by a quarter due to the combination of bending and tension; after the conversion of units from tabulated MNm^{-1} to kNm^{-1})

$$L_1 < \frac{L}{12}, L_p = 5h : \; k = \frac{830Eb\frac{h^{2.6}}{l^{2.6}}}{1.25} = 164.5 \text{ kNm}^{-1}$$

Conclusion

The scarf joint selected for the repair of the tie beam **can not** be used with safety higher than 1.15 because of unsatisfactory load bearing capacity in tension. However, when bending moment is negligible it is possible to add another wooden dowels (with minimal spacing $a_1=5d$ according to EC5). Additional oak dowels having diameter d [mm] can be considered (also according to DIN 1052:2004) as

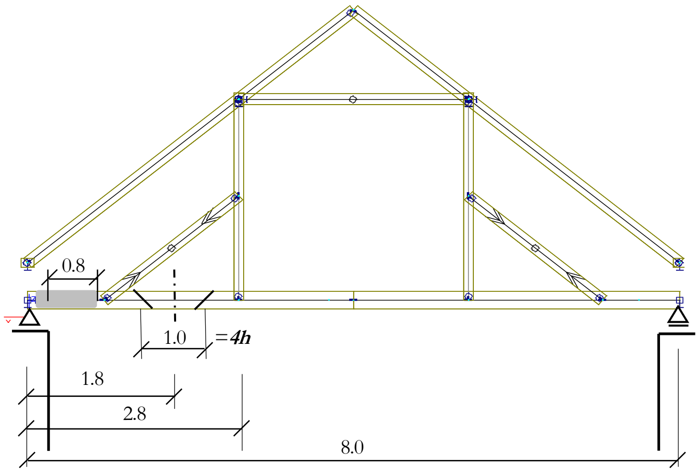
$$R_k = 9{,}5d^2$$

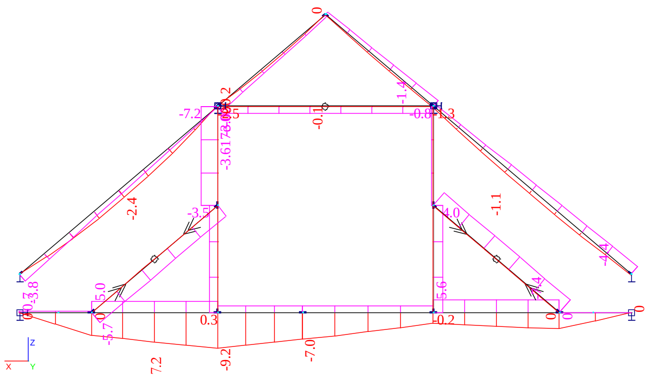
or expression used in this publication giving similar results

$$R_k = 12{,}5d^2 - 54d.$$

A.2 Design of Scarf Joint on Binding Beam - Vertical Stool

Design an extension scarf joint on a damaged binding beam of a vertical bench. The tie beam has a rectangular section of 200×250 mm. Normal loading is considered, internal forces and deformations are determined using FEM software, see below. The beam damage reaches a distance of 0.8 m from the face of the vertical wall. The quality of the original member corresponds to timber of class C20.





$M_{SP} = M(x = 1.8) = 7.5 \text{ kNm}$
$N_{SP} = N(x = 1.8) = 5.0 \text{ kN}$

$M_{max} = M(x = 2.8) = 9.2 \text{ kNm}$
$N_{max} = 5.0 \text{ kNm}$

Sectional characteristics

$A = bh = 0.2 \cdot 0.25 = 0.05 \text{ m}^2$

$$W_y = \frac{bh^2}{6} = \frac{0.2 \cdot 0.25^2}{6} = 2.08 \cdot 10^{-3} \text{ m}^3$$

$$I_y = \frac{bh^3}{12} = \frac{0.2 \cdot 0.25^3}{12} = 2.6 \cdot 10^{-4} \text{ m}^4$$

Material properties (according to EN 338, coefficients according to EN 1995-1-1)

$\gamma_M = 1.3$ $\qquad k_{mod} = 0.8$ $\qquad k_{def} = 0.6$

$f_{m,k} = 20$ MPa $\quad f_{m,d} = k_{mod}\frac{f_{m,k}}{\gamma_M} = 0.8\frac{20}{1.3} = 12.3$ MPa

$f_{t,0,k} = 12$ MPa $\quad f_{t,0,d} = k_{mod}\frac{f_{t,0,k}}{\gamma_M} = 0.8\frac{12}{1.3} = 7.38$ MPa

$E_{mean} = 9.5$ GPa

1. Assessment of beam without joint

ULS

- **Bend -** at the point of greatest moment

$$\frac{\sigma_{t,0,d}}{f_{t,0,d}} + \frac{\sigma_{m,d}}{f_{m,d}} \leq 1 \quad \rightarrow \quad \sigma_{m,d} = \frac{M_d}{W_y} = \frac{9.2 \cdot 10^3}{2.08 \cdot 10^{-3}} = 4.42 \text{ MPa}$$

$$\sigma_{t,0,d} = \frac{N_d}{A} = \frac{5.0 \cdot 10^3}{0.05} = 0.1 \text{ MPa}$$

$$\frac{0.1}{7.38} + \frac{4.42}{12.3} = 0.37 \quad \rightarrow \quad 0.37 < 1$$

cross-section SATISFACTORY

SLS

- **Maximum deflection** (limit values according to EN 1995-1-1)

$$w_{lim,inst} = \frac{\text{L}}{250} = \frac{8}{250} = 0.032 \text{ m}$$

→ from MKP calculation the maximum deflection is determined $w = 0.017$ m

→ cross-section SATISFACTORY

- **Beam bending stiffness**

$$k = \frac{48EI}{L^3} = \frac{48 \cdot 9.5 \cdot 10^9 \cdot 2.6 \cdot 10^{-4}}{8^3} = 232 \text{ kNm}^{-1}$$

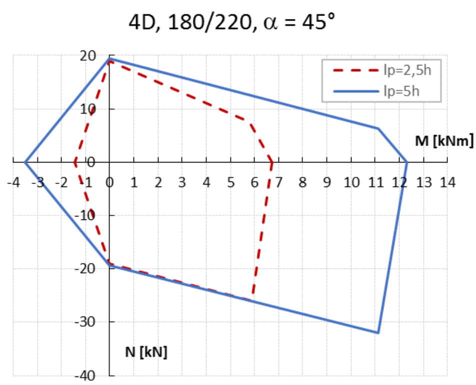
2. Assessment of beam with joint

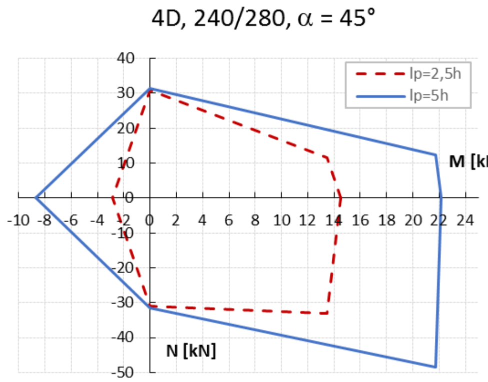
Selected joint – **4K** (4 dowels), $L_p = 4h = 1.0$ m, it is placed behind the support towards the centre of the beam!

$M_{SP} = M(x = 1.8\ m) = 7.5$ kNm, $N_{SP} = N(x = 1.8) = 5.0$ kN

ULS

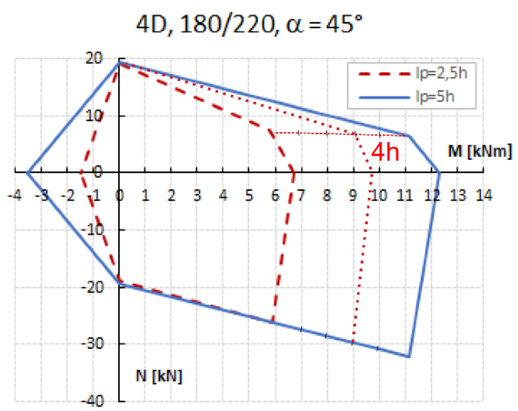
$M_{max,k}$ for the cross-section 200/250 - the values from the load bearing capacity diagram of *M-N* are interpolated for profiles 180/220 and 240/280





	Only M [kNm]			M [kNm]	N [kN]	200/250	$M_{max,k}$ [kNm]	$N_{max,k}$ [kN]
180/220	2.5h →	6.6	4h → 9.96	9.96	7.0	acc. to ***b***	**13.0**	**8.7**
	5h →	12.2						
240/280	2.5h →	14.5	4h → 19.0	19.0	12.0	acc. to ***h***	**14.5**	**9.5**
	5h →	22.0						

Note: The interpolated values of M and N for $L_p = 4h$ are read acc. to the figure below (4K, 180/220).



safety

The values for interpolation according to h are considered (dimension with a greater influence on the load bearing capacity).

	M_{max} [kNm]	N_{max} [kN]	safety	$M_{max,d}$ [kNm]	$N_{max,d}$ [kN]
200/250	14.5	9.5	1.5	9.7	6.3
			1.9	**7.6**	**5.0**

Note: Safety value of 1.9 corresponds to k_{mod}=0.7 and γ_M=1.3.

SLS

- **Maximum deflection of beam with joint**

  This joint card lists data for parameters

  $L_1 = 1.425\ m,\ \frac{L}{12} = 0.66\ m, L_p = 4h = 1.0\ m, b = 0.2\ m, h = 0.25$ m.

  Relationships (with the deflection correction - increase by one quarter - in case of tension and bending):

  $$L_1 > \frac{L}{12}, L_p = 2.5h : w = w_0 \frac{40}{\left(8.7-16\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)} \frac{h^{0.4}}{L^{0.4}} = 0.017 \cdot 1.392 \cdot 1.25 = 0.03 \text{ m}$$

  $$L_1 > \frac{L}{12}, L_p = 5h : \quad w = w_0 \frac{40}{\left(8.3 - 9.4\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)} \frac{h^{0.4}}{L^{0.4}} = 0.017 \cdot 1.35 \cdot 1.25 = 0.0029 \text{ m}$$

  If it is reasonable, it is possible to scale between these two values to *4h*.

  $$w < w_{lim,inst}$$

  deflection SATISFACTORY

- **Bending stiffness of beam with joint**

  Analogically

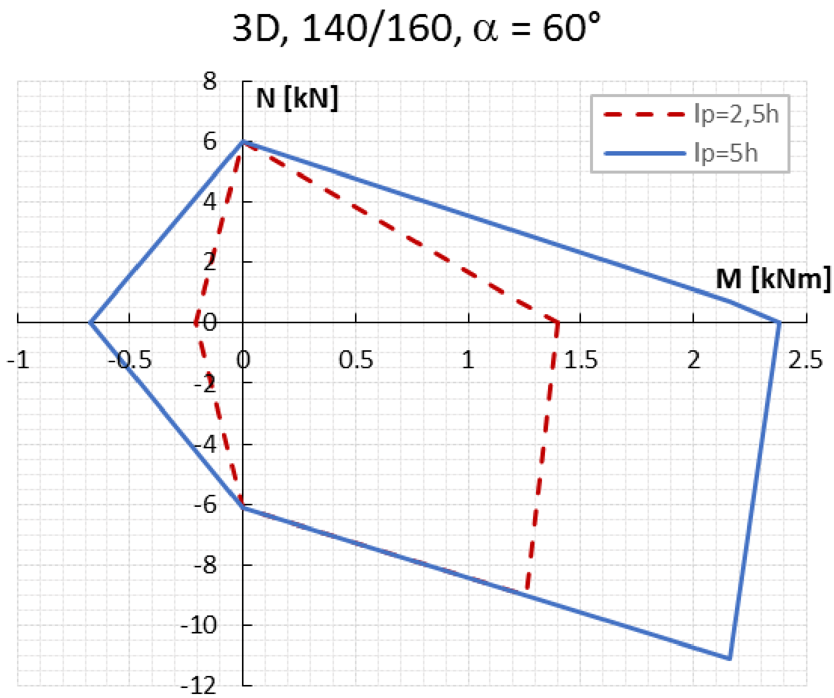
  $$L_1 > \frac{L}{12}, L_p = 2.5h : k = \frac{100Eb\left(8.7-16\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}}}{1.25} = 133.2 \text{ kNm}^{-1}$$

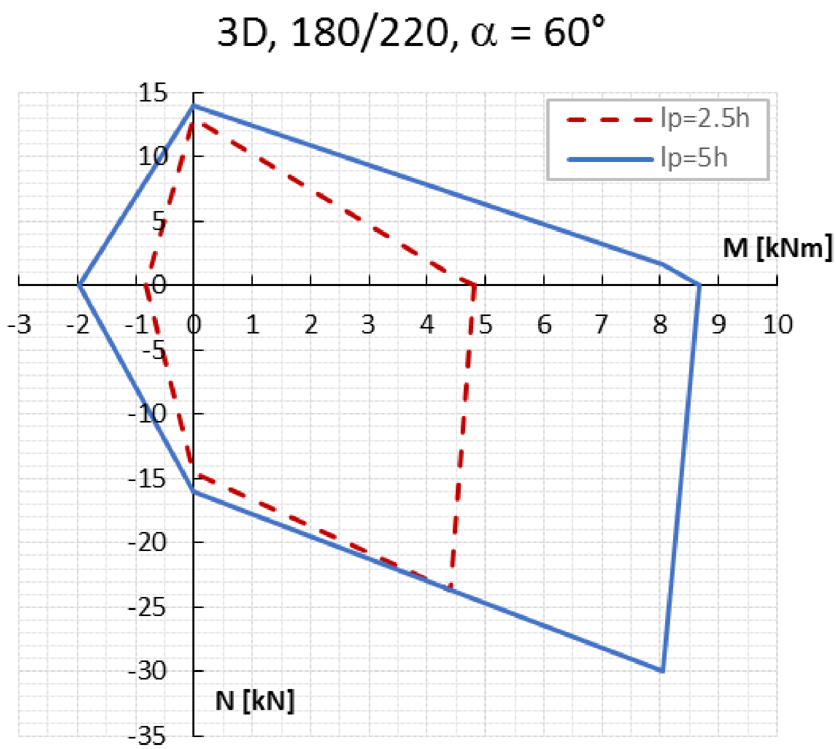
  $$L_1 > \frac{L}{12}, L_p = 5h : k = \frac{100Eb\left(8.3 - 9.4\left(\frac{L_1}{L}-\frac{1}{12}\right)\right)\frac{h^{2.6}}{L^{2.6}}}{1.25} = 137.3 \text{ kNm}^{-1}$$

Conclusion

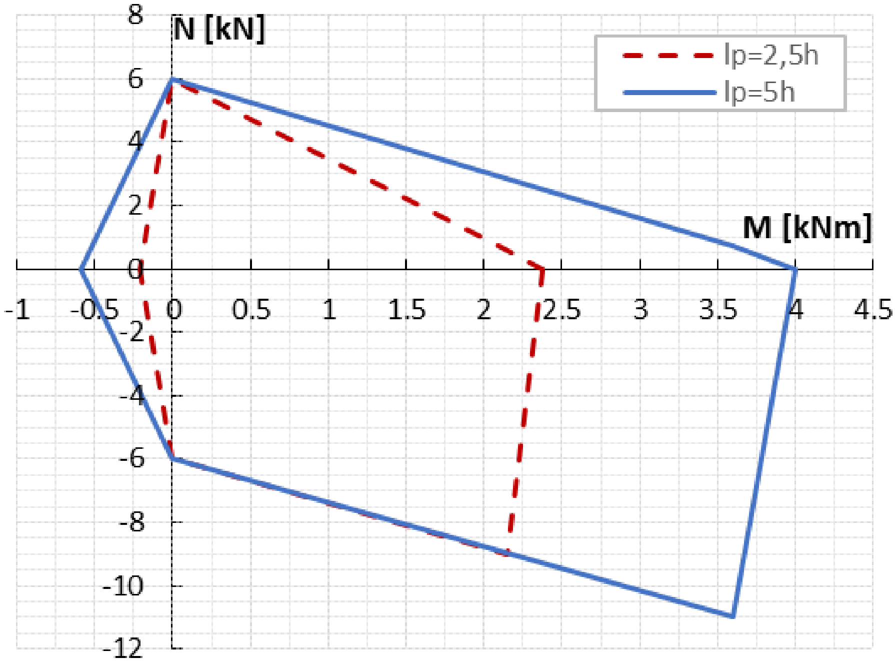
The scarf joint selected for the repair of the tie beam **can** be used with safety equal to 1.9.
If higher safety is required, the length of the scarf joint L_p can be increased (if possible).

B. DETAILED DESIGN LOAD BEARING CAPACITY CHARTS

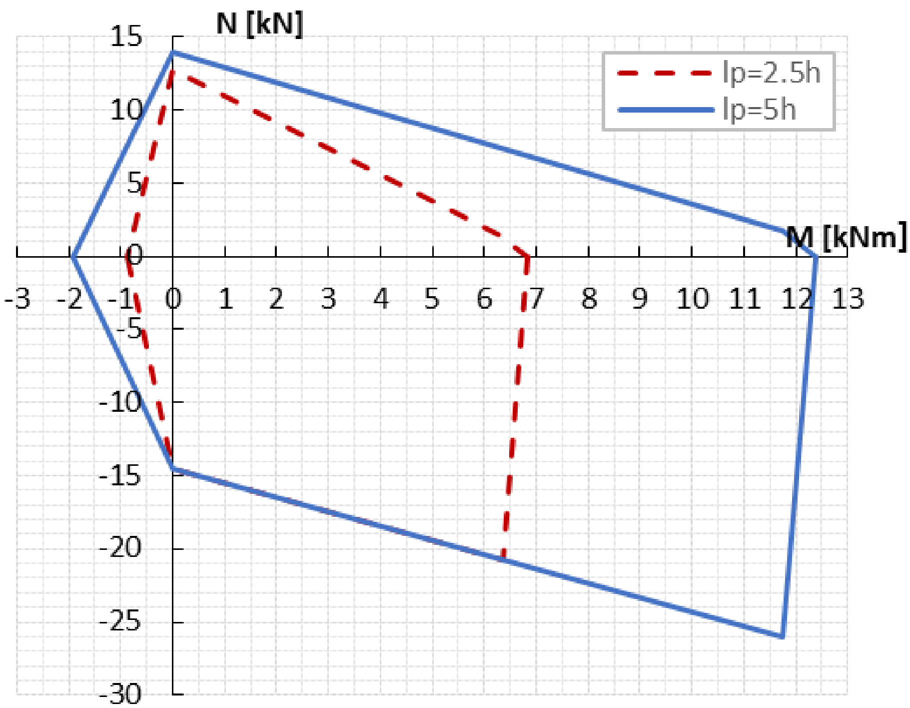


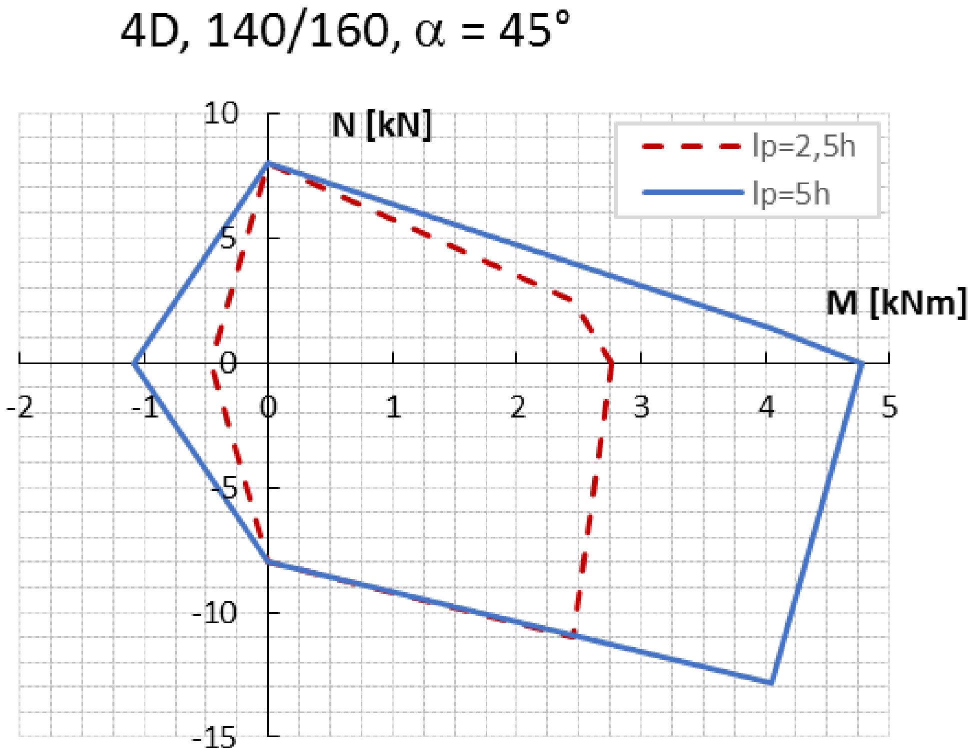


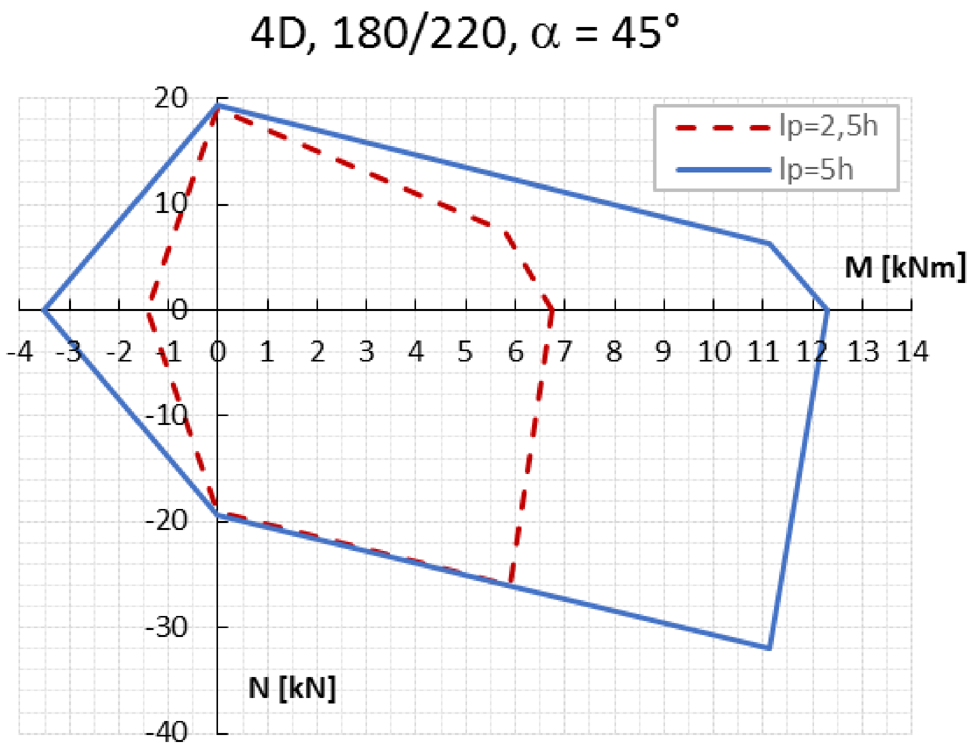
3D, 140/160, α = 45°



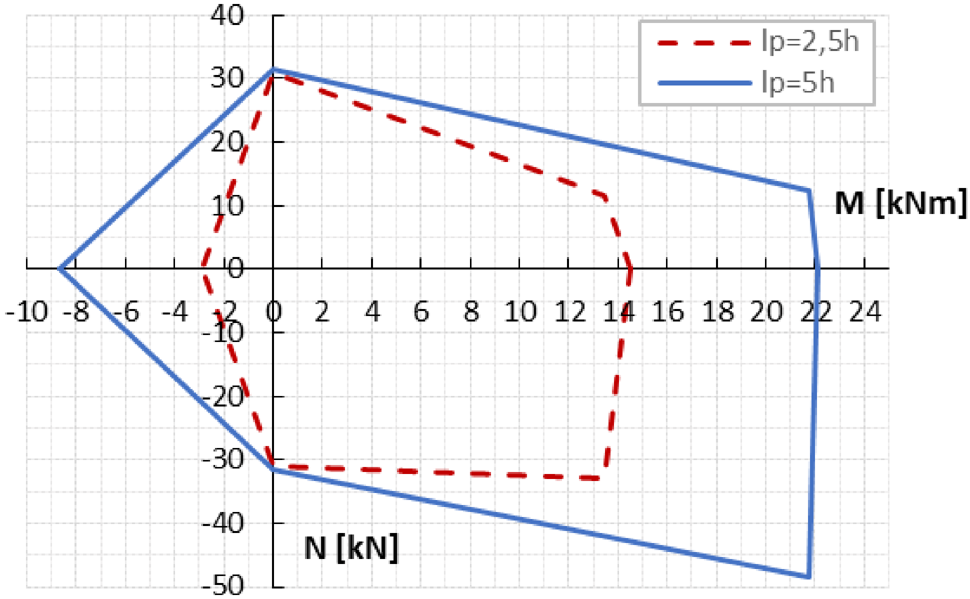
3D, 180/220, α = 45°



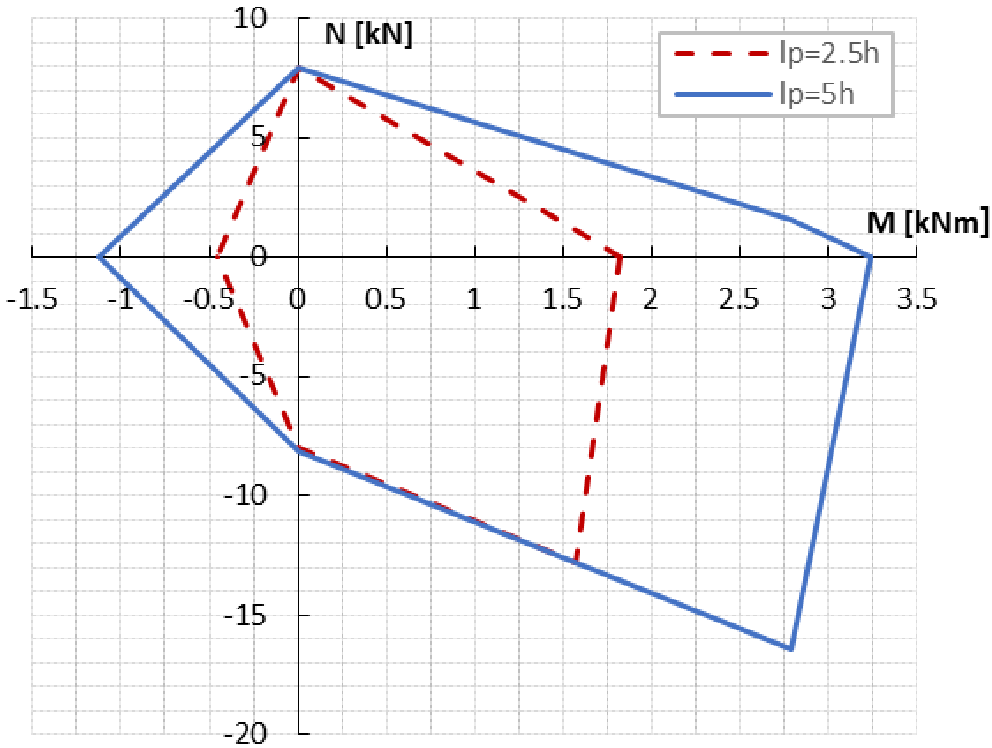

4D, 140/160, α = 45°
N [kN]
M [kNm]
lp=2,5h
lp=5h
10
5
0
-5
-10
-15
-2
-1
0
1
2
3
4
5

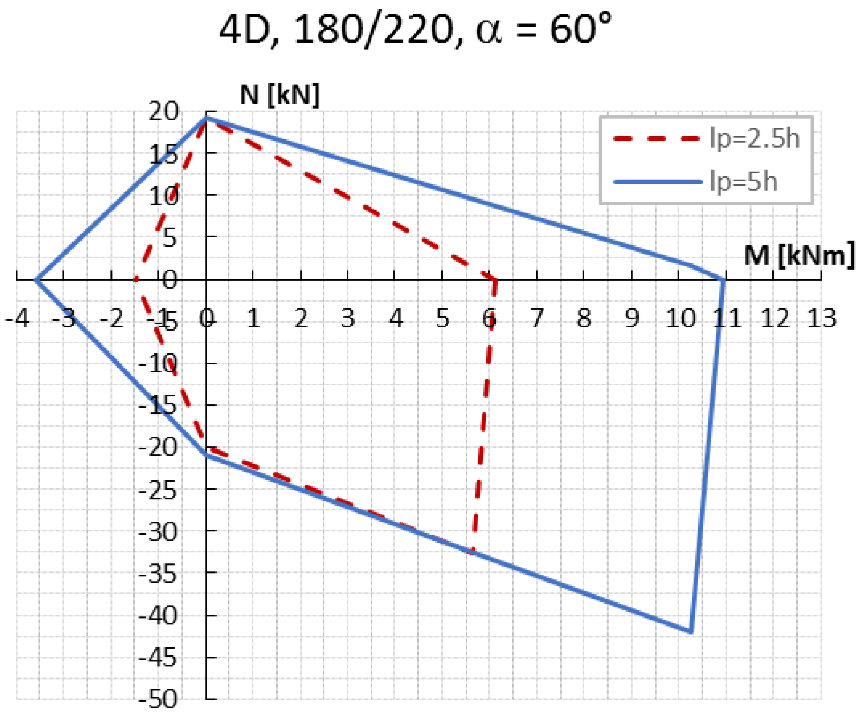

4D, 180/220, α = 45°
M [kNm]
N [kN]
lp=2,5h
lp=5h
20
10
0
-10
-20
-30
-40
-4
-3
-2
-1
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14

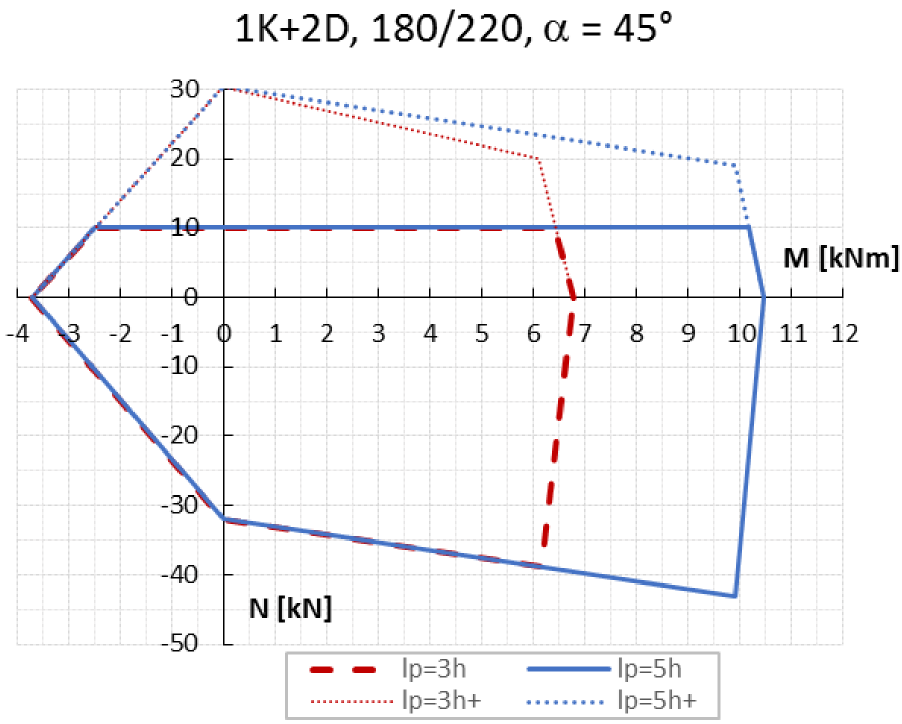
4D, 240/280, α = 45°



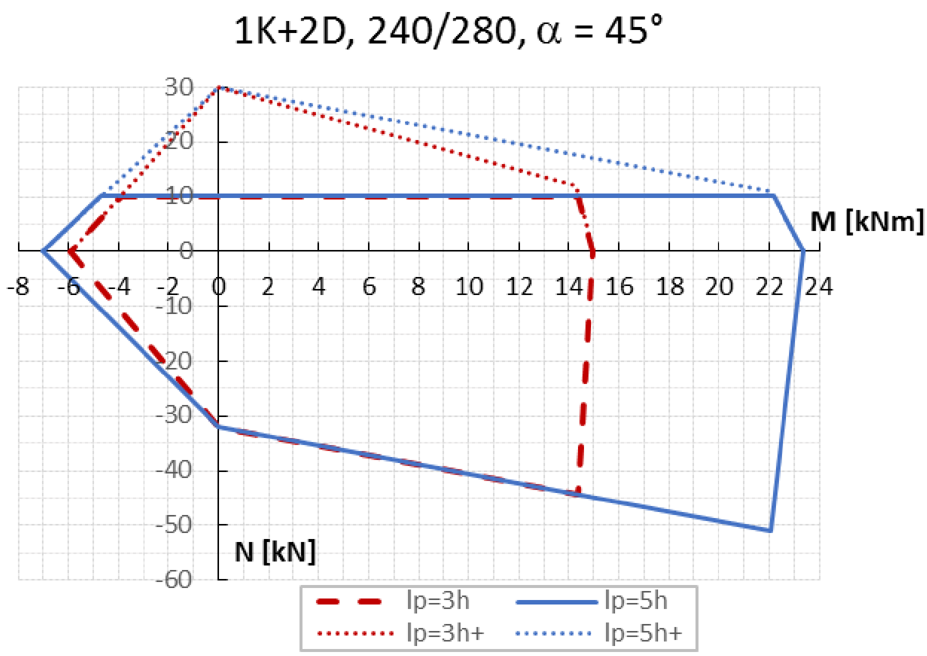
4D, 140/160, α = 60°




4D, 180/220, α = 60°
N [kN]
M [kNm]
lp=2.5h
lp=5h
20
15
10
5
0
-5
-10
-15
-20
-25
-30
-35
-40
-45
-50
-4 -3 -2 -1 0 1 2 3 4 5 6 7 8 9 10 11 12 13

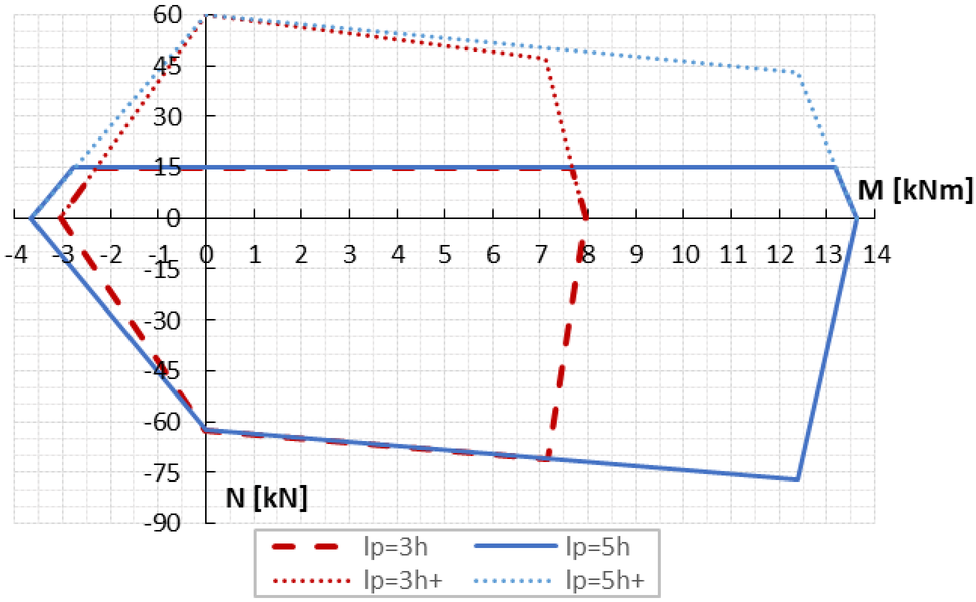


1K+2D, 180/220, α = 45°
M [kNm]
N [kN]
lp=3h
lp=5h
lp=3h+
lp=5h+

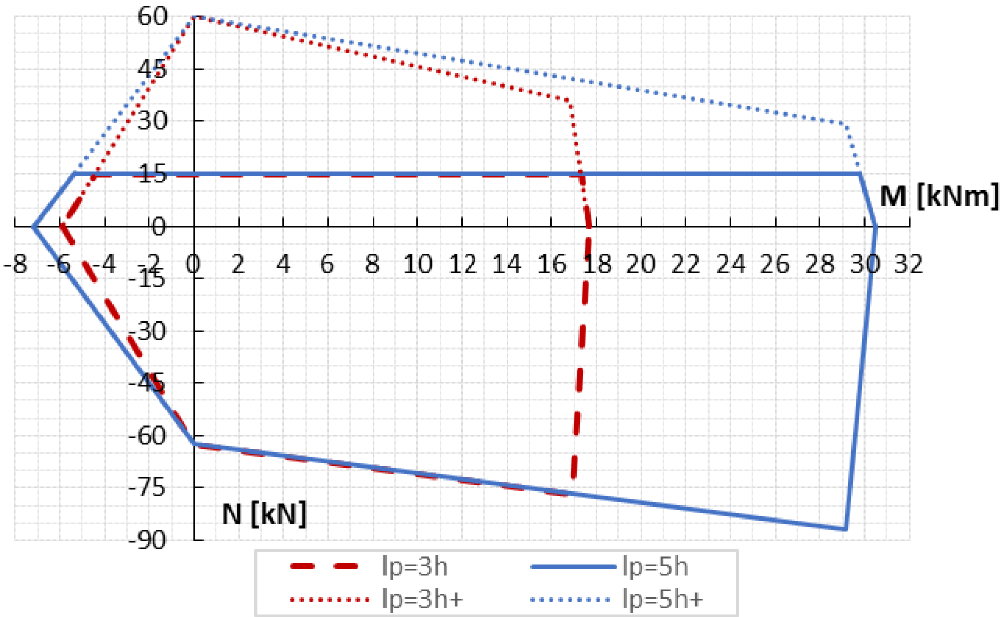


1K+2D, 240/280, α = 45°
M [kNm]
N [kN]
lp=3h
lp=5h
lp=3h+
lp=5h+

2K+1D, 180/220, α = 45°



2K+1D, 240/280, α = 45°



C. CARPENTRY GLOSSARY

The glossary relates to the technology of the manufacture of an extension joint, other terms can be found in [6].

wooden dowel

a coupling element made of split hardwood, with round cross section (Fig. 15)

wooden nail (Holznagel)

a coupling element made of split hardwood, with square cross section (Fig. 37)


Fig. 37 Wooden nail in the joint (left), wooden nails removed from the joint (right)

wooden key

a coupling element of square cross-section, usually a wedge-shaped one in extension joints (Fig. 34)

chisel axe

a tool merging the forms of an axe and chisel for taking off wood by applying only hand pressure, used for finishing of joints or surfaces (Fig. 38)

drawknife

a planing tool used for chamfering and fitting to a wane (Fig. 38)


Fig. 38 Chisel axe (left), drawknife (right)

Fig. 39 Saw band for longitudinal cutting (left), saws band for cross cutting (right)

foxtail saw

a one-man saw with a broad blade for precise guiding in the cut (Fig. 29)

compass saw

a one-man saw with a narrow blade for cuts with limited space, for cuts starting in a hole (Fig. 34)

calliper

a tool for measuring the diameter of trees and logs, the calliper measures with an accuracy of 0.5 cm

clamp (carpentry, locksmith clamp)

a tool for fixing assembled parts of the joint for the purpose of fitting coupling elements (Fig. 30)

bevel gauge (templates)

a tool for marking cross cuts at an angle (Fig. 40), it may be fixed or adjustable.

chalk line with clay (reel)

a tool for marking a line, according to which a part is processed (Fig. 40)

Fig. 40 Bevel gauge (left), chalk line with clay (right)

Carpentry process steps:

notching

after marking the future plane with the chalk line, the slab of the log is divided by cross notches made by a hewing axe into shorter longitudinal sections which will facilitate subsequent rough hewing (Fig. 41)

rough hewing

cutting off roughly excess wood by a hewing axe to facilitate subsequent flattening (Fig. 41)

Fig. 41 Notching (left, centre) [16], rough hewing (right)

fine hewing flattening

actual hewing (finishing) is carried out using a broad axe; in the case of logs with a smaller diameter where only small slab is cut off, roughing may be omitted; only when the timber is processed and only a thin layer remains to be removed (5 to 20 mm), the carpenter begins fine hewing - i.e. finishing the face indicated by the line (Fig. 42)

Fig. 42 Fine hewing (left), compression wood of spruce (right)

reaction wood

Reaction wood refers to changes in the wood structure caused by mechanical effects in the growth of the tree, i.e. in the formation of wood. The reaction wood in the case of conifers is known as *compression wood* (Fig. 42) (characterised by a higher proportion of late wood in the rings and colour changes - darker crescents in the cross-section). The reaction wood in the case of deciduous trees is called *tension wood* (appears macroscopically as a shiny white area in the cross section and a lighter rough belt in the longitudinal section).

D. CONTACTS

You can contact the authors by e-mail at: spoje@itam.cas.cz .
The authors of these methods welcome any information or photographic documentation of a project implementation, as well as any observations and experience regarding the long-term behaviour of the joint in a structure, etc. The references regarding these applications can be used as feedback and an incentive for further improvements of the joints.