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DOWELLED JOINTS IN TIMBER STRUCTURES EXPERIMENT–DESIGN–REALIZATION

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ABSTRACT

The paper describes experimental research in the real behaviour of connections and its application to the design and realization of new types of timber structures. According to the connection type, primarily dowelled joints with slotted-in steel plates made from solid and glulam timber have been examined. A vital factor in designing joints of timber structures is respecting wood properties related to its changes in humidity. It is namely the case of strength changes as well as volume changes in particular directions. The experimental tests have been used to evaluate the influence of material strength, diameter and dowel number on the load-bearing capacity of joints. Substantial strengthening of joint's load-bearing capacity can be attained by eliminating transverse tensile stresses in the region of dowels. Thus the conclusions derived from the experimental research and from the real behaviour have been implemented by the authors to develop new types of timber structures.

KEYWORDS: Timber structures, connection fasteners, dowelled and bolted joints, steel-to-timber-joints, real behaviour.

INTRODUCTION

Dowelled connections belong to fundamental still perspective types of joints in timber structures (Šmak and Straka 2014). Joints with dowel fasteners and slotted-in steel plates used in contemporary timber structures are ranked among more innovative types of mechanical joints. Their implementation is very effective thanks to their favourable strength, stiffness, and construction properties. They can be applied to various types of structures made from both solid and glulam timber (Kuklík 2005, Straka and Novotný 2001). The joints based on slotted-in steel plates appear to be crucial and in many cases the only possible solution, mainly in the structures, where it is necessary to transfer high forces in connections and solve complex spatial structural details. Their essential property, verified in experimental tests as well as in their real behaviour, is the ductility of these connections, which is manifested in their sufficient resistance to brittle fracture. The joints also have the advantage of being fire resistant and they are also appreciated for their aesthetic appearance. As for fasteners, steel dowels, bolts, self-drilling screws or possibly nails can be used. Typically, overall behaviour of timber structures is greatly affected by the load-carrying capacity and slip of mechanical joints (Kanócz et al. 2013, 2014). This impact is critical and decisive especially in large-span structures.

Structural eccentricities negatively influence the load-bearing capacity of connections. If the connections based on slotted-in steel plates enable to design connection with significantly less eccentricities in comparison with other connection types. Current standards for designing timber structures do not contain sufficiently detailed provisions to evaluate this connection type. Especially, they do not include a more objective consideration of the impact created by the distribution of transferred forces on individual fasteners spaced in rows one after the other. Our aim is to assess the influence of connection strengthening on the overall load-bearing capacity and behaviour of these connections.

The paper also presents several cases of concrete application of knowledge derived from designing, verification and of the real behaviour of slotted in-steel plates connections (Straka et al. 2016).

MATERIAL AND METHODS

The issues of designing the dowelled connections stressed by axial forces are elaborated in the standards for designing of timber structures. These design procedures are based on the theory of connection failure mechanism, so-called European Yield Model, created for steel dowel elements in single or double shear joints 'timber-to-timber' or 'steel-to-timber connections'. Design methods presume ideal elastic-plastic behaviour of timber elements and ideal rigid-plastic behaviour of steel dowels.

The doweled connection failure can occur in various failure modes – through bending of dowel fasteners, embedding of wood or simultaneous failure of both dowels and wood. Besides the above mentioned individual failures of the components, the connections with multi-dowelled fasteners in a row in the grain direction can collapse due to brittle fracture, wood splitting or block failure (Blesák et al. 2012).

The overall load-carrying capacity of the dowelled connection depends on the embedding strength of wood and on the load-carrying capacity of dowel fasteners. In the case of the block failure it is also dependant on mutual spacing of dowels and their end and edge distances (Blass et al. 2008). Dowel slenderness (the ratio of the dowel length and its diameter) is also a significant factor. If the dowel slenderness is low, the risk of brittle fracture and wood splitting increases before the possible redistribution of forces to individual dowels. If the dowel slenderness is higher, it results in a major plastic deformation with excessive slip.

Individual components of dowelled joints are exposed to a complex spatial stress. With respect to the plastic behaviour of wood and steel the forces between individual dowel fasteners are redistributed under load action, which is caused by local plastic deformations (Ehlbeck and Werner 1995).

Due to embedding, spatial stresses occur in the hole walls of dowel fasteners. They can be broken down to the component parallel with the force direction, which causes local compressive stresses in grain direction and the perpendicular component of the force, which gives rise to tensile stresses perpendicular to the grain. These stresses can cause splitting the wood (Fedorik et al. 2015). The contemporary standards for designing dowelled connections make a number of recommendations for usual cases. If the standard requirements are met, the connection is considered reliable according to the ultimate and serviceability limit states.

The load-carrying capacity of individual components and the corresponding connection failure mode were determined according to EN 1995-1-1 (2006) and EN 1993-1-8 (2006). Fig. 1 displays design load-carrying capacities of individual components in the analyzed dowelled connection with the following parameters:

- basic profile: material GL24h, dimension 120x160 mm
- slotted-in steel plate: thickness 6 mm, width 160 mm, steel class S355
- dowels: smooth, 16 mm in diameter, steel class S355

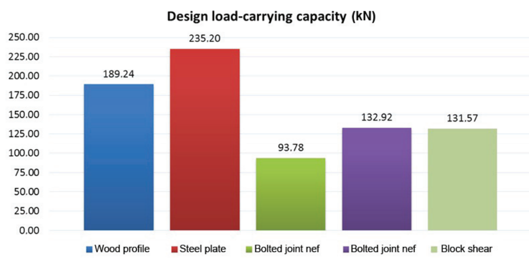

Fig. 1: Design load-carrying capacities of connection components for individual types of failures (wood profile: design load-carrying capacity of the basic timber member; steel plate: design load-carrying capacity of the slotted-in steel plate; bolted joint 'nef' design load-carrying capacity of the connection with reduced number of bolts in a row; bolted joint 'n': design load-carrying capacity without reduction of number of bolts; block shear: design load-carrying capacity in block shear failure).

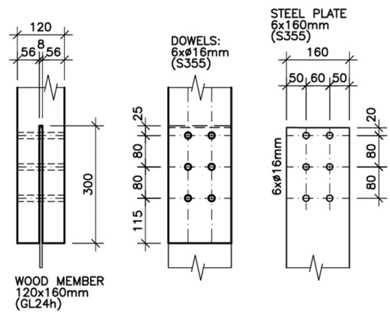

Fig. 2: Configuration of the analyzed connection.

Configuration of the connection is shown in Fig. 2.

As seen in Fig. 1, design load-carrying capacity is significantly affected by a reduction of the number of elements in the row in the grain direction. By strengthening the connection i.e. by considering the unreduced number of dowel fasteners, a considerable increase in the load-carrying capacity of the whole connection can be attained. The purpose of the strengthening is to eliminate transverse tensile stresses in the area of dowels.

Connection strengthening can be carried out by various structural methods as follows:

- using screws perpendicular to the wood grain (perpendicular to the dowel axes);
- using glued-in bolts;
- using high strength carbon or glass fibres to strengthen the member surface;
- using additional glued cover plates made from wood-based materials.

A proposed strengthening method has to meet the requirements of sufficient load-carrying capacity, labour intensity, cost-effectiveness, feasibility of the structure in given conditions or aesthetic criteria (Partov et al. 2015).

The design of dowelled connection strengthening is not sufficiently covered in the current standard EN 1995-1-1 (2006). In Brno University laboratories the dowel connection strengthening has been investigated, with the aim to verify selected strengthening methods of dowelled connections with slotted-in steel plates, namely the effects of static and repeated (cyclic) stresses by axial tensile force.

Connection strengthening to eliminate transverse tensile stresses is carried out alternatively by screws, double-threaded screws, punched metal plate connectors or FRP fibres. The aim of the tests was to verify the configuration of connection strengthening as for arrangement and parameters of strengthening elements.

Diagnostics of timber structures and their components serves to evaluate a number of physical and mechanical wood properties and to determine the possible range and intensity of insect attack, fungal attack or wood rotting. Diagnostic methods can be successfully applied to determine material quality in timber structures from massive elements made of solid timber, such as log cabins (Kuklík et al. 2014).

There is a great range of devices for determining wood quality, which can measure different variables or parameters of timber.

The following measurements of physical and mechanical timber properties were made in the tested members:

- determination of moisture content;
- determination of mechanical resistance using micro-drilling;
- determination of stress wave propagation velocity.

In practice it is necessary to determine the moisture content quickly, which can be done using electric devices. The method is not very accurate but mostly sufficient for this purpose. The devices utilize the dependence of electrical conductivity of wood on its moisture, as in the case of digital moisture meter with integrated measuring needles GMH 3810. The measurements were compared with the readings obtained from dielectric moisture meter Wagner L 601-3, which serves for non-destructive measurements. Due to the design of the meter, the moisture can be measured to the depth of about 25 mm. Measured values of absolute moisture content after adjustment for various species of wood (*Abies alba, Picea abies*) are shown in Tab. 1.

Tab. 1: Values of absolute moisture content and wawe propagation velocities.

Member No.	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Absolute humidity (%)	16.5	18.5	16.5	17.5	15.5	14.5	15.5	13.5	13.5	13.5
Wave velocity propagation ($m.s^{-1}$)	1450	1552	1530	1461	1433	1553	1457	1542	1454	1551

The most common damage of wooden elements is caused by damage to the inner condition of wood, which cannot be visually assessed. A very suitable instrument for testing is, in particular for build-in wood, resistance micro-drill Resistograph 4453-S.

Resistance drilling is based on measuring of resistance to slow penetration of a fine drill needle through the examined material. Its advantage is that the inner condition of a structural member can be detected. Thanks to a minimum damage of material testing, the method belongs to semi-destructive modes, which can determine the condition of timber structures (Kloiber and Kotlínová 2008).

The drill resistance is concentrated in the drill needle tip with 3.0 mm in diameter. The shaft of the drill needle has a diameter of 1.5 mm, which enables to lower the drill friction in the cutting seam in deeper layers of the structural element. The thin drill needle scans the resistance in penetrating the wood.

A lower drilling resistance, which requires a smaller torque of the motor, is given by a lower wood density, cavities, decay, splitting and cracks. Resistograph provides an output in the form of a graphical record - density profile, dendrogram (see Fig. 3).

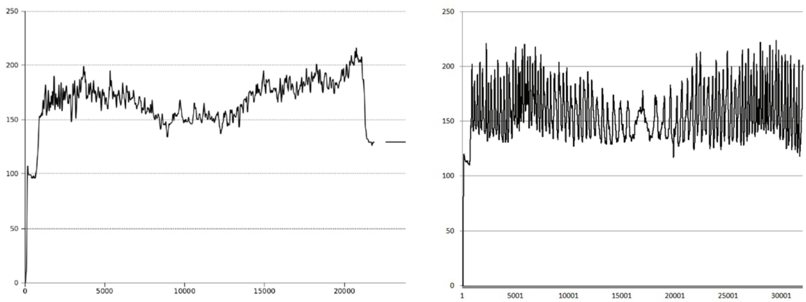

Fig. 3: Density profile (dendrogram): a –timber sample without damage, b –reference timber sample – decrease in timber resistance due to decay.

Fig. 4: Acoustic tomography Fakopp 2D.

In order to detect changes in material properties and defects, the sample cross sections were drilled though. In the course of drilling at drill-feed constant revolutions, the needed electric input power is scanned, from which the output mechanical resistance can be derived. The following relative mean values of mechanical resistance were found: floor beams with ground surface 10.0, 10.6; 11.5 %; floor beams with smooth surface 15.0; 14.3 and 15.2 %.

The drilling record corresponds with the consumed energy needed for maintaining the constant drilling speed plotted along the y-axis while the distance from the surface of the measured element is plotted along the x-axis. The peaks in the graphical record correspond with a higher energy, i.e. a higher resistance and a higher density, while the lows are related to a lower energy, i.e. a lower resistance and density (Kloiber et al. 2014).

In evaluating the measurement results no significant defects and quality difference in the tested members were found. Based on the assessment of the resistance in their cross section, common timber structure could be identified (alternating resistance values correspond with alternation of zones between spring and summer wood of the annual ring) and also numerous, but for the usage of timber acceptable occurrence of drying related cracks (areas with reduced mechanical resistance). None of the evaluated resistance charts showed any occurrence of mechanically significant decay, such as timber zones with mechanical resistance reduced by wood-destroying fungi.

In order to evaluate the inner condition of the trunk, acoustic tomography - Fakopp Microsecond Timer with piezoelectric sensors was used (Fig. 4). The device is able to evaluate the inner condition of the trunk non-destructively on the basis of measuring the velocity of sound wave, generated by hitting two interconnected sensors with the hammer.

Two sensor probes interconnected with the measurement device are attached to the tested material. An acoustic signal is generated by striking the probe with hammer and a computer measures the time needed for the transmission of the signal from the activated probe to the other probe. The propagation time is displayed on the screen in microseconds. Based on the travel time and the geometry of the given cross section, wave velocity is calculated, which is used to reconstruct condition of the trunk.

Measurement of wave propagation time was made in radial transverse direction, in the whole cross section (diameter) of the member, in the areas with the least possible occurrence of cracks and knots and with regard to moisture distribution in log-cabin wall in the end distance of 60 cm from the beam head. After tapping the sensor with hammer stress wave propagation times were read. Knowing the distance between the sensors, the velocities were calculated from the average time (the arithmetic average of 4 time readings) of wave propagation. The calculated wave propagation velocities are tabularized in Tab. 1.

The measured stress wave propagation velocities correlate completely with the velocities of undamaged wood and the differences calculated for individual members fall within normal variability of wood properties. At constant volume density the wave velocity is directly proportional to the modulus of elasticity of wood.

The sound velocity in wood is proportional to the density and stiffness of measured wood. It decreases with the increasing density and increases with the growing elasticity modulus. Both properties are a sensitive indicator of wood condition. The damage caused by e.g. wood-destroying fungi would cause a change in the wave propagation velocity and could be detected. If there is a cavity inside the beam, the stress wave has to go around it and so travel a longer path. As a result signal velocity decreases and the decrease can be detected.

RESULTS AND DISCUSSION

One of the crucial issues in designing timber structures is to investigate the strength, stiffness and ductility of joints. The slip of mechanical joints significantly affects the overall behaviour of timber structures. The joint slip is closely connected not only to material and strength characteristic of wood and connectors but also with structural design of connection details. 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 (Lokaj and Klajmonová 2014).

Connections with slotted-in steel plates and doweled joints are frequently incorporated in the design of timber element connection in the load-bearing systems, since they are effective regarding their manufacture and erection technique. Moreover, they can transfer both axial forces of high intensity and shear forces and bending moments.

The design of dowelled connections and slotted in steel plate is usually performed in accordance with the normative documents, currently EN 1995-1-1 (2006). When a more detailed structural design is required, other factors should be considered, which significantly influence the overall behaviour of the connection and are not explicitly included in the standards. It is particularly true of the influence of bending moments from the eccentric action of the connections, the effect of the additional bending moments, resulting from the structural arrangement of fasteners in the connection, the influence of the environment (moisture), the type of loading (static, repetitive, dynamic) or the necessary bending stiffness of connections. Thus, a safe and reliable connection design and its structural execution must objectively reflect the real behaviour of the designed detail within the structure (Straka et al. 2005).

Therefore, an experimental research is done in the above area at the Faculty of Civil Engineering in Brno. Its purpose is, besides verification of the behaviour of connections under load, to examine the effect of connection strengthening with screws reducing the adverse effect of transverse tensile stresses.

Dimensions of test samples and connector fasteners were chosen in accordance with those used in real structures. As the basic material was chosen glued laminated timber of the strength class GL24h glued from spruce lamellas (*Picea abies*), which is the most frequently used glulam material in timber structures. Cross-section dimensions of tested members were 120x160 mm. The elements were tested for action of tensile axial forces.

The steel plate was 6 mm thick, steel strength class S355 (11523). Its dimension is sufficient even for the case of slightly eccentric stress acting on the connection, when the steel plate can be loaded by the additional bending in the plane about the weak axis.

Smooth dowels were 16 mm in diameter, steel S355, whose mutual spacing and the distance from the edges was designed in accordance with the conditions stipulated in EN 1995-1-1 (2006), including the recommended slenderness, preventing the formation of brittle fracture in the wood. The connection was fitted with 6 dowels in three rows, which were oriented in the wood grain direction.

The tested connection was loaded with the continuous axial tensile force until the failure occurred. The testing apparatus recorded the values of the loading force and deformations - both the connection elongation and the changes of cross-sectional dimensions at the end of the element.

The experiments were arranged in order to convey the real behaviour of the connection in the structures, whose members are stressed by axial forces. The influence of additional transverse forces and bending moments was minimized. The arrangement of the experiment is illustrated in Fig. 5.

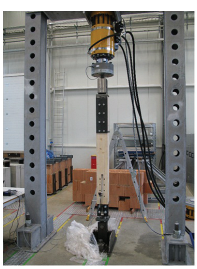

Fig. 5: Experimental test arrangement.

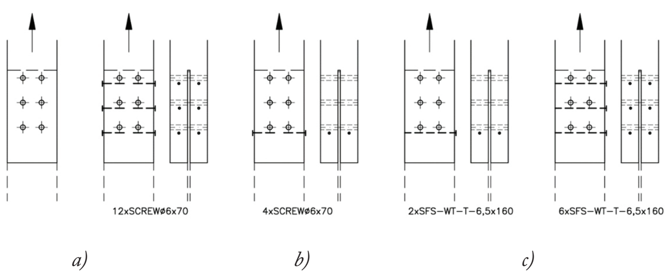

Fig. 6: Arrangement of connections: a) without strengthening, b) strengthened by means of pairs of screws ø 6x70 mm, c) strengthened by double threaded screws SFS-WT-T 6.5x160 mm.

The tests were made using the EH system of INOVA Praha, s.r.o. Loading was carried out by EH cylinder AH-500-100-V1 Inova, fitted with dynamometer K 630 kN, Tp 0.05, GTM testing and metrology and piston position sensor MESSOTRON DU100, Tp 0.25. All deformations of the samples (slips) were continuously scanned by inductive sensors WA50-T, HBM, Tp 0.2. The following slips were measured: longitudinal elongation of the dowelled connection, changes of cross-sectional dimensions at the end of the element in the direction of dowel axes and perpendicular to the dowel axes. Signal conditioning and recording was carried out by the data acquisition system QANTUM, HBM, sampling frequency 10 Hz for each channel. Software package: CatmanEasy, HBM.

The experimental analysis verified the behaviour of the basic connection with slotted-in steel plate and dowels, the second variant of connection strengthened by means of pairs of screws ø 6x70 mm threaded along their entire length and the third variant with double threaded screws SFS-WT-T 6.5x160 mm in different positions of the connection and different number of pieces. Arrangement of the analyzed connections is shown in Fig. 6. Fig. 7 shows individual connections after the loading tests.

During the assembly of one testing sample – probably due to inaccurate drilling in timber – a longitudinal crack appeared in the grain direction, passing through one row of dowels. Since this is a situation that may realistically occur during assembly, the connection was included in the selection of samples analysed. It was the case of joint strengthened by pairs of screws ø 6x70 mm threaded along their entire length located at each dowel.

Results and conclusions from the experimental research of connections and analyses were applied to the design and realization of concrete timber structures. Based on inspections of these structures we can draw the conclusion that the application of that type of connections proved to be successful (Straka 1998, Straka et al. 2016).

Fig. 7: Examples of connection failures.

Fig. 8: The mountain hotel in the Krkonoše Mountains. Connections of main load-carrying members are solved as spatial nodes using slotted-in steel plates with dowelled and bolted joints. The hotel is situated in the area with high snow load actions.

The representative examples of practical application of doweled connections in new types of timber structures include the connections of the mountain hotel in the Krkonoše Mountains (2012), multi-purpose centre in Říčany (2016) and footbridge for pedestrians and cyclists in Brno under Veveří Castle (2015) – Figs. 8, 9 and 10 (Bajer and Barnat 2012, Sandanus et al. 2016, Straka and Šmak 2008).

Based on the results obtained in experimental measurements the following conclusions can be made:

- The designed load-carrying capacity of the connection, determined in accordance with EN 1995-1-1 (2006), is F_{Rd} = 93.78 kN.

  This value was safely reached for all tested members, even if the connection was damaged during the assembly with the resulting longitudinal crack (timber was split) along the axis of dowels. During the experiment the highest load-carrying capacity of the connection was F_{Rd} = 255.12 kN, while the lowest load-carrying capacity of the connection was F_{Rd} = 193.96 kN (member T2 – connection strengthened with pairs of screws ø 6 x 70 mm threaded along the whole length of the shank, which was damaged during assembly by formation of a longitudinal crack).

- The influence of effective number of dowels in the row in the grain direction: Considering the effective number of dowels nef (or reduction rate of dowel number) to determine the overall load-carrying capacity of the connection in accordance with EN 1995-1-1 (2006) proved to be conservative. The experimental measurements for the given joint configuration in the linear region of joint behaviour no significant differences in load-carrying capacities or deformations were found in strengthened (n) and not strengthened (n_{ef}) joints.

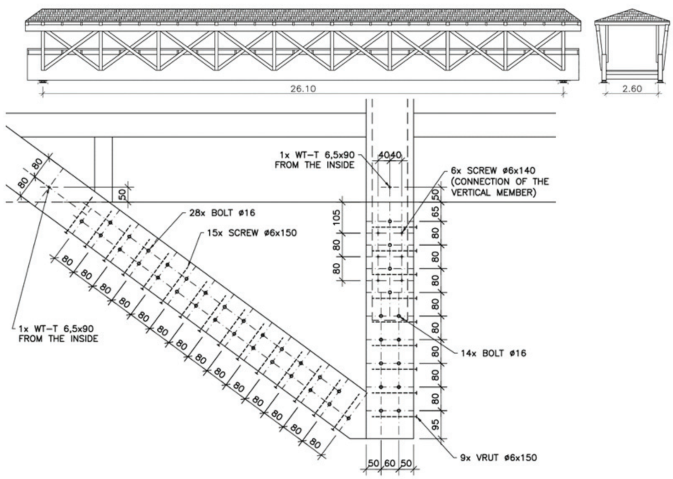

Fig. 9: The footbridge for pedestrians and cyclists in Brno under Veveří Castle. Connection of diagonal and vertical members of the truss system to the glued laminated main beam of the footbridge. With respect to extreme humidity condition, the joints were strengthened by screws to eliminate crack formation in timber members.

Fig. 10: The multi-purpose centre in Říčany. Connection of the floor beam and longitudinal members to the column and connection of the column. The joints are constructed using slotted-in steel plates with dowels and bolts.

The results - evaluation of experimental measurements in connections in the form of test samples – are shown in the diagrams (stress–strain relationship in the direction of force) in Fig. 11.

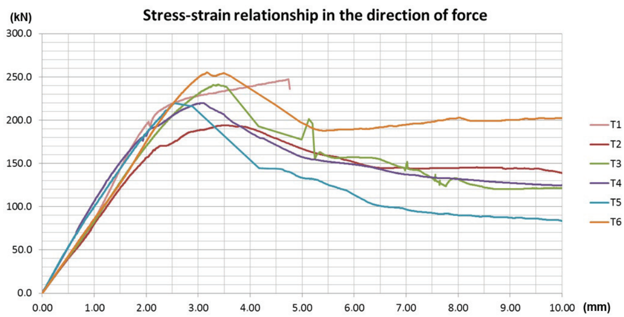

Fig. 11: Stress-strain relationship in the direction of force for tested members T1 - T6.

When a member is axially loaded under tension, the dimensions of the cross section of the member in the region of connection are changed. The stress–strain relationship of the cross section perpendicular to the member axis (in the direction of dowel axes and perpendicular to dowel axes) is captured in Fig. 12. Dimension changes were measured at the end of the member.

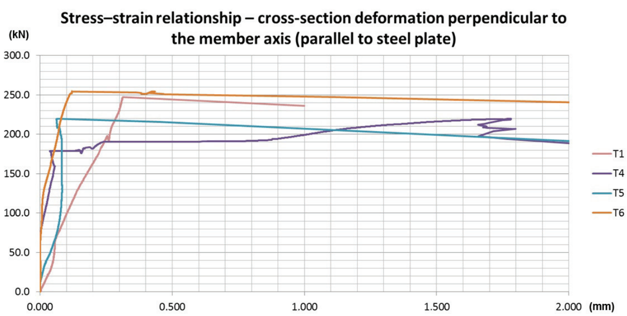

Fig. 12: Stress–strain relationship – cross-section deformation perpendicular to the member axis.

CONCLUSIONS

The aim of experimental measurements was to verify the behaviour of the dowelled connections after loading with axial force and also the influence of variant connection strengthening with screws on the overall connection behaviour in terms of real construction and load. In the experiments the effect of structural eccentricities was taken into account, since they usually occur in manufacture and assembly of the connections. At this stage of research, accuracy of design relationships and procedures defined in standards was not examined.

As the authors presumed, the results of performed tests and implementation of the joint in real structures confirmed their high load-carrying capacity and reliability. Furthermore, their versatility of application in various types of timber structures was demonstrated by authors' designs of building structures and bridges reviewed in the paper.

Since the load-bearing capacity of joints is significantly affected by wood quality, the paper also introduced diagnostic methods to determine material quality in timber structures, principally determination of moisture content and mechanical characteristics of wood using state-of-the-art electric and electronic devices.

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