TIMBER − CONCRETE COMPOSITE ELEMENTS WITH VARIOUS COMPOSITE CONNECTIONS PART 1: SCREWED CONNECTION

Ján Kanócz
Technical University of Košice, Faculty of Art
Košice, Slovak Republic

Viktória Bajzecerová
Technical University of Košice, Faculty of Civil Engineering
Košice, Slovak Republic

Štefan Šteller
Pulp and Paper Research Institute, Department of Slovak Forest Product
Research Institute
Bratislava, Slovak Republic

ABSTRACT

In this paper theoretical and experimental investigation of timber-concrete composite members acted by short and long term loading is presented. The analysis was focused to the beams with screwed composite connection. In the theoretical analysis for the short term loading the simplified elastic calculation model and for the long term loading analytical calculation model considering the most significant rheological behavior such as: viscous-elastic creep of concrete and wood, mechano-sorptive creep of wood, creep of shear connection, concrete shrinkage and strains due to thermal and relative humidity changes of environment was applied. The obtained theoretical results were compared with the experimentally measured data to confirm the validity of the short and long term analytical calculation model.

KEYWORDS: Timber-concrete composite, screw connection, shear test, short term bending test, long term behavior.

INTRODUCTION

This paper is the first part of the series of papers describing theoretical analysis and experimental investigations of various timber-concrete composite slab systems in the framework of the research project oriented to their different composite connection under short and long term loading.

At the first phase of the project, timber-concrete composite deck system consisting from separated vertically oriented timber planks in certain distance covered by fiber reinforced concrete layer with OSB sheets was investigated. The shear transfer between the timber planks and upper layers with the pair of steel screws spaced along the timber beams was provided. At the next phase, the composite deck system consisting from the nail-laminated timber plate with fiber reinforced concrete on the top was examined. Shear connection between the concrete layer and timber members with grooves in timber members was performed.

For theoretical analysis of timber-concrete composite elements number of calculation methods was developed by different authors (Kenel and Meierhoffer 1998, Franghi and Fontana 2003). Some of them are based on the quite simple conditions without including semi rigid composite action of layers. The more faithful models take to the accounts flexibility of the connecting system between layers, nonlinearity of the wood, shrinkage of the concrete and time dependency of the composite action, Schänzlin (2003), Fragiacomo and Cecotti (2006), Fragiacomo (2006) Glazer (2005). In practice selection of the useful calculation model depends on the type of connection between the timber and concrete and from the required accuracy of calculation results.

For the theoretical analysis of the experimentally investigated timber-concrete composite beams under short term loading the simplified elastic analytical model according to (EN 1995-1-1, 2004) was used to verify its applicability for practical use. For the case of long term loading the new calculation model based on the elastic model was developed, which considers the influence of rheological properties of composite materials as shrinkage, eventually bulking of materials, the influence of composite on creep coefficient and the influence of environmental changes. Result of the developed theoretical model was compared with measured data from 5 year period experimental loading test.

MATERIAL AND METHODS

Characteristic of the specimens and materials

For experimental investigation real-size timber-concrete beams were fabricated. The beams was 5.0 m long and 600 mm wide and consists from three separated longitudinal vertically oriented timber planks (grade C24) with cross-section 45.0 x 220.0 mm. The planks were covered by 15.0 mm thick OSB sheet. The thickness of the concrete layer was 50.0 mm. The problem of this composite system, mainly from the point of view of long term action, is the shrinkage of the wood and concrete respectively. To eliminate the influence of this phenomenon, steel fiber reinforced concrete was used for beam specimens. This type of reinforcement, in addition to eliminating the cracks due to shrinkage of concrete, also improves the strength parameters of the concrete layer, which leads to a high performance composite action of the beam. The shear connection between the concrete and planks was performed by common steel screws for wood with 5.0 mm diameter and 120.0 mm length. The distance between the screws along the planks is 150.0 mm. In each position a pair of screws was driven in with a slope of 45° to the planks top edge (Fig. 1 and Fig. 2).
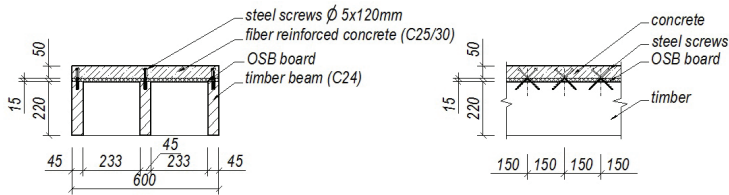
Fig. 1: Cross–section and shear connection of experimental beams.

Fig. 2: Preparing of specimens.

The required mechanical parameters of used wood and concrete were determined separately according to the relevant standards. See overview in Tab. 1 and Tab. 2.

Tab. 1: Parameters of the concrete layer.

Compressive strength	34.9	MPa
Tensile strength in bending	5.4	MPa
E-Modulus	29100	MPa
Density	2342	$kg.m^{-3}$
Thermal expansion coefficient	$1.0.10^{-5}$	$°C^{-1}$

Tab. 2: Parameters of the timber layer.

Bending strength	25.3	MPa
Shear strength	6.66	MPa
E-Modulus	8441	MPa
Moisture content	14.2	%
Density	435	$kg.m^{-3}$
Thermal expansion coefficient of timber	$5.0.10^{-6}$	$°C^{-1}$
Humidity expansion coefficient of timber	$3.0.10^{-3}$	

To determine behavior of the shear connection between the concrete and timber, short term shear tests was carried out. Special arrangement of the shear test setup was suggested to receive similar strain effect as in the bended specimens.

Mechanical parameter of a pair of screws with a slope of 45° was determined according to the relevant standards (EN 26891, 1995). See overview in Tab. 3.

Tab. 3: Parameters of one pair of screws.

Instantaneous slip modulus	11.54	kN.mm^{-1}
Load carrying capacity	14	kN

Beam bending test under short term loading

Four point bending test with short term static load was carried out on each of three beam specimens (Fig. 3). The loading schedule was suggested with incremental steps with unloading loop in each step up to 40 % of estimated failure load level. Above this level the loading process was increasing continuously. In the middle of beam span vertical sag were gauged. Also horizontal movement of the each layer was measured on the both ends of beam to determine mutual slip of the concrete and timber part. To discover the character of deformation on the middle cross section of composite beam, horizontal displacement was gauged in several levels on the beam depth.
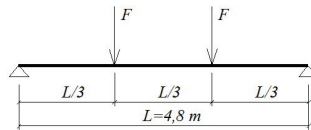

Fig. 3: Experimental setup.

Beam bending test under long term loading

In the period from 2005 to 2010 the long term experimental bending tests of timber-concrete composite beams were carried out. Four point bending test with long term constant static load 2x1.0 kN was carried out on three beam specimens. Permanent load was applied after removal of temporary support at 121st day since the concrete casting. In the middle of beam span the vertical sag was gauged. The experiment was carried out inside, moreover humidity and temperature of the internal environment was continuously recorded (Fig. 4). Concrete curing was finished at 3rd day age of concrete.

Tab. 4: History of load application since the concrete casting.

Beginning of drying shrinkage "*cs*"	3	days
Removal of temporary support - self weight "g"	121	days
Permanent load "*F*"	121	days

Tab. 5: Parameters of environment.

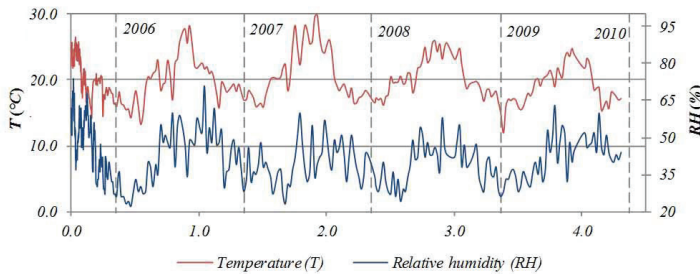|		
Average value of relative humidity	45	%
Maximum value of relative humidity	66	%
Minimum value of relative humidity	24	%
Average value of temperature	20.7	˚C
Maximum value of temperature	27.7	˚C
Minimum value of temperature	13.7	˚C

Fig. 4: Environmental condition during the long term test.

Calculation model for the short term loading

Screw connection is characterized by semi-rigid composite action. Therefore calculation model requires considering the flexibility of connections. One of the developed methods is called "γ-method" which is based on the linear elastic solution of the simply supported timber-concrete composite beam (Möhler 1956). The semi-rigid composite action is introduced by the interlayer slip between the timber part and concrete deck. The effective bending stiffness $(EI)_{ef}$ of the simply supported composite beam accordance to the "γ-method" is calculated as:

$$(EI)_{ef} = E_c I_c + E_t I_t + \gamma E_c A_c a_c^2 + E_t A_t a_t^2 \qquad (1)$$

where: E_c - Young's modulus of elasticity of concrete in bending,
E_t - Young's modulus of elasticity of timber,
A_c - the cross-section area of concrete part,
A_t - cross-section area of timber part,
I_c - the moment of inertia of the concrete,
I_t - the moment of inertia of timber part.

The distance between the center of gravity of the timber at and concrete part ac and the center of gravity of the effective cross section is:

$$a_t = \frac{\gamma E_c A_c (h_c/2 + t + h_t/2)}{\gamma E_c A_c + E_t A_t}, \quad a_c = \frac{h_c}{2} + t + \frac{h_t}{2} - a_t \qquad (2)$$

where: γ - factor - defined by the formulae (3)

$$\gamma = \left[1 + \pi^2 E_c A_c s / \left(K\ L^2\right)\right]^{-1} \tag{3}$$

h_c - depth of the concrete part of cross-section,
h_t - depth of the timber part of cross-section,
t - the thickness of the OSB sheet,
s - the spacing between the connectors,
L - the span of the beam,
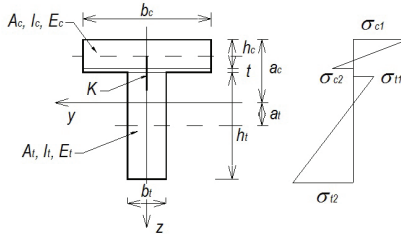K - the slip modulus.

Fig. 5: Cross-section and distribution of bending stress.

Normal stress distribution in the timber-concrete composite cross-section (Fig. 5) is given by:

$$\sigma_{c,1} = \frac{E_c M}{(EI)_{eff}}\left(-0.5h_c - \gamma a_c\right), \quad \sigma_{c,2} = \frac{E_c M}{(EI)_{eff}}\left(0.5h_c - \gamma a_c\right) \tag{4}$$

$$\sigma_{t,1} = \frac{E_t M}{(EI)_{eff}}\left(-0.5h_t + a_t\right), \quad \sigma_{t,2} = \frac{E_t M}{(EI)_{eff}}\left(0.5h_t + a_t\right) \tag{5}$$

The resistance of the timber-concrete composite beam is given by the ultimate stresses in the top and bottom edge of the concrete (6) or timber (8) cross-section, by the resistance of composite connection or by the ultimate beam deflection.

$$\sigma_{c,1} = \frac{E_c M_{u,c1}}{(EI)_{eff}}\left(-0.5h_c - \gamma a_c\right) = f_{cm}, \quad \sigma_{c,2} = \frac{E_c M_{u,c2}}{(EI)_{eff}}\left(0.5h_c - \gamma a_c\right) = f_{ctm} \tag{6}$$

where: f_{cm} - the compressive strength of the concrete,
f_{ctm} - the tension strength of the concrete.

The ultimate moments of the concrete part in the top ($M_{u,c1}$) and bottom ($M_{u,c2}$) edge of the concrete are received from the strength conditions (6) in forms:

$$M_{u,c1} = \frac{f_{cm}(EI)_{eff}}{E_c\left(-0.5h_c - \gamma a_c\right)}, \quad M_{u,c2} = \frac{f_{ctm}(EI)_{eff}}{E_c\left(0.5h_c - \gamma a_c\right)} \tag{7}$$

The ultimate moment of timber part $M_{u,t}$ should be derived from the strength condition (8)

$$\frac{E_t a_t M_{u,t}}{(EI)_{eff} f_{t,o,d}} + \frac{0.5 E_t h_t M_{u,t}}{(EI)_{eff} f_{md}} = 1.0 \tag{8}$$

where: $f_{t,0,d}$ - the tensile strength of the timber,

f_{md} - bending strength of the timber, and can be expressed as:

$$M_{u,t} = \frac{(EI)_{eff}}{\dfrac{E_t a_t}{f_{t,o,d}} + \dfrac{0.5 E_t h_t}{f_{md}}}$$

(9)

In case of four points bending test according to Fig. 3 from the condition for the ultimate moment the resistance F_u^σ given by the ultimate stresses of the composite beam is possible to express with equation (10):

$$M_u^\sigma = \frac{F_u^\sigma L}{3} + \frac{gL^2}{8} \rightarrow F_u^\sigma = \frac{3}{L}\left(M_u^\sigma - \frac{gL^2}{8}\right)$$

(10)

where: $M_u^\sigma = \min\left(-M_{u,c1}, M_{u,c2}^+, M_{u,t}\right)$,

$M_{u,c2}^+$ - explicity positive value of $M_{u,c2}$ according to equation (7) is considered,
g - the self weight of the beam.

The ultimate resistance of the composite connection F_u^s of beam depends on the load carrying capacity of applied connectors F_{su} and can be derived from the following condition:

$$F_{su} = \frac{\gamma E_c A_c a_c s}{(EI)_{eff}}\left(F_u^s + \frac{gL}{2}\right) \rightarrow F_u^s = \frac{F_{su}(EI)_{eff}}{\gamma E_c A_c a_c s} - \frac{gL}{2}$$

(11)

From the condition for limit deflection δ_{lim}, the resistance F_u^δ given by the ultimate displacement of the timber-concrete composite beam is expressed

$$F_u^\delta = \frac{648(EI)_{eff}}{23L^3}\left(\delta_{lim} - \frac{5}{384}\frac{gL^4}{(EI)_{eff}}\right)$$

(12)

Calculation model of the long term loading

The developed calculation model for the timber-concrete composite beams under long term loading considers the most significant rheological phenomena such as: Viscous-elastic creep of concrete and wood, mechano-sorptive creep of wood, creep of shear connection, concrete shrinkage and strains due to thermal and relative humidity changes of environment. This model is based on the linear elastic solution, is applicable for simple beam with linear material properties and allows determining the final deflection in the middle span and stressing distribution in the middle cross- section of the composite beam.

The visco-elastic creep of concrete according to the Eurocode 2 (2006) is inserted to the calculation of the effective bending stiffness (13).

$$E_{c,eff} = \frac{E_{cm}(t)}{1 + \varphi_c(t, t_0)}$$

(13)

where: φ_c - the creep coefficient of concrete at the time t and with respect to the time of load application t_0,

$E_{cm}(t)$ - the concrete modulus of elasticity at an age t according to Eurocode 2 (2006)

The visco-elastic and mechano-sorptive creep of wood is also involved to the effective stiffnes in form (14) developed by (Toratti 1992):

$$E_{t,eff} = \frac{E(u)}{1+\varphi_t(t,\tau,u)} \tag{14}$$

with the following creep coefficient of timber:

$$\varphi_t(t,\tau,u) = \frac{E_t(u)}{E_t(u_{ref})} \left(\frac{t-\tau}{t_d}\right)^m + \varphi^\infty \frac{E_t(u)}{E_t(u_{ref})} \left[1 - e^{-c_t \frac{2\Delta u}{100\Delta t}(t-\tau)}\right] \tag{15}$$

where: $E_t(u) = E_{t0}(1-k_u u)$,

E_{t0} - the modulus of elasticity of dry timber,

k_u=1.06, u is the moisture content of timber,

u_{ref} = 0.2 is the reference moisture content,

Δu - the amplitude of moisture content deferent within the time period Δt,

$(t-\tau)$ - load duration,

t_d = 29 500 day, m = 0.21, φ^∞ = 0.7, c_t = 2.5.

For the shear connections with mechanical fasteners the following expression of creep coefficient is proposed:

$$\varphi_s = 2\sqrt{\varphi_c \cdot \varphi_t} \tag{16}$$

Expression (16) considers creep of both connected materials and can be used for the calculation of creep coefficient in case of different shearing fasteners. The suitability of the proposed expression (16) was confirmed by comparison with experimental results of (Kenel and Meierhofer 1998).

Connecting the concrete layer to timber element the shrinkage of concrete is prevented by the timber, which leads to increase of deflection of timber-concrete composite beam. In cross-section the concrete shrinkage causes the eccentric force. The influence of this force on the stress distribution in the cross-section depends on the stiffness of fastening which is characterized by γ coefficient of fastening stiffness.

The stress distribution in timber-concrete cross-section affected by concrete shrinkage can be calculated according using the following expressions:

$$\sigma_{cs,c} = \gamma \, \varepsilon_{cs} \, E_c \left(1 + \frac{E_c A_c a_c}{(EI)_{eff}} (\mp 0.5h_c - \gamma a_c) - \frac{E_c A_c}{E_c A_c + E_t A_t}\right) \tag{17}$$

$$\sigma_{cs,t} = \gamma \, \varepsilon_{cs} \, E_c \left(\frac{E_t A_c a_c}{(EI)_{eff}} (\mp 0.5h_t + a_t) - \frac{E_t A_c}{E_c A_c + E_t A_t}\right) \tag{18}$$

The deflection affected by concrete shrinkage in the beam middle span can be calculated from the equation (19):

$$\delta_{cs} = \frac{\gamma \, \varepsilon_{cs} \, E_c A_c a_c}{(EI)_{eff}} \cdot \frac{L^2}{8} \tag{19}$$

where: ε_{cs} - the strain of concrete affected by shrinkage according to the Eurocode 2 (2006)

Influence of environmental changes

The different physical properties of timber and concrete concerning the heat and moisture diffusion processes lead to diverse responses of these materials with the environmental thermo-hygrometric variations. Relative humidity increase and temperature decrease of environment

cause rising of middle span deflection value, which can be obtained according to:

$$\delta_u = \frac{\alpha_{t,u}\,\Delta u\,E_t A_t a_t}{(EI)_{eff}} \cdot \frac{L^2}{8} \qquad \delta_T = \frac{\gamma(\alpha_{c,T} - \alpha_{t,T})\Delta T E_c A_c a_c}{(EI)_{eff}}\,\frac{L^2}{8} \qquad (20)$$

where: δ_u - the deflection in the beam middle span affected by moisture content changes Δu,

$\alpha_{t,u}$ - the moisture expansion coefficient of timber,

δ_T - the deflection in the beam middle span affected by temperature changes ΔT,

$\alpha_{t,T}$ - the thermal expansion coefficient of timber,

$\alpha_{c,T}$ - the thermal expansion coefficient of concrete.

Analogically to equations (17) and (18) there were derived the expressions (21), (22), (23) and (24) for stress distribution in timber-concrete cross- section in the middle span affected by the temperature and moisture content changes of environment:

$$\sigma_{u,c} = \alpha_{t,u}\,\Delta u\,E_t\!\left(\frac{E_c A_t a_t}{(EI)_{eff}}\!\left(\mp 0.5 h_c - \gamma a_c\right) + \frac{E_c A_t}{E_c A_c + E_t A_t}\right) \qquad (21)$$

$$\sigma_{u,t} = \alpha_{t,u}\,\Delta u\,E_t\!\left(-1 + \frac{E_t A_t a_t}{(EI)_{eff}}\!\left(\mp 0.5 h_t + a_t\right) + \frac{E_t A_t}{E_c A_c + E_t A_t}\right) \qquad (22)$$

$$\sigma_{T,c} = \gamma(\alpha_{c,T} - \alpha_{t,T})\Delta T\,E_c\!\left(1 + \frac{E_c A_c a_c}{(EI)_{eff}}\!\left(\mp 0.5 h_c - \gamma a_c\right) - \frac{E_c A_c}{E_c A_c + E_t A_t}\right) \qquad (23)$$

$$\sigma_{T,t} = \gamma(\alpha_{c,T} - \alpha_{t,T})\Delta T\,E_c\!\left(+\frac{E_t A_c a_c}{(EI)_{eff}}\!\left(\mp 0.5 h_t + a_t\right) - \frac{E_t A_c}{E_c A_c + E_t A_t}\right) \qquad (24)$$

The effect of environmental changes is considered as a short term load, the material creep is negligible in the formulas.

RESULTS AND DISCUSION

Short term loading

The failure mode of all tested beams was similar. Approximately on the 70 % of ultimate load level, shear cracks was occurred on the both sides surface of the concrete slab near to screw connection (Fig. 6). After the further increasing of load, cracks appear also in the timber lamellas. The cracks in timber occur near to locations with various imperfections.

Fig. 6: Failure modes of the experimental timber-concrete composite beam.

The load-deflection relationship of beams DBK 1-1 and DBK 1-3 seems to be similar and the beam DBK 1-2 appears slightly higher stiffness (Fig. 7). Collapse values indicate some differences between the three specimens. These differences of collapse and stiffness values might be caused

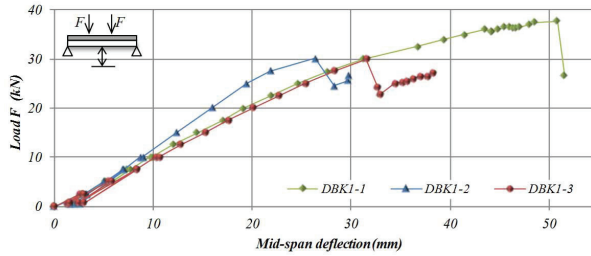by different degree of imperfections in timber lamellas.

Fig. 7: Load – vertical displacement diagram in middle span.

Fig. 8 shows average mutual slip of the concrete and timber on the both ends of beams. Load-slip relationship shows the similar stiffness of screwed connection of all specimens.
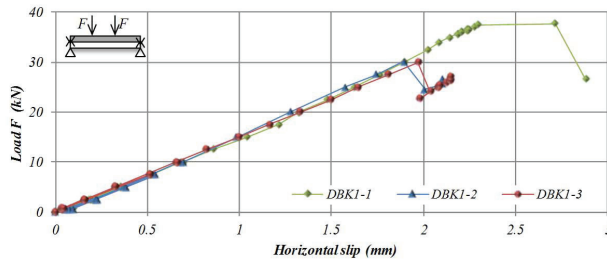

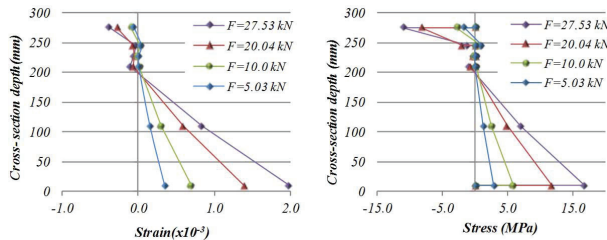Fig. 8: Load –horizontal slip diagram on the ends of beams.

Fig. 9: Experimental strain and stress distribution in middle cross section.

Strain and stress distribution evaluated from measured horizontal deformation in several levels on the beam depth in mid-span are presented on Fig. 9. As estimated, the concrete part of cross-section was exposed with compressive stress and major of the timber part of cross-section was tensioned. Using experimentally determined timber and concrete modulus of elasticity and measured strain values, stress distribution across the cross-section depth was calculated. Tension stress in bottom timber grains (16.7 MPa) on the 27.53 kN load level practically reach the ultimate tension stress value of used timber. This fact confirms the collapse mode of tested beams, that's mean failures of timber lamellas.

To verify the upper described analytical calculation model for the short term loading, numerical calculation on the experimentally tested beam was performed. Geometrical parameters of beam was I=4.8 m; b_c = 0.60 m; h_c = 0.50 m; b_t = 0.135 m; h_t = 0.22 m. Characteristics of used materials are presented in Tabs. 1 and 2. Results of the numerical calculation are listed in Tabs. 6 and 7.

Tab. 6: *Theoretical short term resistance of tested beam.*

$M_{u,c1}$	$M_{u,c2}$	$M_{u,t2}$	M_u^σ	F_u^σ	F_u^s	F_u^{ULS}	F_u^{SLS}
(kNm)				(kN)			
-103.70	226.81	51.25	51.25	30.54	57.64	30.54	16.52

The value of F_u^{SLS} was calculated for the limit deflection 1/300 of beam span. The relationship between the load F and the displacement in middle span is *0.89F+1.9 mm*. 1.9 mm is the value of beam deflection after last unloading process. This relationship is illustrated on the Fig. 10 graphically as a theoretical deflection.

Tab. 7: *Theoretical normal stress distribution in the mid–span cross–section.*

F	σ_{c1}	σ_{c2}	σ_{t1}	σ_{t2}
(kN)	(MPa)			
10.00	-5.39	0.38	-1.15	6.21
20.00	-10.78	0.76	-2.31	12.42
27.50	-14.84	1.05	-3.17	17.10
30.54	-17.26	1.22	-3.69	19.90

The theoretical normal stress distribution on various load levels according to the Tab. 7 is illustrated on the Fig. 11.

Comparison of results

Results obtained by analytical calculation model predict short term behavior of experimental beams with sufficient accuracy. Estimated theoretical collapse load (F=30.54 kN) is in accordance with measured experimental collapse load in case of beams DBK 1-2 and DBK 1-3. Real ultimate load of the beam DBK1-1 is rather different. However, on the estimated load level some crack occurred and therefore stiffness of beam decreased (Fig. 10).
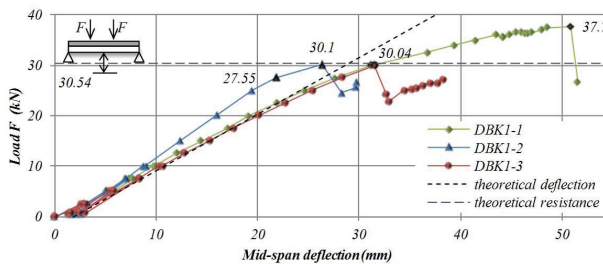

Fig. 10: *Comparison of experimental and theoretical deflection.*

Comparison of calculated stress distribution across the cross-section in several load levels with values evaluated using measured horizontal deformations on Fig. 11 shows very good accuracy, what validate above mentioned calculation model of timber-concrete composite beams under short term loading.
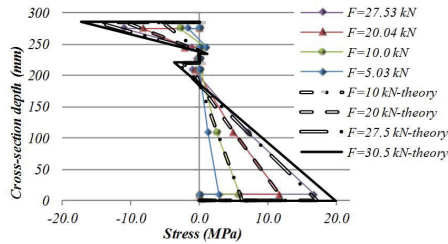

Fig. 11: Comparison of experimental and theoretical stress distribution.

Long term loading

All specimens DBK 1-1D, DBK 1-2D, DBK 1-3D prove identical time depending behavior, see Fig. 12. Comparison of measured deflection diagrams with diagrams of the thermal and humidity changes in time indicates high sensitivity of the timber-concrete composite beams to the environmental conditions. On the Fig. 12 some specific responses of experimental beams on environmental changes are pointed out. For example, in time 0.9 year, relative humidity of environment was degreased and temperature increased, consequently deflection of the tested beams was decreased. Reversely, in time 1.8 year, environmental changes caused increase of mid-span deflection. The average annual variation of deflection 4,8 mm due to the changes of environment seems to be high value in comparison to maximum measured value of deflection 8.5 mm. In similar environmental conditions after 4 years deflection increased up to 6 mm, if the initial deflection was 1.1 mm.
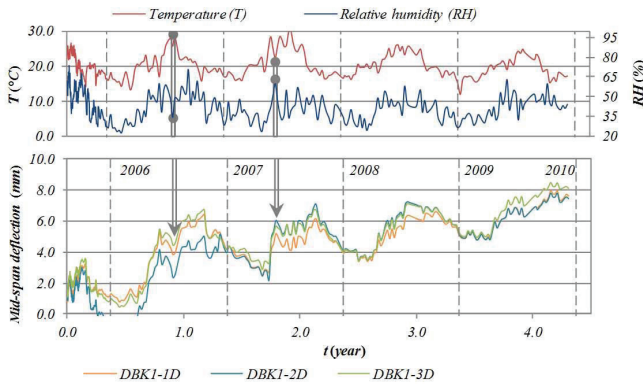

Fig. 12: Measured mid-span deflections compared with environmental changes in time.

The presented analytical model for long term loading was also verified with numerical calculation of tested beams. Geometrical parameters of beam was L=4.8 m; b_c = 0.60 m; h_c = 0.50 m; b_t = 0.135 m; h_t = 0.22 m. Characteristics of used materials are presented in Tab. 1, Tab. 2.

Environmental conditions are in Tab. 5. Results of the numerical calculation are listed in Tab. 8 and Fig. 13.

Tab. 8: Numerical calculation of mid-span deflection caused by long term load.

	t	$E_{cm}(t)$	φ_c	$E_{c,eff}$	$E_t(u)$	φ_t	$E_{t,eff}$	φ_f	K_{eff}	$(EI)_{ef}$	δ	$\Delta\delta$
	(days)	(MPa)	(-)	(MPa)	(MPa)	(-)	(MPa)	(-)	(N.mm^{-1})	(MPa.mm^4)	(mm)	(mm)
Self weight	121	30255	0.00	30255	8374	0.00	8374	0.00	34620	4.451E+12	1.40	0.00
	559	30844	2.03	10179	8538	0.81	4726	2.56	9726	1.974E+12	3.16	1.76
	1644	31061	2.29	9441	8487	1.33	3643	3.49	7711	1.579E+12	3.95	2.55
	∞	31274	2.43	9111	8855	2.13	2825	4.56	6230	1.279E+12	4.88	3.48
Permanent load F	121	30255	0.00	30255	8374	0.00	8374	0.00	34620	4.451E+12	0.94	0.00
	559	30844	2.03	10179	8538	0.83	4667	2.60	9629	1.955E+12	2.14	1.20
	1644	31061	2.29	9441	8487	1.35	3611	3.52	7665	1.568E+12	2.66	1.72
	∞	31274	2.43	9111	8855	2.14	2820	4.56	6223	1.277E+12	3.27	2.33
Concrete shrinkage	121	30255	3.31	7019	8374	0.50	5581	2.57	9686	2.024E+12	5.80	0.00
	559	30844	4.36	5755	8538	0.92	4458	3.99	6931	1.582E+12	6.83	1.03
	1644	31061	4.79	5367	8487	1.38	3560	5.15	5631	1.305E+12	7.15	1.36
	∞	31274	5.06	5158	8855	2.14	2819	6.59	4564	1.075E+12	7.36	1.56

Maximal middle span deflection variation caused by humidity changes δ_u was calculated as 2.69 mm, maximal deflection variation caused by thermal changes δ_T as 1.02 mm.

Expected measured mid-span deflection value of experimental beams in time t = 1644 days measured from concrete casting can vary:

$$\delta = \Delta\delta_g + \delta_F + \Delta\delta_{cs} \pm (\delta_u + \delta_T) = 2.55 + 2.66 + 1.36 \pm (2.69 + 1.02) = 6.57 \pm 3.71 \qquad (25)$$

Comparison of results

The theoretical deflections correspond with measured values of deflections with sufficient accuracy, therefore above presented analytical calculation model involving rheological behaviors of timber and concrete can be used for predicting the long term changes of timber-concrete composite beams.

Fig. 13 shows significant influence of concrete shrinkage on composite beam deflection. In time 1644 days, the deflection due to shrinkage of concrete takes 20 % of final deflection. Using the calculation model, the final deflection with value 8.42 mm caused by permanent load was determined. Furthermore, final global creep coefficient value 3.3 of experimental beam was possible to obtain.
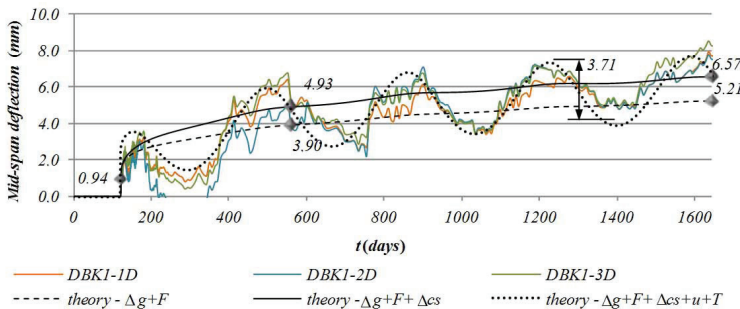

Fig. 13: Comparison of experimental and theoretical deflection.

Calculated annual variation of deflection due to changes of environment is 3.71 mm, what represents 44 % of expected final deflection. Influence of thermal changes represent 12 % of expected final deflection and is a bit less in comparison with humidity influence. Changes of environmental condition had the significant influence to the tested beams deflection. These types of displacements are regular periodic deviations of deflection but they are not the permanent part of deflection.

CONCLUSIONS

Timber-concrete composite beams with screw connections are very efficient structural system for the floor structures of timber buildings. This structural solution gives economically advantageous and statically very effective bearing structure, which design and analysis methods and process has to be detailed and clearly specified in design standard for the practical use.

Investigation indicates significant influence of concrete shrinkage on composite beams deflection. Increase of deflection in consequence of this phenomenon comes to 20 % of expected final deflection. The final global creep coefficient of experimental beam with value 3.3 was obtained.

Comparison of measured deflection and thermal and humidity changes in time indicates that the timber-concrete composite beams are very sensitive to the environmental conditions. Calculated annual variations of deflection in consequence of environment changes come to 44 % of expected final deflection. Influence of humidity changes seems much essential in comparison to thermal changes influence. Deflection movements caused by changes of environmental conditions are regular periodic, but they are not the permanent part of deflection.

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JÁN KANÓCZ
TECHNICAL UNIVERSITY OF KOŠICE
FACULTY OF ART
LETNÁ 9
SK-042 00 KOŠICE
SLOVAK REPUBLIC
Corresponding author: jan.kanocz@tuke.sk

VIKTÓRIA BAJZECEROVÁ
TECHNICAL UNIVERSITY OF KOŠICE
FACULTY OF CIVIL ENGINEERING
VYSOKOŠKOLSKÁ 4
SK-042 00 KOŠICE
SLOVAK REPUBLIC

ŠTEFAN ŠTELLER
PULP AND PAPER RESEARCH INSTITUTE
DEPARTMENT OF SLOVAK FOREST PRODUCT RESEARCH INSTITUTE
LAMAČSKÁ CESTA 3
SK-841 04 BRATISLAVA
SLOVAK REPUBLIC