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DEVELOPMENT OF NEW TYPES OF TIMBER STRUCTURES BASED ON THEORETICAL ANALYSIS AND THEIR REAL BEHAVIOUR

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ABSTRACT

The paper addresses the challenges of designing novel approaches to develop timber load-carrying structures. For this reason it is crucial to apply the results acquired from the sophisticated real behaviour of timber structures. Equally important is the work aimed at analysis of load-carrying capacity of connections and their application in timber structures. The paper presents experimental test results based on the principle of steel-to-timber connections. The dimensions of tested samples and configuration of connectors corresponded with the elements used in presented structures. The results of our long-term geodesic measurements of deformations and displacements are included, which provides feedback on the suitability of the discussed timber structural systems.

KEYWORDS: Timber structures, wooden materials, connections, structural imperfections, deformations, real behaviour.

INTRODUCTION

Wood is a structural building material with a millennium-long tradition. Recently, there has been a growing trend towards using wood as a structural building material thanks to its convenient mechanical and structural qualities, a growing interest of architects and investors in designing and building timber structures (Kuklík et al. 2014). Moreover, wood is ecologically friendly in comparison with other common building materials.

Apart from being used in traditional roof structures and residential buildings, wood can be employed in non-residential modern structures with considerable spans, for high-rises, foot bridges and bridges as well for special structural systems (Straka et al. 2013). Unfortunately, only a fraction of potential of wood has been exploited so far.

Development of new types of timber structures has been enabled by using cost-effective materials with guaranteed properties, higher values of material characteristics and by designing new types of connections and fasteners. A great benefit for designers of timber structures was brought about by the advent of new types of wood-based elements and glue-laminated wood.

Typically, overall behaviour of timber structures is greatly affected by the load-carrying capacity and slip of mechanical joints (Kanócz et al. 2008).

This impact is crucial and decisive especially in large- span structures.

Apart from considering loading effects, defining material properties, ambient conditions and principal construction structure, computational models we have to objectively assess the effects of initial imperfections, eccentricity in connections, interactions with the substructure and foundations, or other design-related factors (Straka 2008).

The paper presents several cases of concrete application of knowledge derived from designing, erection, and verification of the real behaviour demonstrating all the complexity of these processes if all interactions and variable influences must be taken into account (Šmak and Straka 2014).

Our objective is to demonstrate some of the new approaches to exploiting timber and efficient and well-functioning connections in contemporary and perspective types of timber structural systems.

MATERIAL AND METHODS

Timber structures presented here are made of solid timber, glued laminated timber (glulam timber) and wood-based materials. In some cases gypsum fibreboards were used for sheathing of buildings.

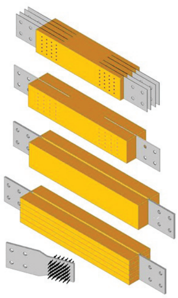
The basic timber material was spruce (*Picea abies*), whose material properties are defined in the standard EN 338, 2009 while the standard EN 1194, 1999 establishes material properties of glued laminated timber with homogeneous lamella structures. As for wood-based materials we employed oriented strand boards, technical class OSB/3 as well as hard fibreboards (Koželouh 2014).

When analyzing the structures we had to consider their behaviour in various thermal and humidity conditions. Therefore it was vitally important to place each structure into an appropriate class of use in compliance with EN 1995-1-1, 2004. Particularly, the difference between behaviour of structures in the conditions corresponding to class 3 and class 2 or class 1 is substantial. If we apply the results from measuring wood properties and structure deformation, we can determine more objectively an appropriate class of use (Kuklík and Kuklíková 2000).

The choice of a connection type has a great impact on both the structure's configuration and dimensions of its load-carrying members. Load-carrying capacity of the connector stiffness can also be decisive for the design and behaviour of a structure as a whole. For this reason assessment of the impact of connection slip on the overall behaviour of structure ranks among key tasks in designing load-bearing structures. It is the principal issue mainly for large-span structures with many mechanical connections and for structures with heavily stressed joints. Stiffness is closely linked not only with material and strength characteristics of wood and connectors but also with structural solution of details. Therefore we must take into account the influence of ambient conditions as well as load types, which are to be transferred. In general, the influence of joint slip is reflected in increased deformations and redistribution of internal forces. As a rule, simplified methods included in timber structures standards are applied to designing connections, but if more accurate methods are needed, they must be based on the results of experimental tests and analyses of real structure behaviour.

In large-span structures and intensively loaded structures, which have to transfer large forces acting in the connection, steel-to-timber joints with slotted steel plates incorporated in the wood are preferred. In these cases design rules, defined in the standard (EN 1995-1-1, 2004), can be applied, since we can conservatively predict the failure pattern in the joint component parts. Behaviour and mechanics of joints with slotted steel plates are quite complex (influence of local strain of wood perpendicular to the grain, combination of individual and block failure). Further research into this field is directed to more meaningful modelling of their behaviour and possible improvements of their characteristics (Lokaj and Klajmonová 2013).

The testing of joints was carried out at the Faculty of Civil Engineering, Brno University of Technology (Fig.1, Straka et al. 2005). The samples corresponded with real joints used in the structures (Melcher 2004). Connectors included nails, dowels and nails welded on the plate.



a) Joints with four 1 mm thick steel plates connected with 20 nails

b) Joints with a slotted 7 mm thick steel plate connected with 20 steel dowels

c) Steel-solid timber joints connected by means of inserted 10 mm thick steel plate and 55 ø3 mm nails welded on both sides

d) Steel-glulam timber joints connected by means of inserted 10mm thick steel plate and 55ø 3mm nails welded on both sides

e) Steel plate with nails welded on both sides and with holes for attachment of clamping device used in cases of b, c joints

Fig. 1: Experimentally tested samples.

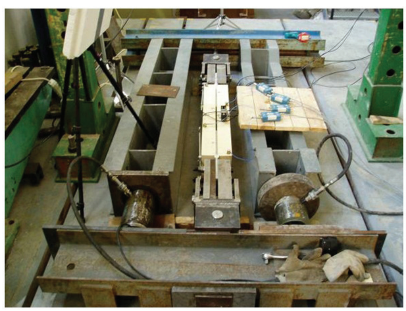


Fig. 2: Samples ready for the load bearing tests on the testing bench.

The tests consisted in non-contact measurement of sample deformation using the video tensometer, the acoustic emission testing and the radiation defectoscopy (Fig. 2, Fig. 3, Hobst et al. 2003). The applied software enabled post-test evaluation of video recordings made by picture cameras. The video extensometer measurements provided relatively complex information on joint behaviour. Evaluation of acquired data could specify displacements of individual points on a timber element or their group with respect to a reference point on the clamping device. Acoustic emissions were monitored independent of other measurements. The running of the experiment using incremental loading was divided into two steps: the initial phase and the phase prior to failure. In this way we could detect initiation and spreading of cracks through wood and on the interface between steel and timber parts of the joint. By comparing the results it became obvious that the acoustic emission method suitably complements the classic measurement. A sharp growth in cumulative energy of acoustic emissions in joint failures is easy to notice and can signal overloaded joints.

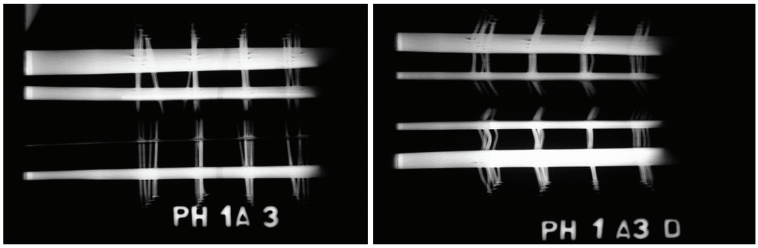


Fig. 3: Nail connection deformation with thin slotted plates of 1 mm shown in an X-ray image of nailed joint before and after the experiment.

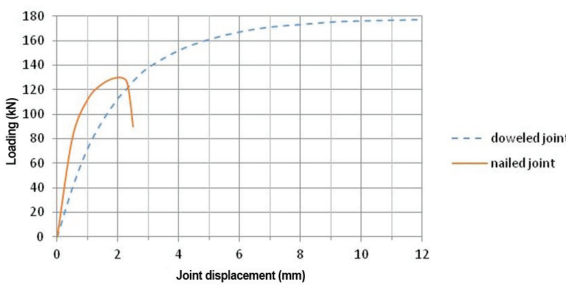


Fig. 4: Comparison deformations in tested joints.

Surveying methods applied to monitoring of timber structures

With the advent of advanced computer systems, enabling procession of a detailed analysis of the whole structure or its parts from the point of view of their stress state of deformations, the possibilities of designing original timber structures were significantly enhanced so that large-span structures, high-rises or structure carrying heavy loads can be built. It is a case of structurally unusual or novel solutions in combination with modern shapes, such as organic architecture. Consequently, hosts of problems can arise if we apply design procedures and verifications defined in the current standards. As a result, the standards must sometimes be modified to suit a given structure. In that case the correctness of chosen procedures has to be verified. It can be done by monitoring the behaviour of the structure or its part over time, which can subsequently serve for refinement of computational models and design parameters. Surveying measurements proved to be most appropriate for this purpose, because they can provide high-precision measurement of displacement and deformations of exactly specified measuring points. In such a manner, an accurate and complex picture of structure behaviour can be obtained throughout a certain time period. Particularly, it can be used for monitoring the impact of creep occurring in principal structural members and mechanical joints with respect to variable temperature, humidity, snow loading, etc.

RESULTS AND DISCUSSION

One of the crucial issues in designing building structures is to investigate how joint slip affects the overall behaviour of structures, particularly in the case of large-span structures with multiple mechanical joints. The joint slip is closely connected not only to material and strength characteristics of wood and connectors but also with structural design of details. In addition, it is necessary to take into account the ambient conditions and types of load actions the structure has to carry requires a careful consideration.

Depending on the structure type and importance of the problem solved, simplified methods can be chosen as indicated in the appropriate standards. If more accurate methods are needed, they are based on the results of experimental testing of joints as well as on the analysing their behaviour in real structures.

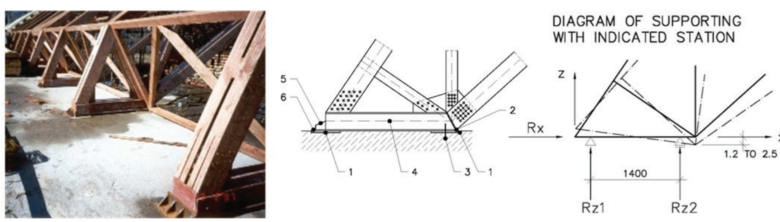
The structure's load-carrying capacity and creep are also greatly influenced by interaction with the substructure and foundations.

In general, the impact of joint slip is manifested through changes in deformations and redistribution of internal forces in load-carrying members. Therefore, this influence has to be assessed and respected in designing timber structures and their safe carrying capacity and usability has to be verified.

Trusses

Timber trusses comprise a number of types, whose behaviour is significantly affected by the type of connectors and the type of supporting on the underlying structure. Due to a large number of mechanical fasteners, joint slip has to be considered, particularly in large-span structures.

The hinged supporting proved to be efficient for arched and framed trusses, glulam arches and frames. It can be designed using a pivot joint or steel bearing, enabling free rotation in the supports. This arrangement was also found advantageous because it is easy to manufacture, transport and erect.



1 – Steel plates 30 mm thick anchored in concrete
2 – Rectification steel plate 25 mm with oval holes
3 – Anchor bolts 20 mm
4 – Steel bar made from welded I profile
5 – Stiffeners
6 – Steel plate 25 mm thick welded to the anchor plate

Fig. 5: Structural solution of a clamped arched truss support by means of steel bar showing the anticipated support rotation.

Frame and arched systems with support that corresponds with clamping, shows greater stiffness; however, it is necessary to take into consideration possible displacement and rotation of support. Moreover, we have to respect connector slip of truss internal members to the chord members. The values of estimated displacement and rotation of supports depend on the type of substructure and foundation conditions.

Our example shows a structure with clamped arched trusses spanning over 40.4 m (Fig. 5 - Straka 1998, 1999). The impact of support slip and interaction of the timber structure with concrete frames appear to be significant. Displacements and rotations owing to the interaction with the substructure (Fig. 5), were considered in the calculation model using the values ±8 mm (horizontal displacement), 5 mm (vertical displacement) and rotation of the steel support bar by 0.10° to 0.20°. The effect of support slip was manifested in a relatively significant redistribution of internal forces in the system members and the components of support reactions.

Glulam framed and arched structures

Glulam arches and frames are frequently used in halls, ribbed domes and other structural systems. Diagrams in Fig. 7 summarize the calculation results of a hall with glulam arches of the span of 51.90 m (spacing of arches is 5.50 m – Fig. 6) considering real stiffness of the apex and the support details. The structure analysis was carried out in order to assess the existing condition of the structure and its further behaviour (Bajer and Barnat 2012, Straka and Šmak 2008).

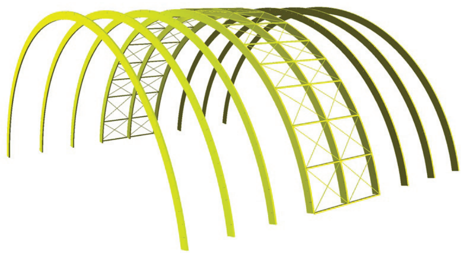
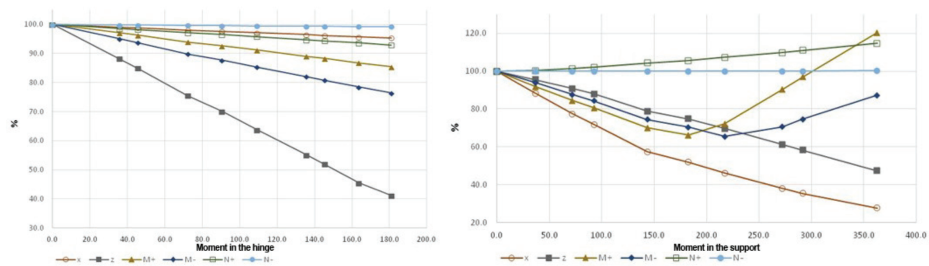


Fig. 6: Configuration of the principal load-carrying structure of the winter stadium – glulam arches with the span of 51.90 m and spacing of 5.5 m.



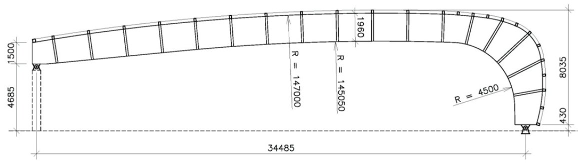
M … moment in the hinge (in the support) — *x … horizontal deformation*
z … vertical deformation — *M+ … max. positive bending moment*
M– … max. negative bending moment — *N+ … max. normal (tensile) force*
N– … max. normal (compressive) force — *100 % … ideal hinge*

Fig. 7: Influence of apex detail stiffness on internal forces and arch deformations. Influence of support detail stiffness on internal forces and arch deformations.

It was necessary to thoroughly investigate and verify timber structures in interaction with the concrete substructure, which can be illustrated by the following example of roofing of the swimming hall in Brno-Kohoutovice, designed as a system of individual vault segments with centrally located curved glued-laminated frames. The span of the glulam frames varied from

23 to 35 m (Straka et al. 2010, 2013, Straka and Šmak 2008).

One of the vital problems in designing the roof structure was to determine the horizontal slide in the position of support of glued laminated frames on relatively high concrete columns and to investigate the influence of slide value on the whole concrete wall, which incorporates the columns and the timber structure itself (Fig. 8). Stiffness of the support affected internal forces and frame deformations and was critical for designing the supporting concrete wall. Selected values of decisive quantities are given in Tab. 1. Real horizontal displacement in the support on the concrete wall was considered only up to 20 mm.



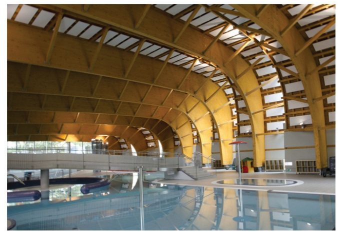


Fig. 8: Configuration of the main frame rib of the span of 34.05 m. Realised timber structure.

Tab. 1: Influence of support slip on internal forces, reactions and portal frame deformations.

u (mm)	w (%)	M+ (%)	M- (%)	N (%)	Ry (%)	Rz (%)
0.0	100.0	100.0	100.0	100.0	100.0	100.0
5.0	106.6	104.1	95.0	98.2	96.4	100.4
10.0	113.1	108.2	90.1	96.4	92.7	100.9
15.0	119.5	112.4	85.3	94.6	89.0	101.3
20.0	126.5	116.5	80.5	93.5	85.4	101.8
25.0	132.6	120.6	76.0	92.0	81.8	102.2
30.0	139.2	124.8	71.4	90.6	78.1	102.7
35.0	145.7	129.0	67.1	89.2	74.5	103.1
40.0	152.5	133.6	62.6	87.8	70.8	103.5

u … horizontal displacement of the support *w … max. vertical frame deformation*
M+ … max. positive moment *M– … max. negative moment*
Ry … horizontal reaction in the displaced support *N … max. normal force*
Rz … vertical reaction in the displaced support *100 % … rigid support*

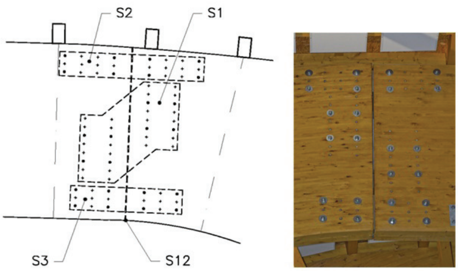
The structural solution of connections was optimized both from the viewpoint of steel dowel connectors and their overall stiffness.

Structural solution and configuration of the assembly connection is shown in Fig. 9.

Surveying measurements of the swimming pool timber structure have continuously been made since the structure completion in 2011. During the erection stage measuring marks in the form of special reflection foil were glued on the steel dowels or on the frame surfaces. A detail of mark positioning is shown in Fig. 10.

Fig. 11 indicates the mechanics of measuring points displacement in two stages – after completed erection and 12 months later (Bureš et al. 2012, 2014).

The deformations of curved glulam frames obtained from the surveying measurement confirmed our original assumptions about the structure behaviour. As expected, the measured horizontal displacement ranged from 3.1 mm to 4.5 mm in 12 months after completing the building. The measurements also corroborate that the measured structure deformations are in correlation with the solution results of spatial computational models developed for the given structure.



S1 – steel plate 8 mm, 16 dowels 24 mm, 8 bolts 24 mm
S2 – steel plate 8 mm, 24 dowels 24 mm, 8 bolts 24 mm
S3 – steel plate 8 mm, 10 dowels 24 mm, 8 bolts 24 mm
S12 – steel plate 2x5 mm

Fig. 9: Assembly connection of the glulam frame – design, realization.

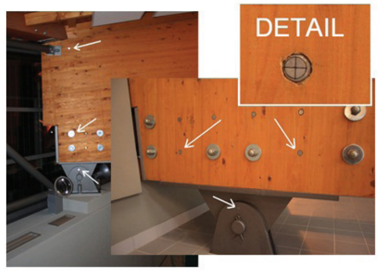


Fig. 10: Fitting of measuring marks on the frame.

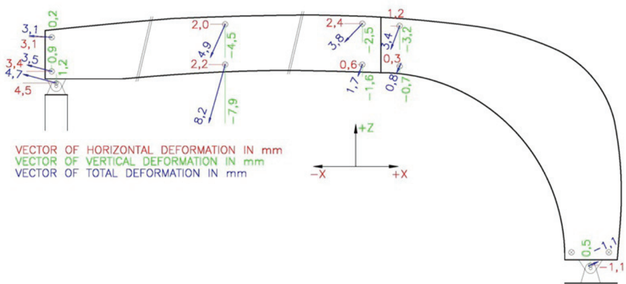


Fig. 11: Positioning of measuring marks on the frame and mechanics of movement during the monitored stage.

A timber structure of an original modern house serves as an example of application of newly developed curved glulam elements. The house cross-section is shaped in the form the euro symbol, therefore it was made from curved arched ribs, which meets the requirements of the investor (Fig. 12). The glued laminated elements are manufactured from sawn spruce timber (*Picea abies*) strength class C24. The curved shape was obtained by cutting straight plank elements to form the required shape.

In order to obtain the necessary height of the cross-section (250 mm and more), it was necessary to carry out longitudinal glued lamella connections. The lamellas were connected by means of heel joints glued together with a polyurethane adhesive. Application of these new elements was preceded by a detailed theoretical analysis, which was verified in experimental tests made on the curved segments (Fig. 13).

Fig. 12: Load- carrying structure made from curved segments.

Fig. 13: View of the experimental test of curved segments.

CONCLUSIONS

The paper was aimed at specific issues of development, design, erection and verification of real behaviour of timber structures.

Our analyses of certain types of structural details were focused on the issues of steel-to-timber connections and steel nail and dowel fasteners. The results acquired from experimental testing proved favourable qualities of these connections employed in the structures in view of load transfer and their stiffness. Our long-term monitoring of deformations in realized timber structures considering variable effects of load action and changes in temperature and ambient humidity justified chosen solutions and advantages of employing of these connections in structures.

The results of analyses that studied the behaviour of joints incorporated in structures confirmed the need to consider the real stiffness of structural details as well as their interactions with the substructure with regard to load-carrying system behaviour, especially as far as the design's reliability and economy is concerned.

The obtained results can contribute to the development of novel effective and perspective timber structures and to enhancement of knowledge in the field of their design, implementation and verification.

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