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The Effect of Environment on Timber-Concrete Composite Bridge Deck

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Abstract

In the field of timber bridges progressive static structural solution is if the timber bearing members of the bridge deck are combined with concrete layer applying a shear connection to receive their composite action. The composite timber-concrete bridge deck comparing to the standard timber bridge deck has a higher rigidity, is more resistant to dynamic effects and has protected wooden part from external mechanical actions. The behavior of timber–concrete bridge deck is significantly influenced by the conditions of surrounding environment. In the presented paper, results of theoretical and experimental investigation of the effect of temperature and humidity changes of environment on the timber-concrete composite bridge deck will be presented. The applied analytical calculation model developed for analysis of long term behavior of timber-concrete elements influenced by the environment temperature and humidity will be introduced. In the experimental program, timber–concrete members with different timber structural parts and various composite connections under short and long term loading were investigated. The environmental conditions, temperature and humidity, during the 5 year long test were continually registered. Comparison of theoretical and experimental results and some practical conclusions for design of timber–concrete bridge deck will be finally presented.

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Keywords: timber-concrete; bridge deck; effect of environment.

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1. Introduction

Timber-concrete composite elements are more and more often used to create bearing structure of the floor decks in modern timber buildings or the bridge decks of the road or pedestrian bridges. That is evident from an overview of the use of timber-concrete composite bridges in different geographical areas and climates presented in [1].

In last decade the main disadvantage of timber bridges comparing to bridges from other materials was their durability. This problem was particularly eliminated by use of timber-concrete composite structural elements. Especially in case of bridge decks brings this solution a big progress. The concrete layer protect the timber part against the negative influence as a water or other mechanical effects. Bounding the concrete together with the timber part of bridge deck a composite static solution is reached, which leads to significant increase of stiffness and load carrying capacity of composite deck. According to several publications [1-3] in last years the use of timber for bridge structures was rapidly increased. This was caused not only by above mentioned composite solution, but also with many benefits of timber as a structural material, for example: renewable, sustainable, easy workable, low energy need etc.

In the design process of these composite structures often their deflection is decisive. According to [4] it is advised to limit the value of deflection to 1/400 -1/500 of the timber bridge span. Except of permanent and traffic loads, changes of temperature and humidity of environment may comprise a significant part of deflection of the bridge.

The article gives a simplified method of calculating the effect of temperature and humidity changes on the timber-concrete composite beams. The theoretical results are compared with the results of long-term experimental tests of three different types of beams with different composite connections. The experiment was conducted in indoor environmental conditions; at the end of the paper, the real effect of external environment in the chosen location is analyzed.

2. Simplified calculation model

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. As a result of the different coefficients of expansion there is a different strain of the wood and the concrete part, which cause rise of timber-concrete composite beam´s deflection and also rise of internal stresses. The relative humidity and temperature of environment are constantly changing at the time during the year. The maximum values of temperature are reached at summer time and the minimum values in winter time. The relative humidity is depending on the temperature and atmospheric pressure and their maximum values are in winter time and minimum in summer. These environmental changes are reflected with the periodic changes of deflection of the timber-concrete beam. Increase of relative humidity and decrease of temperature cause rising of the middle span deflection value.

The effect of environmental changes is considered as a short term load, the material creep is therefore negligible. In the formulas instantaneous values of material modulus of elasticity and slip modulus of composite connection can be used.

2.1. Influence of relative humidity changes of environment

The wood reaches equilibrium of moisture condition, if is placed long enough in an environment with constant parameters. In the case of changing environmental conditions, the moisture content of wood adapt to the environment with a lag. The moisture process in the wooden cross-section in relation to the environmental conditions is governed by the law of diffusion. From the practical point of view, to solve complex differential equations of diffusion process is demanding task, therefore the simplified calculation model is applied. In this model the moisture equilibrium in whole cross-section without time delay is considered. The equilibrium of moisture content can be determined by means of sorption isotherms according to various authors ([5], [6]). Concrete moisture expansion can be neglected, because even under extreme conditions for long cycles of absorption and desorption occur in concrete negligibly small deformation.

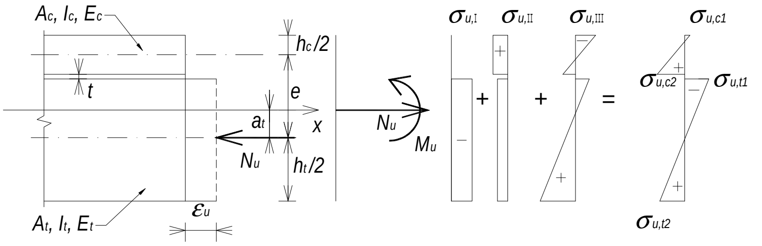

Fig. 1. Stress distribution in composite cross-section affected by timber swelling.

In common practice the designer have no information about the moisture time course in the cross-section. The effect of moisture changes of the timber to the deflection and to the stress distribution in the cross-section can be determined by the interval of possible deviations during the life time of the structure, which may be for the assessment of composite timber-concrete elements sufficient.

The deflection in the beam middle span affected by the humidity changes of environment will change by the following value:

$$\Delta\delta_u = \frac{\alpha_{t,u}\Delta u\, E_t A_t a_t}{(EI)_{eff}} \cdot \frac{L^2}{8} \tag{1}$$

where $\alpha_{t,u}$ is moisture expansion coefficient of timber along the grain; $\Delta u = u_2 - u_1$ - change of timber moisture content; E - modulus of elasticity (index c) for concrete or (index t) for wood; A - area of concrete or wood cross-section; a - distance of gravity of concrete or timber part from the centre of gravity of composite cross-section; L - beam span; $(EI)_{eff}$ - effective stiffness of the composite cross-section in accordance with [7], γ - stiffness coefficient of fastening; h - depth of concrete or wood cross-section.

If $u_2 > u_1$, the moisture content of timber increase and the swelling of timber occur, therefore the deflection value of the composite beam increase. Reversely, if $u_2 < u_1$, shrinkage of timber occur, therefore the deflection value of the composite beam decrease.

The stress changes in timber-concrete cross-section affected by the inelastic strains due to moisture variations σ_u (see Fig. 1) can be predicted using the following expressions:

$$\sigma_{u,c} = \alpha_{t,u}\Delta u\, E_t \left(+ \frac{E_c A_t a_t}{(EI)_{eff}} \left(\mp 0{,}5 h_c - \gamma a_c\right) + \frac{E_c A_t}{E_c A_c + E_t A_t} \right) \tag{2}$$

$$\sigma_{u,t} = \alpha_{t,u}\Delta u\, E_t \left(-1 + \frac{E_t A_t a_t}{(EI)_{eff}} \left(\mp 0{,}5 h_t + a_t\right) + \frac{E_t A_t}{E_c A_c + E_t A_t} \right) \tag{3}$$

2.2. Influence of temperature changes of environment

Temperature changes of the environment are reflected with temperature changes at each point of the cross-section according the heat equations. Their solution is not suitable for practical design. For simplicity, the temperature of the timber and the concrete equal to the environment temperature are considered. This assumption is certainly on the safe side from the point of view of the stress and deflection assessment.

The value of the thermal expansion coefficient of concrete is higher in comparison to the timber. Therefore, the deformation of concrete is prevented by the composite connection. This cause the stress changes in the cross-section and the deflection changes of the composite beam. Rise of deformation occurs by the cooling of environment.

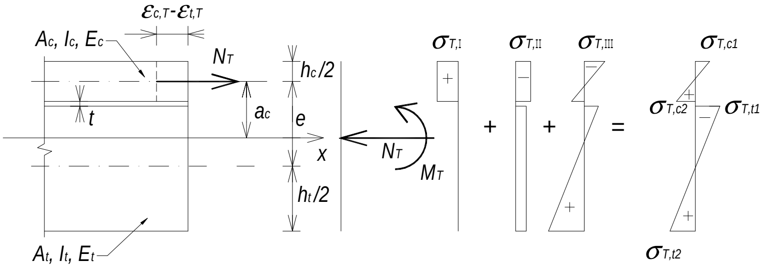

Fig. 2. Stress distribution in composite cross-section affected by cooling of environment.

In case of environmental cooling ($T_2 < T_1$) the whole beam is freely shorten by the value of timber shrinkage, further deformation in concrete is prevented due to the composite connection. The deflection in the beam middle span affected by the temperature changes of environment will change by the following value:

$$\Delta\delta_T = -\frac{\gamma(\alpha_{c,T} - \alpha_{t,T})\Delta T E_c A_c a_c}{(EI)_{eff}} \frac{L^2}{8} \tag{4}$$

where $\alpha_{c,T}$ is thermal expansion coefficient of concrete; $\alpha_{t,T}$ - thermal expansion coefficient of timber; ΔT - temperature changes of environment $\Delta T = T_2 - T_1$.

In the composite cross-section (see Fig. 2) the stress changes caused by the inelastic strain due to thermal variations is possible to determine by the following formulas:

$$\sigma_{T,c} = \gamma\Delta T(\alpha_{c,T} - \alpha_{t,T})E_c\left(-1 - \frac{E_c A_c a_c}{(EI)_{eff}}(\mp 0{,}5h_c - \gamma a_c) + \frac{E_c A_c}{E_c A_c + E_t A_t}\right) \tag{5}$$

$$\sigma_{T,t} = \gamma\Delta T(\alpha_{c,T} - \alpha_{t,T})E_c\left(-\frac{E_t A_c a_c}{(EI)_{eff}}(\mp 0{,}5h_t + a_t) + \frac{E_t A_c}{E_c A_c + E_t A_t}\right) \tag{6}$$

Formulas (1) a (4) will be further verified by results of long term bending tests of timber-concrete composite beams with various stiffness of connection.

3. Long term bending tests

3.1. Screwed composite connection

During the first phase of long term tests, timber-concrete composite beams with screwed composite connection were prepared. The beams denoted as DBK1 were 5 m long and 600 mm wide and consisted from three separated longitudinal vertically oriented timber planks with cross-section 45×220 mm. The planks were covered by 15 mm thick OSB sheet. The thickness of the concrete layer was 50 mm. Softwood - spruce with grade C24 and concrete with grade C25/30 was applied. Steel fiber reinforced concrete was used for beam specimens. The shear connection between the concrete and planks was performed by common brass screws for wood with 5 mm diameter and 120 mm length. The distance between the screws along the planks was 150 mm. In each position a pair of screws was driven in with a slope of 45° to the planks top edge (Fig. 3a). More about material parameters can be find in [8].

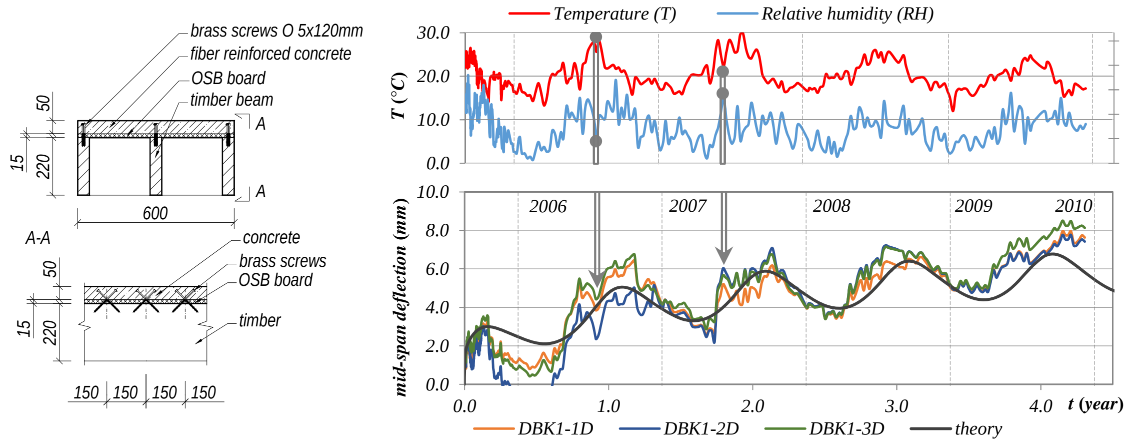

Fig. 3. (a) Geometrical parameters of cross-section; (b).Results of long term test.

Long term bending tests of three specimens were carried out in the period from 2005 to 2010. Four point bending test with span of 4.8 m and long term constant static load 2×1.0 kN at the distance of 1.6 m was applied. In the middle of beam span the vertical sag was gauged. The experiment was carried out inside, the relative humidity and temperature of the internal environment was continuously recorded (Fig. 3b). The temperature ranged between 12°C and 30°C, the relative humidity between 23% and 71%.

All specimens prove identical time depending behavior, see Fig. 3b. 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. 3b some specific responses of 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. Related to the span of beams it is 1/1000 of span value.

Theoretical value of mid span deflection variation caused by humidity changes $\Delta\delta_u$ was calculated as 2.68 mm, maximal deflection variation caused by thermal changes $\Delta\delta_T$ as 1.02 mm.

3.2. Grooved composite connection

At the same time with beams DBK1, long term tests of timber-concrete composite beams with grooved composite connection denoted as DBK3 were carried out. The 5 m long beams was built from 7 vertically nailed timber planks with cross-section of 45×260 mm and concrete layer with depth of 80 mm. Composite connection was achieved by the grooves with depth of 30 mm. Softwood - spruce with grade C24 and fiber reinforced concrete with grade C25/30 was applied. To decrease the influence of wood shrinkage to the groove connection, in each second timber planks the grooves position was shifted by the half length of groove (Fig. 4a). More about material parameters can be find in [9].

Long term bending tests of three specimens were carried out in the period from 2005 to 2010 together with beams DBK1 in same indoor environmental conditions. Static scheme was similar; four point bending test with span of 4.8 m and long term constant static load 2×2.0 kN at the distance of 1.6 m was carried out. In the middle of beam span the vertical deflection was gauged.

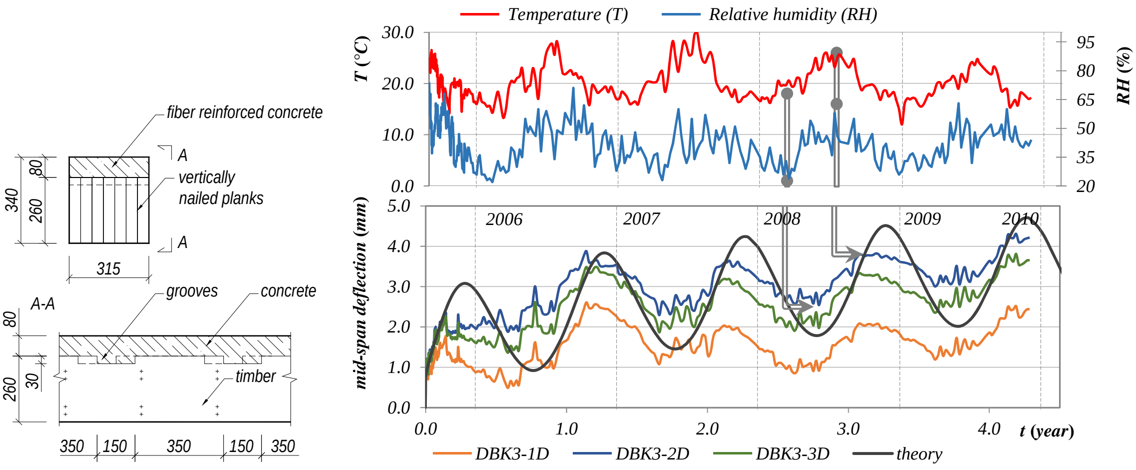

Fig. 4. (a) Geometrical parameters of cross-section; (b).Results of long term test.

In the Fig. 4b time dependent diagram of mid-span deflections of DBK3 beams and temperature and humidity changes of environment during 4 years are presented. In the first half year differences between the measured beam´s deflections was observed, but the effect of environmental thermo-hygrometric variations was similar during the long term tests in case of all beam specimens. From the measured deflection is noticeable that the composite beams are very sensitive to the heat and moisture changes. On the Fig. 4b some specific responses of experimental beams on environmental changes are pointed out. For example, in time 2.9 years, relative humidity of environment reached the annual maximum, the maximum annual deflection of the tested beams was reached a few days later. The average annual variation of deflection was average 1.3 mm. Related to the span of beams it is 1/3690 of span value.

Theoretical value of mid span deflection variation caused by humidity changes $\Delta\delta_u$ was calculated as 2.03 mm, maximal deflection variation caused by thermal changes $\Delta\delta_T$ as 0.77 mm.

3.3. Adhesive composite connection

During the third phase of long term tests, two types of timber-lightweight concrete composite beams with adhesive composite connection were prepared. Length of the beams denoted as TC1_4,5 and TC1_6,0 were 4,5 m and 6,0 m, respectively. Vertically glued laminated timber slab 600 mm width was used (see Fig. 5a). The depth of timber part of beams TC1_4,5 and TC1_6,0 were 80 mm and 120 mm, respectively. The concrete layer with a depth of 50 mm was produced by lightweight aggregates - ceramic Liapor Expanded Clay Spheres. The composite action between the timber and concrete part was performed by adhesive Sikadur T35LVP. More about material parameters can be find in [10].

In August 2013 long term bending tests were started which still are ongoing. Four point bending test of one specimen of each beam type is carried out. Beam specimen denoted as TC1_4,5 with theoretical span of 4.4 m is loaded by 2×3.0 kN at the distance of 1.5 m from supports. Beam specimen denoted as TC1_6,0 with theoretical span of 5.8 m is loaded by 2×4.0 kN at the distance of 2.0 m from supports. The experiment was carried out inside. Humidity and temperature of the internal environment were continuously recorded (Fig. 5b). The temperature was between 6°C and 32°C, values of relative humidity changed between 23% and 68 %. The course of relative humidity was very variable and it was not possible to establish a uniform period of deviation. It was therefore considered in the calculation with the real course.

The Fig. 5b shows the deflection - time dependence. It is obvious to see the response of beams to changes of environmental conditions. In time past 1st year the deflection was reduced due to increase temperature and reduce humidity of environment. At the time 1.6 year the maximum deflection was reached due to the lowest environment temperatures in time.

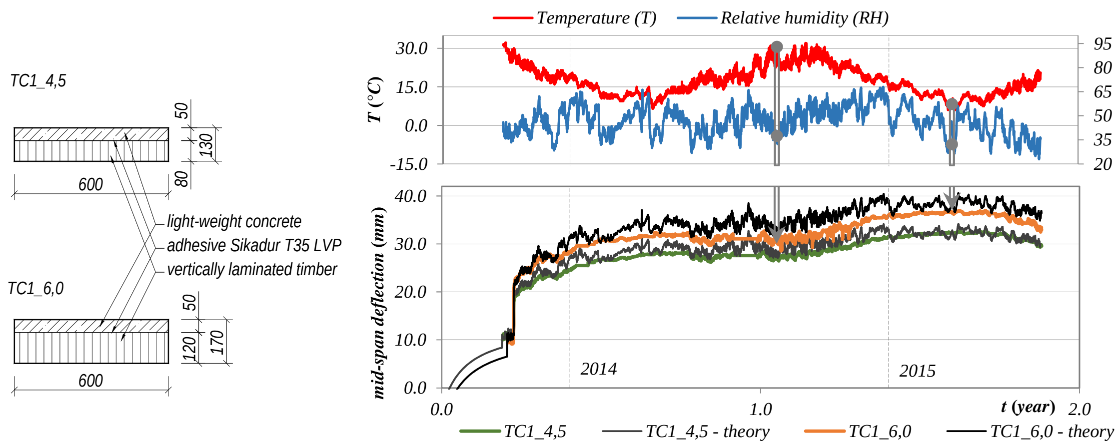

Fig. 5. (a) Geometrical parameters of cross-section; (b).Partial results of long term test.

The difference between the maximum and minimum deflection of TC1_4,5 in the period between 1st and 2nd year was 5.7 mm (1/772 of span) and of TC1_6,0 the difference was 6.6 mm (1/879 of span).

Theoretical value of mid span deflection variation of beam TC1_4,5 caused by humidity changes $\Delta\delta_u$ was calculated as 5.52 mm, maximal deflection variation caused by thermal changes $\Delta\delta_T$ as 3.60 mm. In case of beam TC1_6,0, deflection variation caused by humidity changes $\Delta\delta_u$ was calculated as 6.76 mm, maximal deflection variation caused by thermal changes $\Delta\delta_T$ as 4.38 mm.

4. Discussion

From the comparison of diagrams shapes of temperature, relative humidity of environment and measured deflection it is seen that for the thicker concrete layer (DBK3) or more rigid composite connection (TC1) the shape of the deflection diagram is identical to the shape of the temperature diagram. For elements with subtle timber cross-section (DBK1) deflection curves are similar to the curves of humidity, while elements with more massive timber parts seem to be less responsive to humidity changes. It's because the massive cross-section is enable to adapt so fast to the humidity conditions of environment as quickly as the cross-section built from thin planks of beams DBK1.

The theoretical deflections were calculated using a computational model published in [8]. Analytical calculation model of long term behaviour is based on the linear elastic solution and 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. Results of calculation model are showed in the Fig. 3 to Fig. 5 as a comparison with measured values. From the comparison it is clear that this calculation model gives good estimation of the deformations of timber-concrete elements with different rigidity of composite connections for long-term loads. Periodic fluctuations due to temperature and humidity changes of environmental conditions are also adequately estimated.

For each above presented types of beams there were mentioned calculated values of regular variation $\Delta\delta_u$ and $\Delta\delta_T$. For determining the maximum annual variations of deflection due to changes of environment conditions, it is possible count these values together. But during the experimental tests of DBK the temperature and humidity reached the maximum values at the same time and it caused the interference effects. In the real outdoor conditions it is common that in time of the highest temperature the relative humidity of environment is the lowest. In this case, there is no interference effects and thus adding up the values $\Delta\delta_u$ and $\Delta\delta_T$ we can reliably estimate the maximum annual variations.

Formulas (1) and (4) can be used to predict the behaviour of the tested beams for external environmental conditions, for example for using as bridge construction in the area of Eastern Slovakia in Košice. In 2013 in this area the average daily temperature range from -8°C to 32°C and relative humidity range between 40% and 90%. Such fluctuations in environmental conditions cause in the case of tested beams DBK1, DBK3, TC1_4,5 and TC1_6,0 the maximum annual deviation of ± 8.0 mm, ± 6.1 mm, ± 4.16 mm and ± 4.17 mm, respectively. The values of beams TC1 presents about 1/300 of span. In case of beams DBK1 it is 1/600, in case of DBK3 it is 1/790 of span. It is seen that these fluctuations give significant values which has to be considered in the design process of timber-concrete composite beams.

4. Conclusion

The theoretical and experimental investigation of the effect of environment temperature and relative humidity changes on the timber-concrete composite beams shows their significant influence. The experiments were conducted in indoor environment. Using a simplified computational model the variations of deflection were adequately estimated. In the outdoor environmental conditions the variations of deflection to the 1/300 of span were determined using the model. Thus, the impact of environmental changes should not be neglected in the design of timber-concrete composite bridges. In practice, it is possible to use the above mentioned relations to estimate deflections and stresses in cross-section affected by moisture and temperature changes on the basis of annual changes of environment.

The effect of relative humidity and thermal conditions on the deflection and stress changes is influenced by the size and shape of the composite cross-section. The equilibrium moisture and temperature in the cross-section are reached with some delay, which can be predicted by the diffusion law and heat equations. Environmental conditions during the concrete casting or the removal of temporary support seem to have significant impact. The stiffness of composite connection can be considered as the most significant impact on the reaction of the timber-concrete composite beams on environment changes. These above mentioned parameters will be subject to further analysis.

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