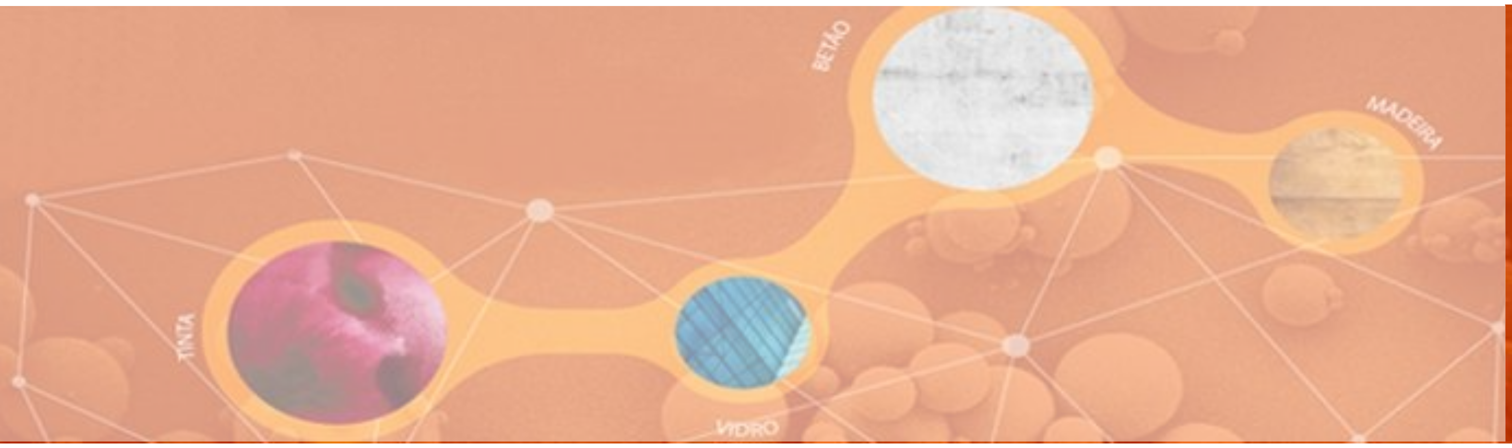

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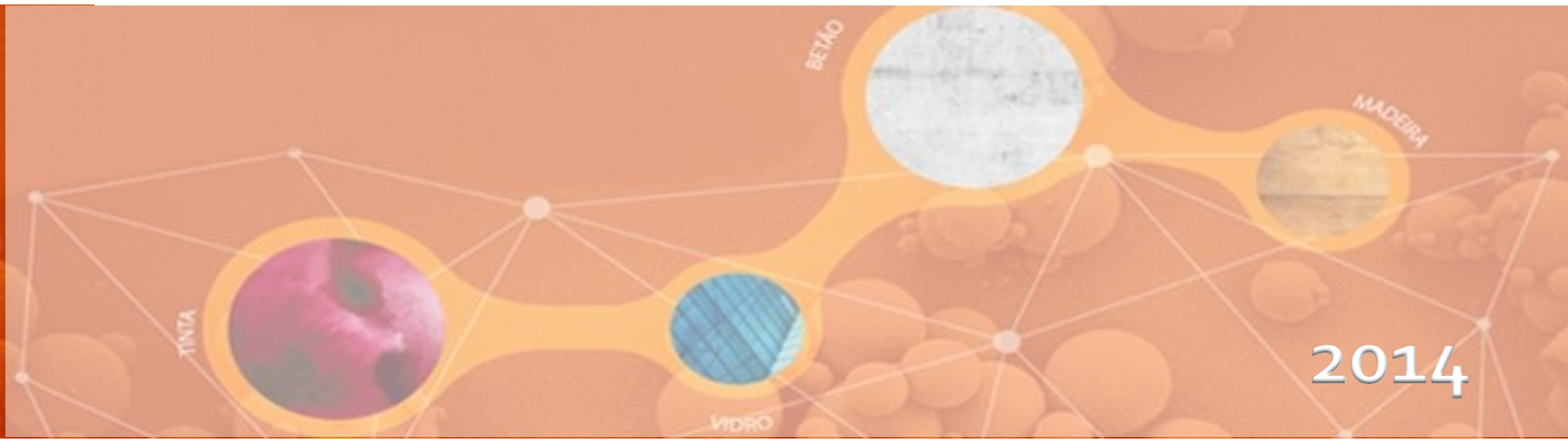

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Tema 03: Materiais e Resíduos

Application of the component method to traditional dovetail joints of timber trusses

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Palavras-chave: Dovetail joint, historical trusses, component method.

Resumo. Timber structures, especially trusses, represent one of the most important ancient engineering structures. But during the lifetime cycle, wood and all members of truss degrade and they need to be repaired.

Collar beam truss is one of the most common types of historical trusses in Czech Republic. The most representative joint of this type of timber system is the dovetail joint. It is important to assess the joint behaviour, both in terms of strength and stiffness, not only for the design of new trusses, but specially, for the intervention on existing structures. Unfortunately, during the ages those joints have been constructed by routine and no recommendation for their design exists.

The behaviour of this carpentry joint can be analysed through the component method based on the use of springs simulating the strength and stiffness of each component. In this paper the application of this method to dovetail joints is presented and discussed. For that, the behaviour of the dovetail joints have been characterized in terms of geometry, materials, stresses involved and common damages.

Introduction

Timber structures, especially trusses, represents one of the most significant and ancient engineering structures. One of the most interesting ones is the trusses of wide constructions as churches, sports hall, storehouses, etc. Those timber structures, with their large span trusses reflected the ability of carpenters and masters builders to create magnificent construction of those times. Unfortunately, due to numerous fires in the Middle Age, few examples of historical trusses remain. In fact, gothic and baroque trusses could be considered as the oldest preserved existing trusses in Czech Republic.

During their lifetime, trusses could be mechanically damaged or degraded due to neglected maintenance, influence of wood-rotting fungus and wood-destroying insects (see Fig. 1*a*), etc. Reconstruction of those structures is normally under supervision of Monument Care Department of Ministry of Culture of the Czech Republic, as frequently they belong to buildings of the Cultural Heritage. Therefore, all interventions must preserve the originality of the construction [1].

In each intervention, an accurate diagnosis and analysis of the existing structures are necessary to support the decision on which elements need reinforcement or substitution. In this analysis phase, the assessment of the behaviour of the carpentry joints is crucial. Joints play an important role in the stress distribution within the structure as they represent the key elements in terms of strength and ductility [2].

If the intervention aims to reinforce the structures, normally this objective includes the reinforcement of the joints. For that, it is fundamental to assess the joint behaviour to achieve a correct improvement of its strength through the reinforcement. On the other hand, if the joint has to be "rebuilt", it is necessary to reproduce the existing joint, with the original behaviour, to preserve the authenticity of the structure. In all conditions, the assessment of the accurate behaviour and preservation of the joints is essential.

a) b)[2]

Fig. 1 Examples of degradation in trusses – a) wood element infested by wood-destroying insects, b) end beam rotted

In spite of that carpentry joint are constructed in the same way during the time, just by routine, there is not many studies, nowadays, focused to historical joints [3-11].

The oldest existing trusses in the Czech Republic are from Gothic and Baroque periods, as was mentioned above. Collar beam trusses with dovetail joints were used in those times. Dovetail joint could be used in many places in the construction, some examples of utilization can see at (Fig. 2).

Because there are almost no studies about dovetail joint, which describes its behaviour, its analysis could help for example with creation of some recommendations for designers, how to use the joint during reconstruction or what is an appropriate approach during its reinforcement.

Collar beam truss

Trusses are constructions which bear and transfer loading from roofs. It is seen that the historical trusses in and around the Czech Republic were made only from wood, mostly from pine (*Pinus sylvestris*) and spruce (*Picea abies*). These wooden trusses were rarely reinforced by metal parts. Roofs are exposed to the weather more than other parts of structures. Due to a combination of factors, degradation of roof trusses is greater than degradation of other parts of a structure.

There are more factors that are responsible for the decline in the number of historical trusses in the Czech Republic. One of those factors can be attributed to a large number of repairs of roofs. Sometimes roofs underwent extensive changes or were completely rebuilt in an effort to modernize buildings. The original shape of the roofs and related construction of trusses was forgotten.

Typical angle of roofs in the Gothic period was about 60°. Although this minimizes the impact of snow loads, it increases influence of wind. Hence the truss has to be stiffened to resist wind loads. The collar beam truss was developed to this. The collar beam truss can be used for wide span construction, because the collar beam minimizes the rafter’s span and at the same time increases the stiffness of the truss as a whole.

In structures where a collar beam supported by posts is used, the loading is transferred directly to purlins, which helps in better force distribution. Only rafters carry bending moment and other elements carry only axial loads [12].

The most common type of damage that collar beam trusses face is due to water that runs off a roof. Due to this, the end beam of the rafter (Fig. 1*b)*) can undergo rot leading to the collapse of the truss.

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[2] http://www.tesarskahut.cz/galerie/0031358497385.jpg

Another typical damage is connected with large tensile forces in the collar beam. The large magnitude of tensile forces can results in a broken rafter in the vicinity of the joints.

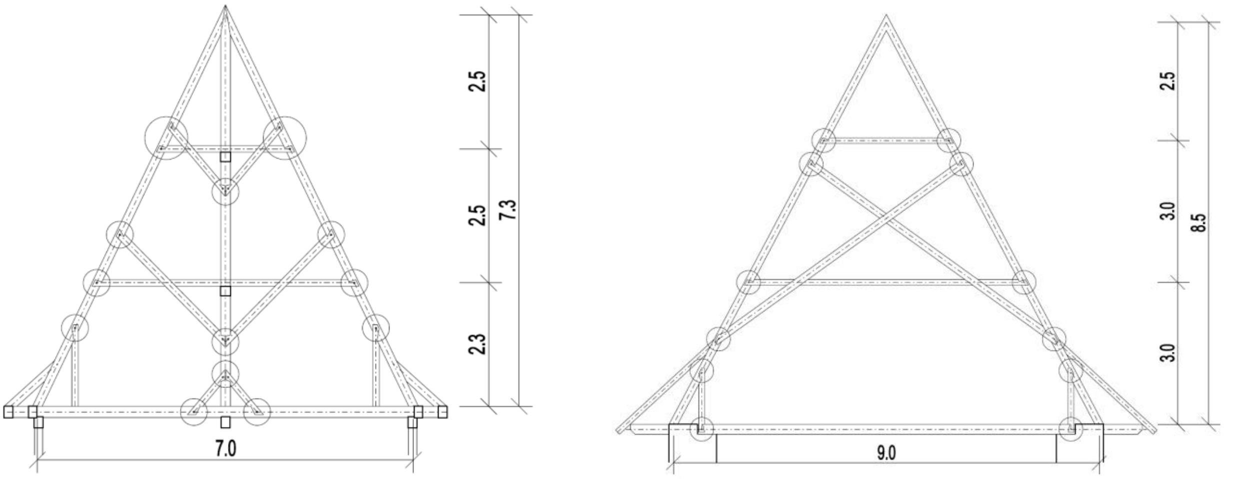


Fig. 2 Collar beam truss: chapel in Kozojedy (Jičín, Czech Republic) in the left and in right truss of Church of Saint Anna in Prague (Czech Republic) – the dovetail joints are in circles

Dovetail joint

The dovetail joint is one of the most commonly used joints in collar beam trusses. The structure of a dovetail joint is seen in Fig. 3. The joint is a complete wooden carpentry joint. It can be used to connect rafters and collar ties, collar ties and posts and many more (types utilization of the joint in a construction are shown at *Fig. 2*). In the joint, both connected elements are weakened of 1/3 of width of thinner one to fit together (seen in *Fig. 3*). The whole joint is held together by a wooden key, which is mainly made from hardwood (oak wood in the Czech Republic).

Inside the joints, loads are transferred through direct contact of its parts by compression. Since dovetail joints are used in various positions in a structure, there are lots of variants of geometry of the joint that means big variety of the compressive areas used to transfer the loading. Examples of compressive areas and forces, which resist to bending moment, are shown at *Fig. 4*.

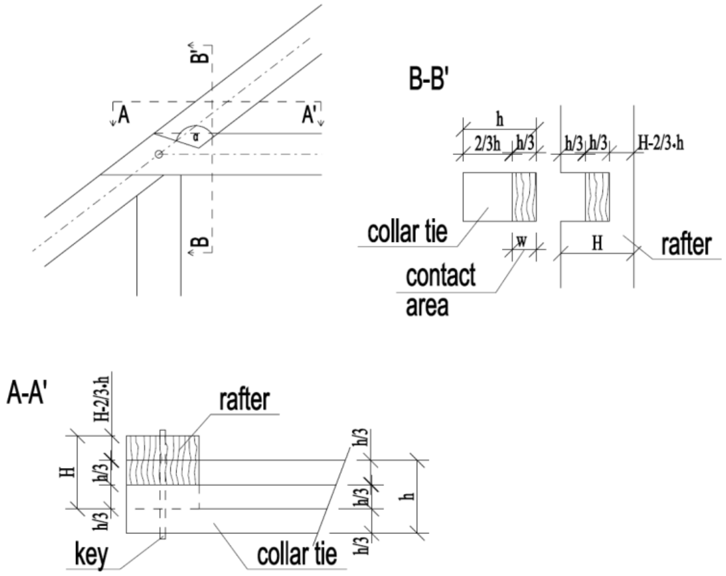


Fig. 3 Dovetail joint – connection of rafter and collar tie

The key of the joint helps in transferring forces too, but its main purpose is to hold the whole joint together. Without the key element, the joint cannot work properly (the joint without the key can transfers only some types of loading). Even though a deformed key can hold the joint together, the gaps created between the elements, reduces efficiency of the transfer of forces. With bigger gaps, the area in compression is smaller and the internal forces as well as local stresses in the joint are bigger.

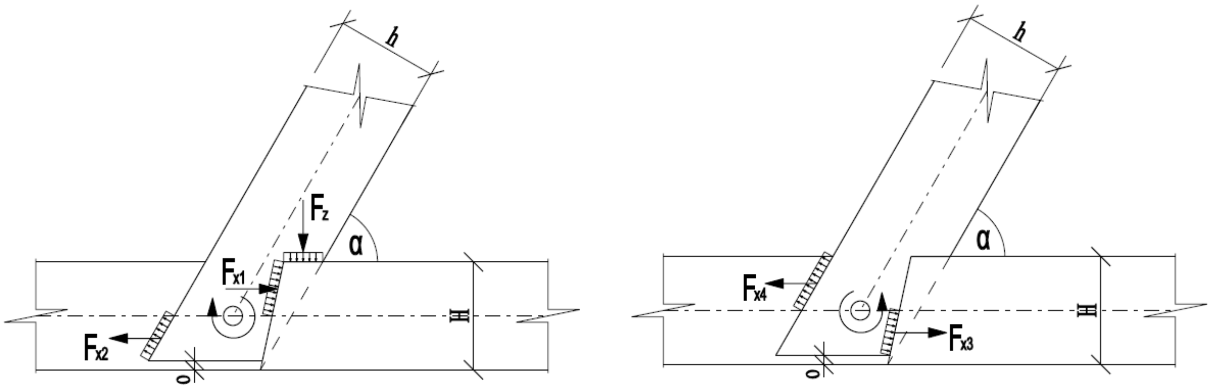


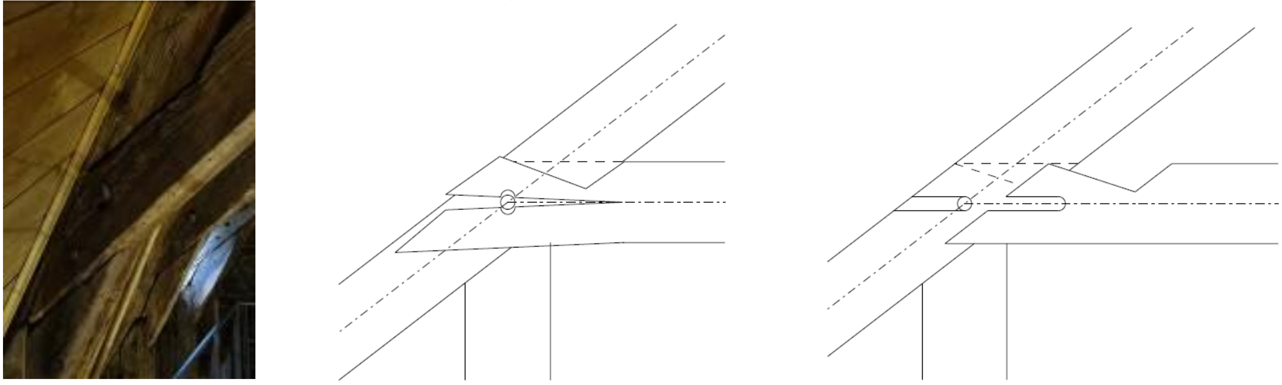
Fig. 4 Compressive areas of the joint

The causes of damage in dovetail joints can be summarized as:

- Inappropriate fabrication;
- The joint can undergo mechanical damage arising from fungal or insect attack. The longhorn beetle is one of the insects that can cause greater damage to dovetail joint. These beetles infest dovetail joints because there are a lot of crannies, where it can put its eggs;
- A collar beam made from turning wood could leads to its bigger torsion deformation. This deformation can further lead to pull out or rupture of the key which in turn can cause the joint to split-up;
- Loss of cohesion around the key. This effect is observed in collar beams which have shrinkage cracks at a joint end.

In other hand, damages in dovetail joints can be divided according to the type of loading:

- Large magnitudes of bending moment could result in the rupture a key. This occurs when massive elements are connected. Otherwise, the dovetail plate could be split up in the key surrounding due to bending moment (direction of splitting is along the grain) (*Fig. 5b)*);
- Rupture of the key due to large tensile forces;
- A peace of plate behind the key could be sheared off when there is a large tensile force and a small gap between the edge of the plate and the hole for the key. Sheared peace of plate got the same width as the key dimension. This type of damage is observed when the dovetail joint is roughly made and parts of the joint do not fit properly (big gaps between elements) (Fig. 5*c)*);
- The joint could be disintegrated due to variable wind and snow loading or varying conditions of humidity during the year.



a) b) c)

Fig. 5 Types of damage of dovetail joint – b) split up of the joint, c) damage due to large tensile force, at a) is joint hardened to resist damage according to damage from b)

It is obvious that compressive areas are dependent on the geometry of the joint (α angle). The geometry of the joint influences compressive areas and hence influences the intensity of resisting forces F_z and F_x from Fig. 4. Compressive areas can be calculated easily from geometry of the joint using equations (1) – (4).

$$x = \frac{h}{3\cos(90-\alpha)} \tag{1}$$

$$x_0 = \frac{x}{2} \tag{2}$$

$$y_0 = x_0^{\,2} + y_{p0}^{\,2} - 2x_0 y_{p0}\cos\alpha = \sqrt{\left(\frac{x}{2}\right)^2 + \left(\frac{\frac{H}{2}-o}{\sin(\alpha)}\right)^2 - \frac{2\cdot\frac{x}{2}\cdot\left(\frac{H}{2}-o\right)}{\mathrm{tg}(\alpha)}} \tag{3}$$

$$z_0 = \frac{\frac{H}{2}-o}{\sin(\alpha)} z_0 \tag{4}$$

Equation (3) is cosine clause only used for the geometry of the joint. The symbols used in equations (1) – (4), are explained in the Fig. 6.

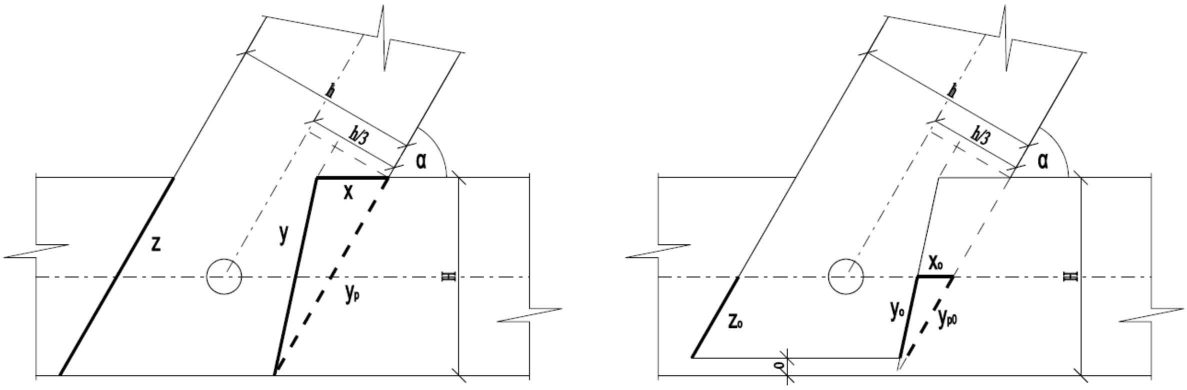


Fig. 6 Dovetail joint – explanation of symbols

It is obvious that the lower angle α causes bigger compressive areas. If there will be the same forces acting on the joint, internal forces in a joint with a smaller inclination will be lower in comparison with forces in joints with higher inclination. Fig. 7 shows the relationship between the angle α and the compressive area in the joint. For the calculation, elements with cross section $b=0.12$m x $h=0.16$m and $B=0.12$m x $H=0.2$m were used. The influence of offset o (seen in Fig. 6) is neglected.

In Fig. 7 A_z is the compressive area, which transfers force F_z. The same principle was used for labelling other compressive areas belong to the forces from Fig. 4. A_c (using part x) is the compressive area transferring compression force in the joint and A_t (using part y) is the compressive area, which belongs to the force which transfers tension in the joint.

Component method

Wood is not a homogeneous material and it has different properties in each direction. Since force depends on the stiffness of the material, the assumption of uniform force distribution does not hold well in the case of wood.

The strength of wood in each direction is influenced by the angle between the grain and the compression force. This relation is shown at Fig. 8 for spruce and pine, using the formula suggested by EC5 [13].

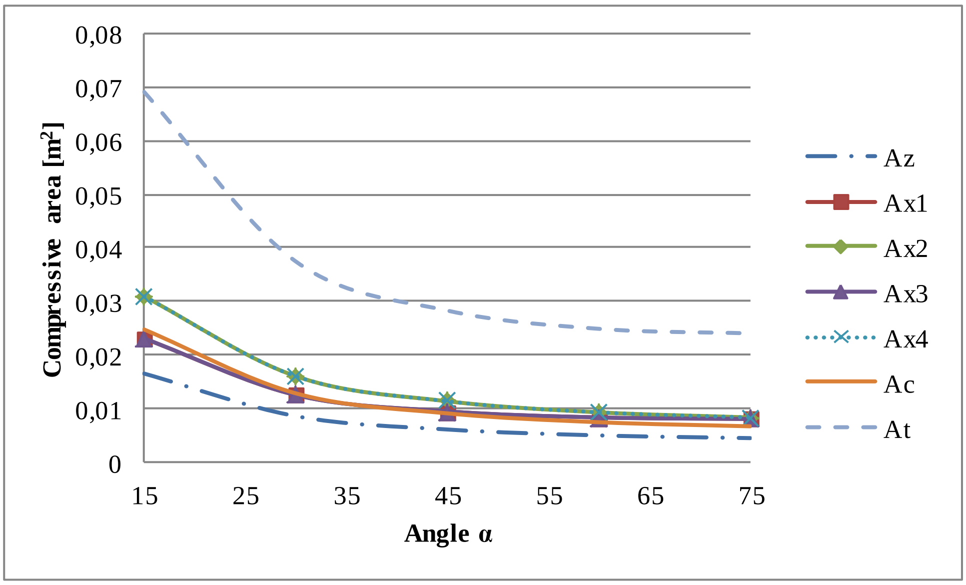


Fig. 7 Relationship between α angle and the compressive area

$$f_{c,\beta,d} = \frac{f_{c,0,d}}{\frac{f_{c,0,d}}{f_{c,90,d}} \sin^2 \beta + \cos^2 \beta} \tag{5}$$

In equation (5) $f_{c,\beta}$ is the compressive strength angled to the grain, $f_{c,0}$ is the compressive strength parallel to the grain, $f_{c,90}$ is the compressive strength perpendicular to the grain and β is the angle of the applied force.

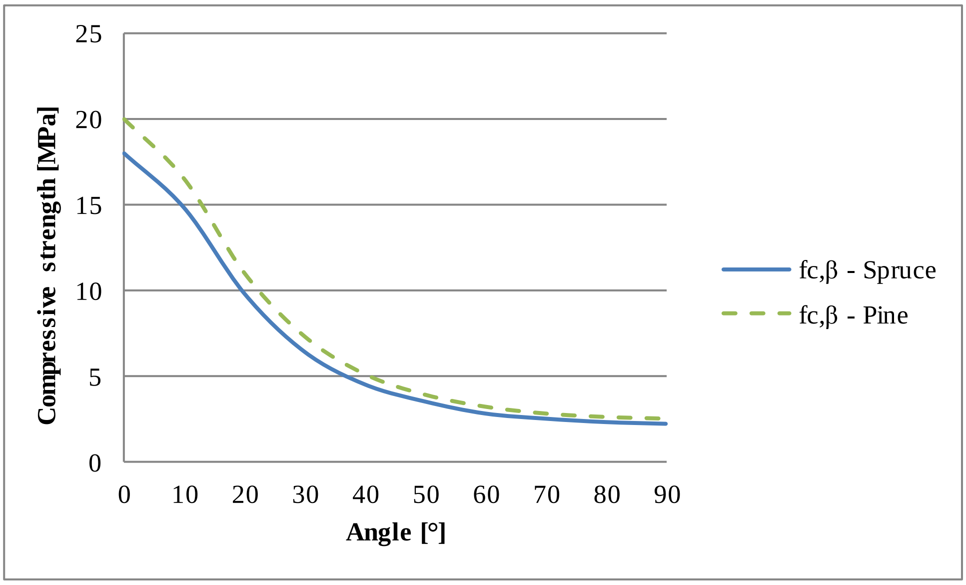


Fig. 8 Relation between strength of wood and angle of applied force

Since joints connect elements with different values of strength, there is a difference in deformation under loading and hence there will be different forces in the joint. For calculating the equilibrium in the joint, it is important to have joint forces dependent on the stiffness of wood, instead of forces dependent on the geometry of joint as was shown in equations (1) – (5). For this purpose it is possible to use component method according to Wald [14].

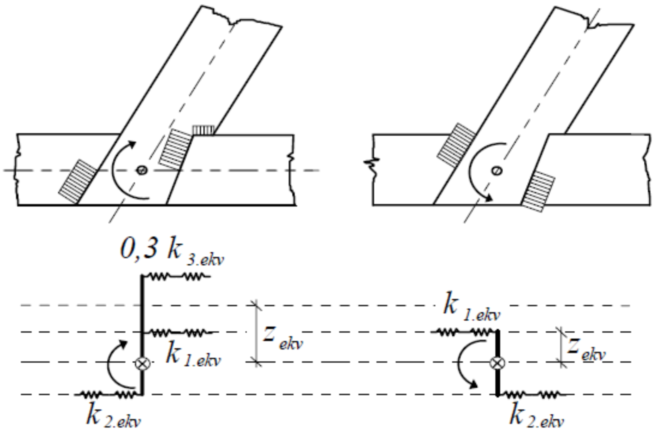


Fig. 9 Draft of component method in dovetail joint [14]

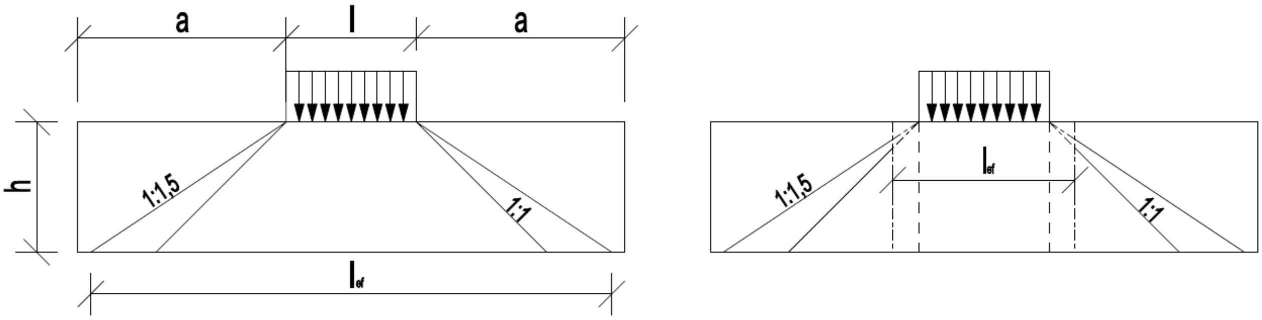
In the component method, the forces in the joint are replaced by springs (seen in Fig. 9) which simulate the strength and stiffness of material. Each spring represents only one force which acts on the joint. This approach allows to create analytical formulae with parameters, which could be used for calculating forces in the joint only with material characteristics (the parameters) of the used wood and the loading. Those forces would be used in equilibrium equations, from which, a joint design or analysis of the joint could be made.

As was mentioned above, loading in the joint is transferred through compressive areas. Unfortunately, wood compression perpendicular or angled to the grain is not easy to understand. According to Van der Put and Leijten [15, 16], there are many factors which influence compression strength of wood. For example, position and type of the loading, dimension of compressed element and the types of supports. But the most significant influence has type of the loading in combination with dimension of element.

Leijten [16] and van der Put [15] have said that maximum compression strength of wood is depended on the ratio (6) between loaded length (l from Fig. 10) and effective – spreading-length (l_{ef}).

$$f_{c,s} = f_{c,90}\sqrt{\frac{l}{l_{ef}}} \tag{6}$$

The loading is not transferred just only with grain under the acting loading, but bigger length of the wood grain is used to transfer loads, as it is possible to see in *Fig. 10*. As it is shown in *Fig. 10b)*, if the element is not long enough, spreading-length is much shorter and the full potential of the material could not be used.



a) *b)*

Fig. 10 Spreading of loading

Two limit situations when increasing the strength perpendicular to the grain is not possible can occur:

- If the element is long enough but has an insufficient height (*h*), spreading is not appropriate. Grain is long enough but load spreading do not occur;
- The same situation arises, when an element is not long enough. In mentioned situation, length of the element is almost the same as its height, from that $\sqrt{l / l_{ef}} \approx 1$. This possibility is shown by dash line in *Fig. 10b).*

On the other hand, it turns up that maximal increasing of compression strength perpendicular to the grain occurs when the element can provide effective length $l_{ef} \geq 3H + l$. Then, spreading ratio is 1:1.5. Typical spreading slope is 45° that means ratio 1:1.

Conclusion and further developments

Historical timber structures, especially trusses degrade during its lifetime and they need to be repaired. When construction is in the bed bad condition, it is necessary to rebuild whole construction or to replace its members. For reconstruction of the historical trusses the historical carpentry joints have to be used to preserve originality of the construction. In other hand sometimes it is sufficient only to stiffen the broken joint.

For both reasons, it is necessary to know behaviour of the used joint and its influence of the construction. Unfortunately, historical joints are all the time constructed in the same way, just by the routine. Since there are not many studies, which describe the joint behaviour, it is necessary to study behaviour of the historical carpentry joints. Basis on the studies, some recommendation for designers can be set. Those recommendations can help to designers to do the effective interventions to the joins during construction recovery.

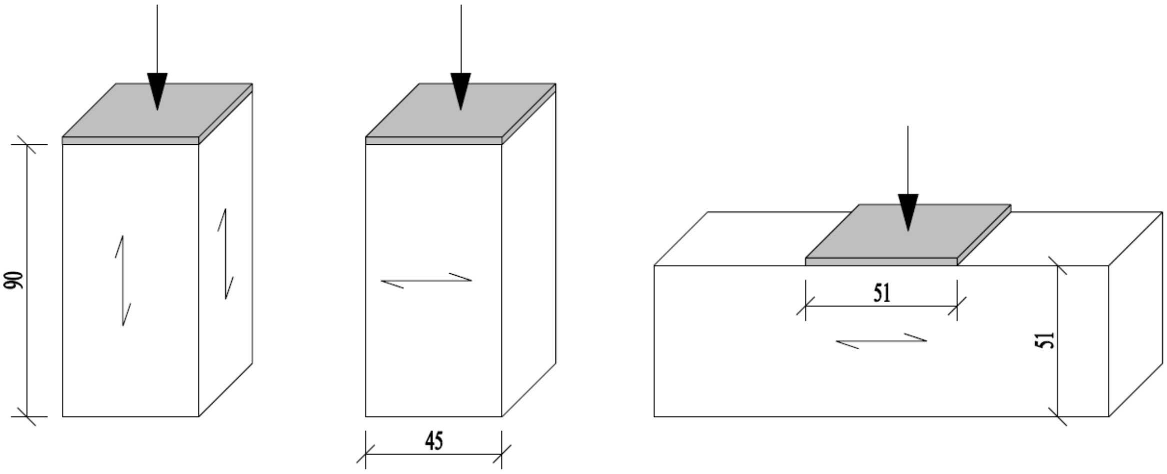
The component method can be used to analyse the mechanical behaviour of dovetail joints. This method links the geometry of the joint with the response of wood under compression. In component method, forces in the joint, which resists to a loading, are replaced by springs for the calculation of equilibrium of the joint. This simplification helps with evaluation of equations of equilibrium.

It is important to know the value of stiffness that needs to be assigned to the spring. Unfortunately, available studies which could help with setting of correct stiffness value of springs are not common [17, 18], what making necessary to set an experimental campaign for the characterization of each spring defined by the component method in the case of dovetails joints.

In other hand, the influence of the key cannot be forgotten. The forces in the key can be solved from equations of equilibrium of internal forces established using the component method and Leijten's [16] and van der Put's [15] theories.

Next step of the research will consist of experimental test of elements according to van der Put's assumptions (*Fig. 11*). From those tests more material characteristics of use wood species (*Pinus sylvestris* and *Picea abies*) will be obtained. The van der Put's theory for tested species will be shown from tests as well. The small elements according to *Fig. 11a)* and *Fig. 11b)* will be tested to the compression parallel and perpendicular to the grain in the first step of the tests. By comparison of the results from the compression perpendicular to the grain tests according *Fig. 11b)* and *Fig. 11c)* the van der Put theory [15] can be validate.

After evaluation of the tests, the stiffness in the numerical model using the component method will be modified. Later, experimental tests of full scale dovetail joints will be made. By those tests, the validity of the stiffness in the numerical model and the numerical model itself will be confirmed.



45x90x70 mm 51x51x152 mm

a) b) c)

Fig. 11 Test according to van der Put [15]

Acknowledgment

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References

[1] M. Gerner, *Woodwork joints, 1st edition*. Prague: Grada, 2003. (in Czech)

[2] J. Branco, *et al.*, "Modelling of timber joints in traditional structures," presented at the International Workshop on "Earthquake Engineering on Timber Structures, Coimbra, Portugal, 2006.

[3] J. Branco, *et al.*, "Experimental analysis of original and strengthened traditional timber connections," Portland, OR, 2006, pp. 1314-1321.

[4] P. Fajman. (2013, Force distribution in a splice skew joint due to the bending moment. *Civil Engineering Journal 2013(04)*. (in Czech)

[5] P. Fajman, "A scarf joint for reconstructions of historical structures," *Advanced Material Research of Trans Tech Publications*, 2014. (in print)

[6] J. Jasienko, *et al.*, "Study of strains and stresses in historical carpentry joints," in *Structural Analysis of Historical Constructions*, New Delhi, 2006, pp. 375-384.

[7] M. A. Parisi and C. Cordié, "Mechanical behavior of double-step timber joints," *Construction and Building Materials*, vol. 24, pp. 1364-1371, 2010.

[8] M. A. Parisi and M. Piazza, "Mechanics of Plain and Retrofitted Traditional Timber Connections," *Journal of Structural Engineering*, vol. 126, p. 1395, 2000.

[9] R. H. Sangree and B. W. Schafer, "Experimental and numerical analysis of a stop-splayed traditional timber scarf joint with key," *Construction and Building Materials*, vol. 23, pp. 376-385, 2009.

[10] R. H. Sangree and B. W. Schafer, "Experimental and numerical analysis of a halved and tabled traditional timber scarf joint," *Construction and Building Materials*, vol. 23, pp. 615-624, 2009.

[11] J. R. Villar, *et al.*, "Analysis of the Stress State at the Cogging Joint in Timber Structures," *Biosystems Engineering*, vol. 96, pp. 79-90, 2007.

[12] J. Vinař, *Historical trusses: typology, survey, reconstruction* vol. 1. Prague: Grada, 2010. (in Czech)

[13] *Standard in the Czech version of the European Standard EN 1995-1-1:2004 including its Corrigendum EN 1995-1-1:2004/AC:2006-06.*

[14] F. Wald, *et al.*, "Component Method for Historical Timber Joints," in *The Paramount Role of Joints into the Reliable Response of Structures*. vol. 4, C. C. Baniotopoulos and F. Wald, Eds., ed: Springer Netherlands, 2000, pp. 417-424.

[15] T. A. C. M. Put, "Derivation of the bearing strength perpendicular to the grain of locally loaded timber blocks," *Holz als Roh- und Werkstoff*, vol. 66, pp. 409-417, 2008/12/01 2008.

[16] A. J. M. Leijten, *et al.*, "Structural design for compression strength perpendicular to the grain of timber beams," *Construction and Building Materials*, vol. 24, pp. 252-257, 2010.

[17] A. Požgaj, *et al.*, *Composition and Properties of Wood*. Bratislava: Príroda, 1997. (in Slovak)

[18] L. J. Markwardt and T. R. C. Wilson, *Strength and Related Properties of Woods Grown in the United States*: U.S. Government Printing Office, 1935.