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MECHANICAL BEHAVIOUR OF TIMBER-TO-CONCRETE CONNECTIONS WITH INCLINED SCREWS

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Abstract. The purpose of this paper is to adopt the Johansen's yielding theory as a possibility to predict the ultimate load for timber-to-concrete joints using self-tapping threaded connectors screwed at an angle into the wood. The ultimate load-bearing capacity of a single connector is predicted to be when either the stresses in the wood reach the plastic failure stress level or when a combination of plastic failure in wood and dowel is attained. K. W. Johansen assumed that no axial tension occurred in the dowel and, thus no frictional contribution affected the lateral load-bearing capacity. However, the joints with inclined fasteners are first affected by tension load, so the withdrawal capacity of the screws has to be taken into account. In order to determine the load bearing capacity for specific connector geometry, the kinematical possible failure modes are determined. The screw in the concrete part of connection was taken as rigidly embedded and thus no deformations appeared. The study showed that the load-bearing capacity for connections with inclined high tensile strength screws can be predicted using the yielding theory, but this theory was unable to predict precisely the failure mode. Possible reasons for that include limited fastener ductility and influence of the screw inclination on the strength properties of timber.

Keywords: timber-to-concrete connections, inclined screws as connectors, yielding theory.

1. Introduction

The general yield theory exists since the 1940s. It is currently used in Europe where it provides a rational basis for setting design criteria for nailed, screwed, bolted and dowelled timber-to-timber joints. The validity of the method based on the general yield theory has been confirmed by experimental investigations [1–4]. Screws, loaded perpendicularly to the fastener axis, are dowel-type fasteners. The ultimate lateral load of timber-to-timber joints using inclined screw connectors can be defined using a theory of "yielding" (Johansen yielding theory) which assumes plasticity in both the wood and the fastener. K. W. Johansen first applied the theory [1] of plasticity to dowel-type connectors in wood. Those design criteria for the single connector now form the basis for the design of nailed timber-to-timber joints given in the Eurocode. Johansen stated that the load-bearing behaviour is composed of two effects. The first one is the "dowel effect" which depends on the screw resistance to bending and the resistance of the wood to crushing. The second one, the "tensional effect" depends on the screw resistance to tension and on the presence of friction between abutting surfaces [1, 2].

The Johansen theory can be applied not only to timber-to-timber connections but also to timber-to-steel and timber-to-concrete connections. Recently, the composite timber-concrete structures have been more and more widely used in buildings [5–8]. Therefore it is necessary to predict the behaviour and load-bearing capacity of such a type of joints. In order to obtain the load bearing capacity of timber-to-concrete connection with inclined screws, which are principally loaded in tension, the Johansen theory is extended, taking into the account the withdrawal capacity of fastener and friction between contact interfaces of connected members.

This paper presents derived basic equations for the determination of ultimate load bearing capacity of timber-to-concrete joints with inclined screws, and the comparison between theoretical and experimental results.

2. Principal equations and failure modes

The three kinematically possible failure modes and the internal forces and stresses as well as the occurring plastic hinges in the screw for timber-to-concrete joints with inclined screws are schematised in Fig 1.

In Mode I the ultimate load-bearing capacity is reached when the wood yields plastically along the screw. The ultimate load-bearing capacity can be calculated as the sum of internal forces (eq 1). The following equations are based on the equilibrium in the non-deformed state.

$$F_u^I = N_t \cos\alpha + V_t \sin\alpha + \mu H_t, \tag{1}$$

where:

$$H_t = N_t \sin\alpha - V_t \cos\alpha, \tag{2}$$

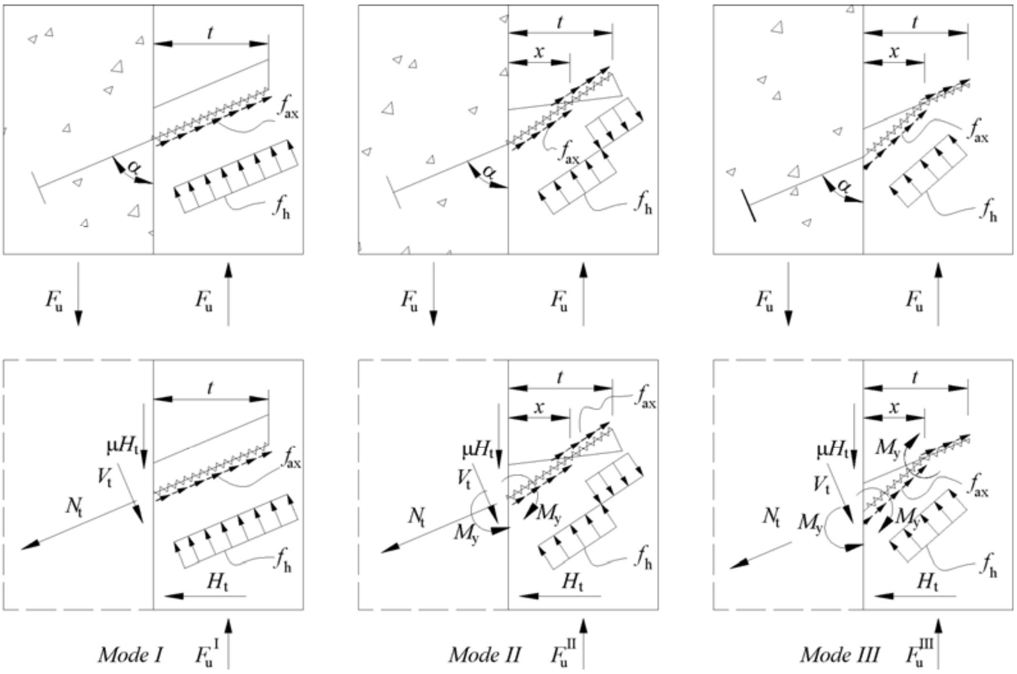

Fig 1. Stresses in a timber-to-concrete connection with an inclined screw for three Johansen's failure modes

$$N_t = \frac{f_{ax}\cdot d\cdot t}{\sin\alpha} \text{ and } V_t = \frac{f_h\cdot d\cdot t}{\sin\alpha}. \qquad (3)\ (4)$$

The meaning of α, f_{ax}, f_h, and t can be seen from Fig 1; μ – is the coefficient of friction; d – is the outer diameter of thread.

Substituting expressions (3) and (4) into eq (2) and (1), the eq (5) is derived:

$$F_u^{I} = f_{ax}\cdot d\cdot t\cdot(\cot\alpha+\mu)+f_h\cdot d\cdot t(1-\mu\cot\alpha). \qquad (5)$$

The Mode II is realised when the embedment stresses are distributed over the length of the screw so that a plastic hinge at the interface between timber and concrete is formed and the screw rotates as a stiff member in the wood. Such failure mode is possible if the embedded length t of the fastener in wood is enough to enable the plastic hinge formation in the screw.

The load-bearing capacity of connection may be determined by using the equilibrium of internal forces (as in Mode I) and the equilibrium of the moment. The distance x (eq 7) between the plastic hinge location in the fastener and the concrete-to-timber interface may be found from the moment eq (6):

$$M_y = f_h\cdot d\cdot\left(\frac{1}{2}\cdot\frac{x^2}{\sin^2\alpha}-\frac{(t-x)\left(\frac{x}{\sin\alpha}+\frac{1}{2}\cdot\frac{t-x}{\sin\alpha}\right)}{\sin\alpha}\right), \qquad (6)$$

$$x=\frac{t}{\sqrt{2}}\cdot\sqrt{\frac{2M_y}{f_h\cdot d\cdot t^2}\cdot\sin^2\alpha+1}. \qquad (7)$$

The shear forces in the fastener are given by:

$$V_t = f_h\cdot d\cdot\left(\frac{x}{\sin\alpha}-\frac{(t-x)}{\sin\alpha}\right)=\frac{f_h\cdot d\cdot t}{\sin\alpha}\left[2\frac{x}{t}-1\right]. \qquad (8)$$

Substituting x from expression (7) into (8):

$$V_t = \frac{f_h\cdot d\cdot t}{\sin\alpha}\left[\sqrt{2}\sqrt{\frac{2M_y}{f_h\cdot d\cdot t^2}\sin^2\alpha+1}-1\right]. \qquad (9)$$

The horizontal force at the interface between timber and concrete is given by:

$$H_t = f_{ax}\cdot d\cdot t - f_h\cdot d\cdot t\cdot\cot\alpha\times\left[\sqrt{2}\sqrt{\frac{2M_y}{f_h\cdot d\cdot t^2}\sin^2\alpha+1}-1\right]. \qquad (10)$$

Substituting equations (3), (9) and (10) into eq (1), the eq (11) is obtained, which expresses the load-bearing capacity of connection for Mode II:

$$F_u^{II} = f_{ax}\cdot d\cdot t\cdot(\cot\alpha+\mu)+f_h\cdot d\cdot t\times(1-\mu\cot\alpha)\left[\sqrt{2}\sqrt{\frac{2M_y}{f_h\cdot d\cdot t^2}\sin^2\alpha+1}-1\right]. \qquad (11)$$

The Mode III failure occurs when the embedment stresses are distributed over the length (t-x) of the screw forming an additional plastic hinge. The load-bearing capacity may be obtained in the same way as for the first two modes by the projection of internal forces (1). The yield moment of the fastener for Mode III is expressed:

$$M_y = \frac{f_h\cdot d}{2}\cdot\left(\frac{x}{\sin\alpha}\cdot\frac{x}{2\cdot\sin\alpha}\right)=\frac{1}{4}\frac{f_h\cdot d\cdot x^2}{\sin^2\alpha}, \qquad (12)$$

where the distance x between two plastic hinges (Fig 1 Mode III) is:

$$x = 2\cdot t\sqrt{\frac{M_y}{f_h\cdot d\cdot t^2}}\cdot\sin\alpha. \qquad (13)$$

Shear force in the fastener and horizontal force at the interface between timber and concrete are expressed by:

$$V_{\mathrm{t}} = 2\sqrt{f_{\mathrm{h}} \cdot d \cdot M_{\mathrm{y}}}\,, \tag{14}$$

$$H_{\mathrm{t}} = f_{\mathrm{ax}} \cdot d \cdot t - 2\sqrt{f_{\mathrm{h}} \cdot d \cdot M_{\mathrm{y}}}\cos\alpha\,. \tag{15}$$

Substituting eq (3), (14) and (15) into eq (1), the eq (16), is obtained, which expresses the load-bearing capacity of connection for Mode III:

$$F_{\mathrm{u}}^{\mathrm{III}} = f_{\mathrm{ax}} \cdot d \cdot t \cdot (\cos\alpha + \mu) + 2\sqrt{f_{\mathrm{h}} \cdot d \cdot M_{y}}\,(\sin\alpha - \mu\cos\alpha). \tag{16}$$

When the inclination angle between the screw axis and the timber plane is $\alpha = 45°$ and the friction between the interface of the members may be neglected ($\mu = 0$), the eq (5), (11) and (16) may be rewritten for the above analysed failure modes as:

$$F_{\mathrm{u}}^{\mathrm{I}} = f_{\mathrm{ax}} \cdot d \cdot t + f_{\mathrm{h}} \cdot d \cdot t\,, \tag{17}$$

$$F_{\mathrm{u}}^{\mathrm{II}} = f_{ax} \cdot d \cdot t + \left[\sqrt{2}\sqrt{\frac{M_{\mathrm{y}}}{f_{\mathrm{h}} \cdot d \cdot t^{2}} + 1} - 1\right], \tag{18}$$

$$F_{\mathrm{u}}^{\mathrm{III}} = f_{\mathrm{ax}} \cdot d \cdot t + \sqrt{2 \cdot M_{\mathrm{y}} \cdot f_{\mathrm{h}} \cdot d}\,. \tag{19}$$

From eq (17–19) it is evident that the ultimate load-bearing capacity for all three failure modes most of all depends on the withdrawal capacity of the screw. The withdrawal strength of the fastener at an angle of 45° to timber is much lower than at an angle of 90°. The characteristic withdrawal strength at an angle α to the grain according to the Eurocode 5 [9] may be taken as:

$$f_{\mathrm{ax},\alpha} = \frac{3{,}6 \times 10^{-3} \cdot \rho^{1{,}5}}{\sin^{2}\alpha + 1{,}5 \cdot \cos^{2}\alpha}\,, \tag{20}$$

where ρ is the density of the timber.

3. Test with self-tapping inclined screws in timber-to-concrete connections

The short-time push-out test was carried-out at Vilnius Gediminas Technical University, at the laboratory of Dept of Steel and Timber Structures. Six specimens of timber-to-concrete connections were tested under short-term loading. The specimens were made as double-shear connections with concrete encased timber from two sides (Fig 2). The fasteners were self-tapping screws (Fig 3) manufactured by BiRA®-IngBAU-Schrauben M6x100 [10] with inclination of 45° with respect to the timber member. The washer and the head were already jointed together during their manufacturing, so it can ensure better bonding with the concrete. Such fasteners are similar to the *Timco II Schrauben* screws [11].

The outer diameter of threaded part and of the smooth shank of the screw is 6 and 4 mm respectively.

Two pairs of screws at both sides of the timber member were used. The screws with 6 mm outer diameter of the threaded part were tapped into 4 mm diameter predrilled holes. Penetration length of the threaded part of the screw is 50 mm, thus the fasteners were driven into the timber approx 50 mm.

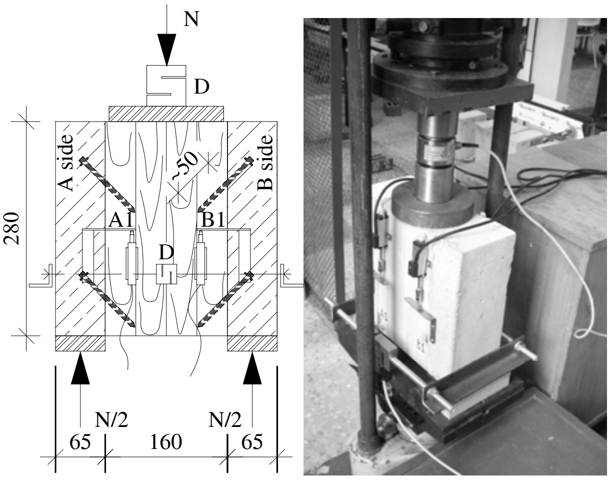

Fig 2. Specimen set-up (left) and view on the specimen in the loading machine (right)

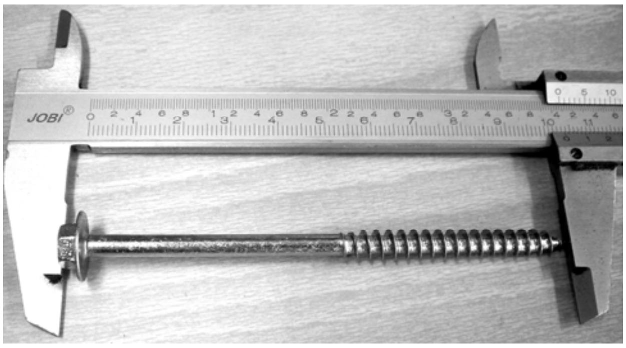

Fig 3. The fastener used as connector in timber and concrete joint

These screws exhibit great hardness and tensile strength which was experimentally obtained – the mean value of tensile strength is $f_{\mathrm{u}} = 1562$ N/mm^2. Therefore the aim of these tests was to estimate the behaviour of timber-to-concrete connections with the so oriented type of fasteners.

The timber was glue-laminated pine, the physical properties of which were determined according to standards [12, 13]. The species for determination of characteristic values of mechanical properties and density of timber were cut from already tested timber-to-concrete joints except the species for withdrawal tests. In Figs 4 and 5 are given the pictures from embedding and withdrawal strength tests respectively.

The test piece for embedding strength test was a rectangular prism of wood (27×60×150 mm^3) with a screw placed with its axis perpendicular to the surface. Loading procedure was followed in accordance to standard EN 383 [14]: the load was increased to $0{,}4F_{\mathrm{ma,est}}$ and maintained for 30 s, then reduced to $0{,}1F_{\mathrm{ma,est}}$ and also maintained for 30 s, thereafter the load was increased till the deformation of 7 mm. This loading procedure is identical to the loading for main tests of connections. The tested species and typical load-displacement curve is shown in Fig 6.

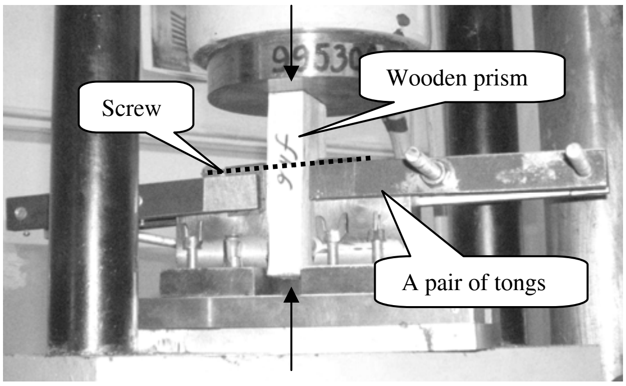

Fig 4. The view test of specimen in loading machine from embedding tests

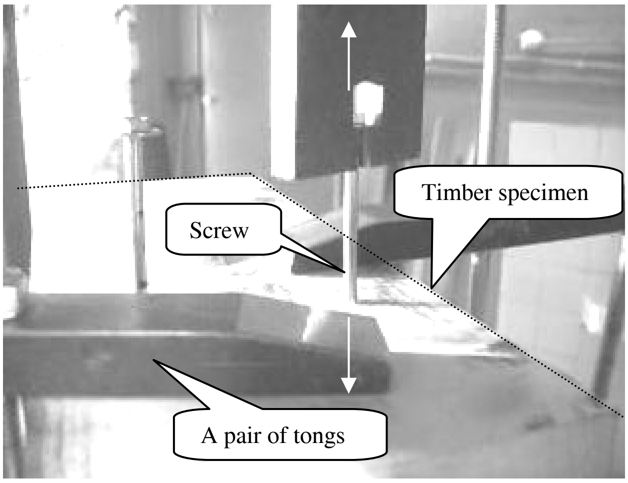

Fig 5. Arrangement of screws in specimen at tests for determination of their withdrawal capacity

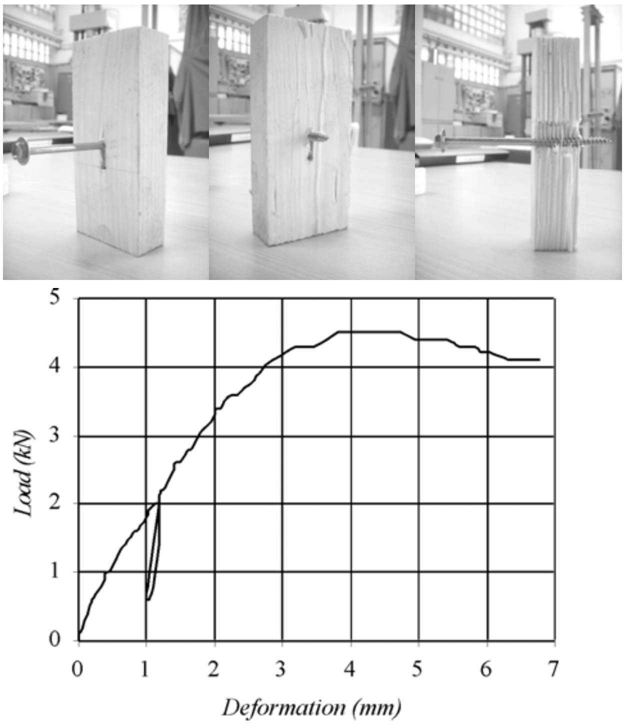

Fig 6. Typical load-displacement curve for embedding strength (below) and view on tested specimens (above)

The withdrawal capacity of fasteners was tested in accordance with standard EN 1382 [15]. The timber specimen was rectangular prism 120×160×280 mm^3, with six screws driven perpendicularly to the timber grain, in pre-bored holes, in distances of at least 60 mm (6*d*) between screw axes. The penetration length of fasteners into the wood was approx 50 mm (8*d*). The tests were performed with a constant rate of load, such that the withdrawal load was reached in 90 seconds.

All the values of physical and mechanical properties obtained from the tests, are presented in Table 1.

Table 1. Experimentally obtained values of the physical and mechanical properties of timber

Properties	Mean value	Characteristic value	Units	Number of samples	Coefficient of variation %
ρ	414	374	kg/m^3	106	5,86
ω	12,00	–	%		3,31
f_h	29,54	27,4	N/mm^2	4	4,46
f_{ax}	22,53	18,65	N/mm^2	6	10,44

To prevent the bleeding of concrete in the timber member during the concreting phase, the timber was protected with 2–3 layers of polythene film. During the concrete hardening the specimens were kept at indoor temperature (17 °C) and humidity (54 %). The age of the specimens at the time of testing was 85 days with concrete compressive strength at that time of 30,47 N/mm^2 (Table 2).

Table 2. Experimentally obtained values of the physical and mechanical properties of concrete

Properties	Mean value	Units	Number of samples	Coefficient of variation %
ρ	2219	kg/m^3	4	0,41
f_{cm}	30,47	N/mm^2		3,30

During the test of joints not only four vertical displacements and the vertical load were measured, but also the horizontal splitting load was controlled. It was decided not to prevent the splitting at the interface between timber and concrete which usually appears in tests of such type of connections, but to control the value of the splitting load. For the implementation of it, two steel angles were installed in the lower part of specimens with the gap between profile and concrete of approx 1 mm (Fig 2).

These two angles were connected to one another through the threaded rods driven into the dynamometer, thus when the gap between the concrete and the steel angles disappeared, the splitting load was measured. The tests showed the appearance of the horizontal splitting load only, when the first pair of screws reached their withdrawal or shear capacity and were dragged through the timber. This phenomenon begins when the vertical slip in both connections reaches 2 mm. At that moment, the ultimate load bearing capacity of the specimen is usually reached.

Before the main test was performed according to EN 26891 [16], the mean value of the maximum test load $F_{est}=9{,}72$ kN was determined from the preliminary tests of the twin specimens. The mean values of the mechanical properties of the specimens tested in the main experimental program are presented in Table 3. Fig 7 shows a typical load–displacement curve of connection.

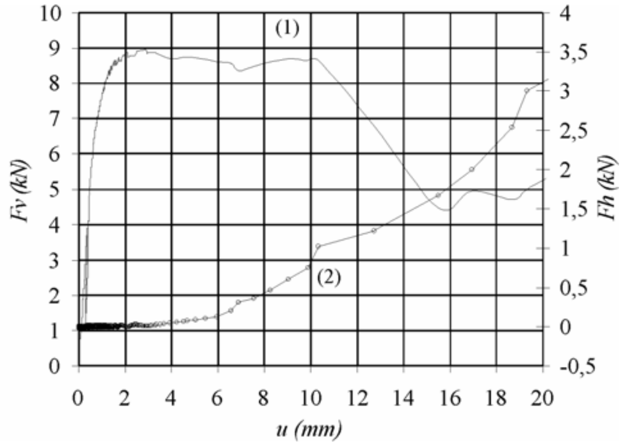

Fig 7. Load-slip curve (1) of specimens for one pair of screws and horizontal splitting load curve (2)

Table 3. Experimentally obtained values of mechanical properties of timber-to-concrete joint

Properties	Mean value	Characteristic value	Units	Number of samples	Coefficient of variation %
F_{max}	9,05	8,54	kN	6	3,39
K_{ser}	10,87	4,83	kN/mm		33,7
K_{06}	10,34	5,55	kN/mm		28,1

Symbols indicate: F_{max} – maximum load for one pair of screws, which is reached before a slip of 15 mm; K_{ser} – the elastic slip modulus of connection; K_{06} – the slip modulus of connection when load reaches value of $0{,}6F_{est}$

During these tests any crack appeared in the concrete around the screws, suggesting that the total vertical deformation at the concrete to timber interface is mainly due to timber crushing, as can be seen in Fig 8.

Fig 8. Specimen failure: concrete (left) and timber (right) parts pulled apart at the end of the push-out test

Failure of such kind of connection under action of shear forces may occur either because of splitting of connected elements or failure of the fastener. In the experimental test, the reason of connection failure was the failure of screws, after their withdrawal capacity is reached.

In all cases the same failure mode occurred – the fasteners were cut at the interface. The screws are under action of shear, tension and bending, which caused the failure of the connection.

4. Comparison between experimental and theoretical results

The equations for the ultimate loads of timber-to-concrete connection with inclined screws for three Johansen failure modes were presented in Section 2. Because the screws were tested only under tension and not under bending, the yield moment was not experimentally obtained. To determine M_y, the following analytical formulae was used:

$$M_y = 0{,}8 \cdot f_u \cdot \frac{d^3}{6}. \qquad (21)$$

The value of the yield moment computed by (21) $M_y = 9{,}72$ Nm is less then $M_y = 14$ Nm, given in DIBT [17]. Using in formulas (17–21) the experimentally determined mean values of mechanical properties of timber (Table 2) and fasteners, the ultimate values of yield loads F_u (denoted as *Theoretically I*) computed for one shear plane and one fastener and are given in Table 4.

Table 4. Experimentally obtained and theoretically computed ultimate loads for one fastener

Ultimate bearing load	F_{max} [kN]	F_u(I) [kN]	F_u(II) [kN]	F_u(III) [kN]
Experimentally	4,57	–	4,57	–
Theoretically I(1)	6,45	10,6	7,29	6,45
Theoretically II(2)	4,25	8,42	5,09	4,25

(1) Eurocode [9] expressions used; (2) DIBT [17] data and expressions used

The theoretical values of the yield load differ from those, obtained from tests, by approx 40 %. As it is mentioned in Section 2, the ultimate load-bearing capacity of inclined screws mainly depends on their withdrawal strength. The withdrawal strength f_{ax} can be computed by the expression given in DIBT [17]:

$$f_{ax,\alpha} = \frac{80 \times 10^{-6} \cdot \rho^2}{\sin^2 \alpha + \frac{4}{3} \cdot \cos^2 \alpha}. \qquad (22)$$

The values of load-bearing capacity for all three failure modes denoted as *Theoretically* II are obtained by substituting the values from expressions (21) and (22) into (17), (18) and (19). These values are much lower than those defined as *Theoretically I* (Table 4). The value of withdrawal capacity of the fastener computed by (22) is more than 2 times lower than that defined by expression (20) given in Eurocode [9]. Therefore the yielding capacity of the connection decreases by 34 % (Table 4). Theoretically in both cases the connection failure mode is Mode-III (Fig 1) characterised by two plastic hinges in the fastener, but the tests show that only one plastic hinge could be developed in the fastener at the interface between the timber and concrete (Fig 9) which means a failure Mode II. After the opening of specimens, no fastener was found to have developed two plastic hinges.

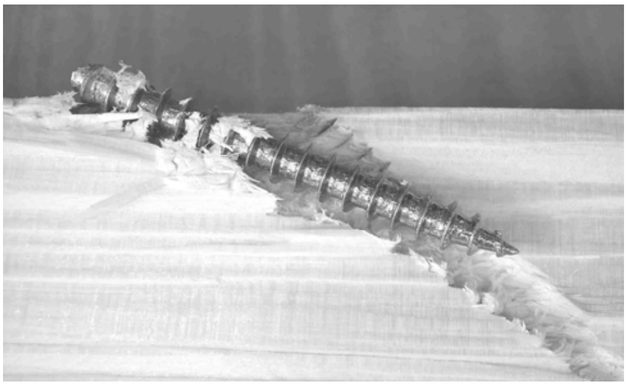

Fig 9. View of the failure mode on the timber side after opening the specimen

A possible reason of inadequacy between theoretically and experimentally obtained values of load- bearing capacity for the connection may be an actual different behaviour of wood with respect to that assumed in the theoretical formulas. Due to the inclination of the fastener, all mechanical characteristics of timber will depend on the angle between the load and grain. Another reason may be that the holes for fasteners in timber were predrilled. Neither Eurocode 5 [9] nor DIBT [17] provide formulas for determing the withdrawal and embedment strengths for inclined screws with predrilled holes. To achieve better correspondence between the test and the theory, those properties should be obtained experimentally.

5. Conclusions

In this paper timber-to-concrete connections with inclined self-tapping screws were analysed according to the European Yield Model. The expressions of ultimate loads for three Johansen failure modes of connection were derived by assuming that the part of the screw embedded in concrete behaves as a stiff supported beam.

Short-time push-out tests on the connection to verify the analytical formulas were performed. In addition, some physical and mechanical characteristics of timber, concrete and the fastener were experimentally obtained. An estimated withdrawal and embedment strengths of screws were used for computing the theoretical value of the ultimate load for a single fastener. Although the theoretical ultimate load of the connection coincided with the experimental one, the failure modes differ. Opened specimens showed that only one plastic hinge was formed in the fastener, and the plastic deformation of wood occurred under the screws – this satisfies the kinematical type of failure for the second Johansen failure mode.

In connections with inclined fasteners, the influence of the screws on withdrawal and embedding strengths was found to be very important. These parameters are very sensitive to the influence of the angle between the fastener axis and the timber grain, and to the construction process (pre-boring). Therefore for predicting the load-bearing capacity for timber-to-concrete connections with inclined screws and predrilled holes, those mechanical properties (withdrawal and embedding strengths) of the timber and screw should be obtained from the additional tests with inclination of the fastener towards the timber grain.

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MEDIENOS-BETONO JUNGČIŲ SU ĮŽAMBIAI ĮSRIEGTAIS MEDSRAIGČIAIS MECHANINĖ ELGSENA

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Santrauka

Straipsnyje atlikta kompozitinių medienos ir betono jungčių skaičiavimo pagal Johanseno takumo teoriją analizė. Naudojantis vadinamosios Europos takumo teorijos (European Yielding Theory) pagrindais, užrašytos lygtys kompozitinei medienos-betono jungčiai su įžambiai į medieną įsriegtais medsraigčiais, atlikti tokių jungčių eksperimentiniai tyrimai ir nustatytos jų laikomosios galios reikšmės, kurios palygintos su teoriškai apskaičiuotomis.

Reikšminiai žodžiai: medienos ir betono jungtis, įžambiai įsriegti medsraigčiai kaip jungės, takumo teorija.

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