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Influence of long term load on timber-concrete composite systems

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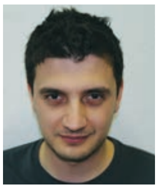

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Subject review

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Influence of long term load on timber-concrete composite systems

Timber-concrete composite systems represent a very good technical solution both in reconstruction activities and in construction of new buildings. The design of such systems is currently conducted using the γ procedure defined in Eurocode 5. The long-term behaviour of such composites is a highly complex problem depending on the creep, swelling, shrinkage and thermal changes within concrete, creep and moisture content in wood, and creep of the connection itself. The design of composite systems according to current regulations is incomplete in some conditions, and there is ample room for improving the existing European standards and regulations.

Key words:
composite systems, timber - concrete, long-term load, design of composite systems, creep, Eurocode 5

Pregledni rad

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Utjecaj dugotrajnog opterećenja na spregnute sustave drvo-beton

Spregnuti sustavi drvo-beton predstavljaju vrlo dobro tehničko rješenje ne samo u sanacijama nego i u izgradnji novih objekata. Zasad se dimenzioniranje tih sustava provodi γ-postupkom definiranim u Eurokodu 5. Dugoročno ponašanje ovakvih sustava vrlo je kompleksan problem i ovisi o puzanju, bubrenju, skupljanju i temperaturnim promjenama unutar betona, puzanju i udjelu vlage u drvu, te o puzanju samog spoja. Dimenzioniranje takvih sustava prema sadašnjim propisima u određenim je uvjetima nedorečeno te postoji velik prostor za poboljšanja postojećih normi i propisa.

Ključne riječi:
kompozitni sustavi, drvo - beton, dugotrajno opterećenje, proračun kompozitnih sustava, puzanje, Eurokod 5

Übersichtsarbeit

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Einfluss langfristiger Lastbeanspruchung auf Holz-Beton-Verbundsysteme

Holz-Beton-Verbundsysteme stellen sowohl bei Sanierungsarbeiten, als auch für Neubauten eine wirksame technische Lösung dar. Derzeit wird die Bemessung dieser Systeme nach dem γ-Verfahren laut Eurocode 5 durchgeführt. Das langzeitige Verhalten von Verbundsystemen ist sehr komplex und hängt vom Kriech-, Schwell-, Schwind- und Temperaturverhalten des Betons, vom Feuchtegehalt und Kriechen des Holzes, sowie vom Kriechen der Verbindung selbst ab. Die Bemessung von Verbundsystemen ist den jetzigen Vorschriften folgend nicht vollständig und weist auf weitreichende Möglichkeiten zur Verbesserung hin.

Schlüsselwörter:
Verbundsysteme, Holz-Beton, langfristige Lasten, Berechnung von Verbundsystemen, Kriechen, Eurocode 5

1. Introduction

The research aimed at optimising construction work and the use of load bearing systems, based on basic materials that are used in construction industry (concrete, steel, wood), has resulted in the development of "hybrid" or "composite systems", but also in various innovations in the field of "composite materials". The best known composite systems are based on the composite action of concrete and steel (covered in Eurocode 4 [1]). The field of wood-based composite systems covers the following systems: wood – wood-based materials, wood/wood-based material – steel, and wood/wood-based materials – concrete and, in recent times, wood/wood based materials – structural glass (panels and precast I-section elements).

Composite systems constitute a very good technical solution, both in remedial activities and in construction of new buildings. Systems in which wood transfers tensile load, concrete transfers compressive load, and the connection itself transfers shear load, are becoming increasingly favoured over systems in which wood only, or concrete only, is used. The principal advantage of these systems lies in their smaller weight compared to thicker RC slabs, or greater bearing capacity compared to traditional wood-based construction. The stiffness is alsobetter, which results in better seismic properties of the building. A bigger mass with regard to traditional wooden structures results in better acoustical properties, better insulation, and lower vibration levels. In addition, these systems have very good thermal properties and a high resistance to fire.

These systems are currently designed according to the γ procedure defined in Eurocode 5 (EC5) [2]. The basic objection to the calculation used in EC5 [2] is that not all parameters are taken into account, and that further research is needed in this area. It can generally be concluded that the method is acceptable for calculation purposes and for the use of wood-concrete composites belonging to the service class 1, while the EC5 solutions are non-conservative and unacceptable already for the service class 2 and this precisely because of the long-term load and significant changes in environmental conditions.

2. Problem definition and basis of design

The shear connection between the concrete slab and wooden beam is the critical part of every composite element as it defines to what extent the composite action between the two materials has been realised. The stiffness and strength of the composite have to be quantified and taken into account in the design, and a special care must be paid to the ductility of the connection itself. Various states of composite action are shown in Figure 1.

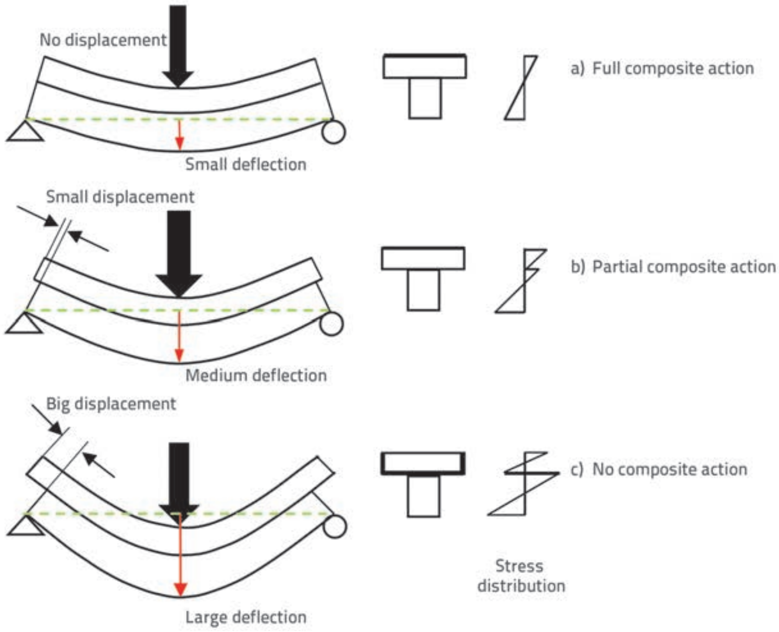

Figure 1. Composite actions

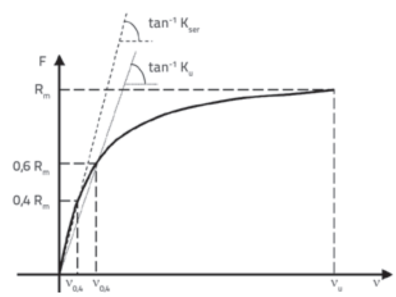

Figure 2. Connection slip modulus for ultimate limit states and serviceability limit states

In 1995, Cecotti [3] presented the approach that takes into account nonlinear behaviour in the shear zone by simulating the behaviour at connection using two stiffness modulus values –40 % (K_{ser}) and 60 % (K_u) of the maximum load that the element is able to withstand (Figure 2).

The approximation of stiffness and slip modulus may necessitate laboratory and experimental confirmation. The calculation of the wood-concrete composite system (Figure 3) is defined in the similar way in EC5 [2] and is composed of several steps:

STEP 1: The effective stiffness must be defined as:

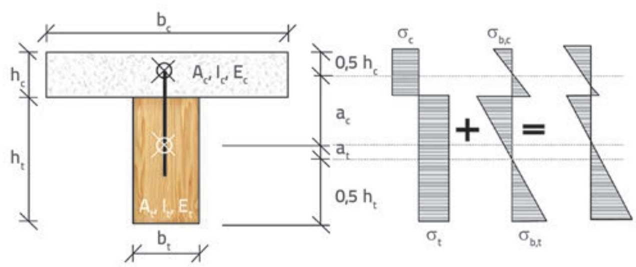

Figure 3. Cross-section of composite timber and concrete element

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

$$I_c = \frac{b_c h_c^3}{12} \quad I_t = \frac{b_t h_t^3}{12} \tag{2}$$

$$\gamma_c = \frac{1}{1+\frac{\pi^2 E_c A_c s_{ef}}{Kl^2}} \quad \gamma_t = 1 \tag{3}$$

$$A_c = b_c \cdot h_c \quad A_t = b_t \cdot h_t \tag{4}$$

$$a_c = \frac{\gamma_t E_t A_t H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \quad a_t = \frac{\gamma_c E_c A_c H}{\gamma_c E_c A_c + \gamma_t E_t A_t} \tag{5}$$

$$H = \frac{h_c}{2} + a + \frac{h_t}{2} \tag{6}$$

$$s_{ef} = 0{,}75 \cdot s_{min} + 0{,}25 \cdot s_{max} \tag{7}$$

Where:
E - Young's modulus,
I - moment of inertia,
A - area,
K - slip modulus (kN/mm),
l - span,
b - width of cross section,
h - height of cross section,
s_{min} - minimum spacings of connectors,
s_{max} - maximum spacings of connectors.

Index *c* denotes concrete, while *t* denotes timber.

STEP 2: Stresses in cross sections are calculated. The following is valid for bending:

$$\sigma_{b,c}(x) = \pm\frac{1}{2}\frac{\gamma_c E_c h_c M_d(x)}{(EI)_{ef}} \quad \sigma_{b,t}(x) = \pm\frac{1}{2}\frac{\gamma_t E_t h_t M_d(x)}{(EI)_{ef}} \tag{8}$$

while the following is valid for longitudinal normal stress:

$$\sigma_c(x) = -\frac{\gamma_c E_c a_c M_d(x)}{(EI)_{ef}} \quad \sigma_t(x) = \frac{\gamma_t E_t a_t M_d(x)}{(EI)_{ef}} \tag{9}$$

STEP 3: Stresses are used to obtain internal forces

$$M_c(x) = \sigma_{m,c}(x) Z_c \quad M_t(x) = \sigma_{m,t}(x) Z_t \tag{10}$$

$$V_t(x) = V_d(x)^{a)} \tag{11}$$

**It is assumed that the timber beam transfers the entire shear load*

$$N_c(x) = \sigma_c(x) A_c \quad M_t(x) = \sigma_t(x) A_t \tag{12}$$

where:
σ_m - bending stress,
σ - stress due to compressive force,
V - internal shear force in timber,
F_d - design load,
N - internal force.

STEP 4: Knowing internal forces, it is necessary to check stress at the connection device and, at that, the load on the connection must be adopted based on expression (11).
STEP 5: The last step is the calculation of the serviceability limit state and mid-span deflection depending on the type of load and static system applied.

Frangi and Fontana [4] described an elastoplastic model for predicting the behaviour of timber-concrete composite beams with ductile connections. Behaviour of the entire composite depends on the type of shear connector and its behaviour. If behaviour of the connection subjected to load is linear until the timber element failure, it can be assumed that the behaviour of the composite is linear elastic. If the load attains the carrying capacity of the connection, the connection will be affected by plastic deformation, and the behaviour of the composite will be nonlinear. The elastoplastic model implies that the connection is rigidly plastic and the calculation is actually analogous to the calculation of the details with dowel type connections. The slip modulus does not need to be calculated, which simplifies the analysis considerably. It is assumed that the behaviour of the wooden element is linear elastic because of the stiff failure at the joint bending and tensile action parallel to the grain. Similarly, the linear elastic behaviour is also assumed for concrete as the failure most often occurs in wood rather than in concrete. The authors differentiate three different cases (depending on connection stiffness):

1. No composite action.
2. Flexible connection – failure occurs due to fracture of the timber element during joint bending and tensile action, at the moment when the connection attains the maximum shear strength. The composite starts acting nonlinearly until failure.
3. Fully stiff connection. The failure occurs in timber before the maximum shear strength is reached at the connection. The behaviour of the composite is linear.

As the fully stiff connection represents the top limit, and the connection without composite action the bottom limit, a simplified linear approximation can be used for the design of a flexible connection. The elastoplastic model provides the top and bottom value for the carrying capacity of the composite which is within 5 % of the capacities realized by linear approximation, and the authors consider it to be satisfactory for the design of flexible composite systems.
The design of the composite for the long-term load is more difficult and complex as mechanical changes in the wood, concrete and steel have to be taken into account due to the changes in moisture, temperature, and load that occur over time. The EC 5 [2] recommends the use of deformation factors for the reduction of material properties over time. Ceccotti [5] recommends the use of the effective modulus where the material creep is taken into account through reduction of the elastic modulus and slip modulus, with the following expressions:

$$E_{c,fin} = \frac{E_{cm}(t_0)}{1+\phi(t,t_0)} \quad E_{t,fin} = \frac{E_{0,mean}}{1+k_{def}} \quad K_{fin} = \frac{K}{1+k_{def}} \tag{13}$$

The marks are defined in EC2 [6] and EC5 [2] as creep factors for concrete $\varphi(t,t_0)$ and deformation factor k_{def} for wood. The above abbreviated expressions for viscoelastic and mechanical creep of wood were developed by Toratti [7]. By linking the concrete layer with the wooden element, the concrete shrinkage is prevented by the wood, which causes deformation increase in the composite beam. The shrinkage of concrete causes an eccentric force in the cross section, which results in an uneven distribution of stress along the cross section, and it can be calculated using the following equations:

$$\sigma_{cs,c} = \gamma\varepsilon_{cs}E_c\left(1+\frac{E_cA_ca_c}{(EI)_{eff}}(\mp 0.5h_c-\gamma a_c)-\frac{E_cA_c}{E_cA_c+E_tA_t}\right) \tag{14}$$

$$\sigma_{cs,c} = \gamma\varepsilon_{cs}E_c\left(\frac{E_tA_ca_c}{(EI)_{eff}}(\mp 0.5h_t-a_t)-\frac{E_tA_c}{E_cA_c+E_tA_t}\right) \tag{15}$$

where E_c i E_t are initial values of elastic modulus.

3. Current state-of-the-art and design proposals

The behaviour of wood-concrete composite systems subjected to long-term load depends on the response of material the system is made of (wood, steel, concrete) to changes: relative humidity of air, temperature, load, and moisture of the material itself. The deformation is the basic "long-term" parameter for the design of composite wood-concrete systems. The long-term behaviour of the composite is a very complex problem and it depends on the creep, swelling, shrinkage and thermal changes within the concrete; creep and water content of wood; and creep of connectors. Factors such as the size of the wood cross-section, wood element area, loading method, number of cycles of changes in environmental conditions, and changes in the relative air humidity, also indirectly influence the behaviour of the composite. The experimental studies of the long-term behaviour of such composites are expensive and time-consuming, but also crucial for confirmation of appropriate design methods, and for calibration of the existing analytical and numerical models.

Several long-lasting and extensive tests of such composites have so far been conducted (Fragicomo [8, 9], Ceccotti [3, 5, 10, 11], Balogh [12], Hailu [13]), and numerical models (Fragiacomo [14, 15], Rajčić [16]) and analytical models (Bou Said [17], Jorge [18]) have been prepared to predict behaviour at connections of composite structures.

Lozančić et al. [19] conducted an experimental and analytic study of the properties of composite wood-concrete structures, where the composite connection was made with one-sided shear connectors, type C connectors in particular. The sample testing was conducted using two shear connectors, E75M16 and E48M12. The behaviour of these systems composed of two different materials, and linked via connectors, was monitored over time (Figure 4). The type of connector and the composite construction method are two crucial factors for such composite systems. Creep factors for the wood and connectors are compared because similar rheological factors for wood and connectors are often assumed in literature for numerical modelling of composite structures. The long-term continuous load results in an increase of deformation, and also in the redistribution of stresses along the wooden cross-section, and in a complex cross-sectional behaviour due to presence of several materials. Creep is greater in case of concrete, and the difference in creep between the wood and concrete decreases over time. Attempts have been made over time to find the analytical expression-function that would be consistent with test results.

The connection creep results are best described in terms of the exponential function of approximation that covers test results for both samples:

$$F(t) = \frac{a}{1-be^{-ct}} \tag{16}$$

where parameters a, b, and c are determined by solving the nonlinear least squares problem, which results in: a =1,7797; b = -0,76097; c = 0,0031784, where t denotes time in days.

Properties of real-size structures were studied on a big model, and significant deformation increase values under long-term load were obtained. The load applied on samples corresponds to the bearing capacity of two shear connectors, and amounts to 19.2 kN for shear connectors E75, and to 10.6 kN for shear connectors E48. The final to initial slip ratio of 2.01 was obtained, while the deflection ratio amounted to 1.84. The measurement of unloaded girder after 411 days revealed significant residual deformation,

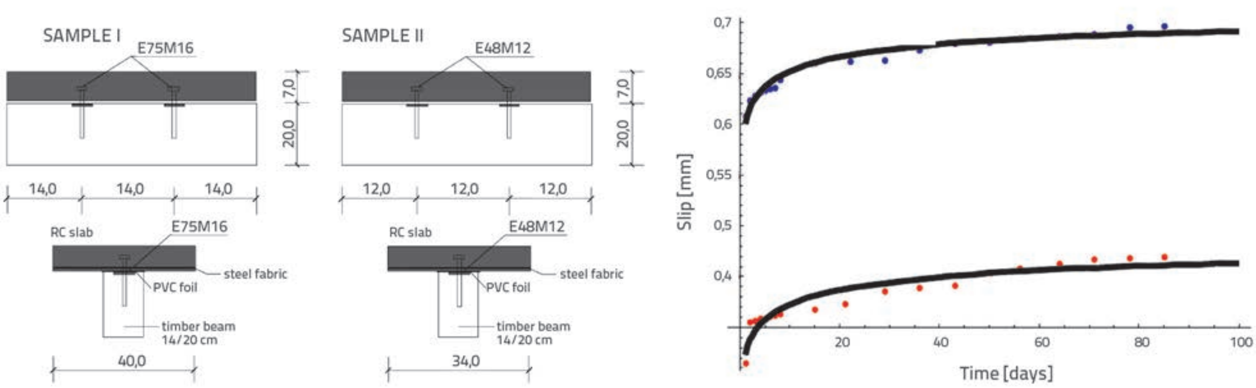

Figure 4. Wood and concrete connection with shear connectors; approximation of connection slip values with polynomial curve [19]

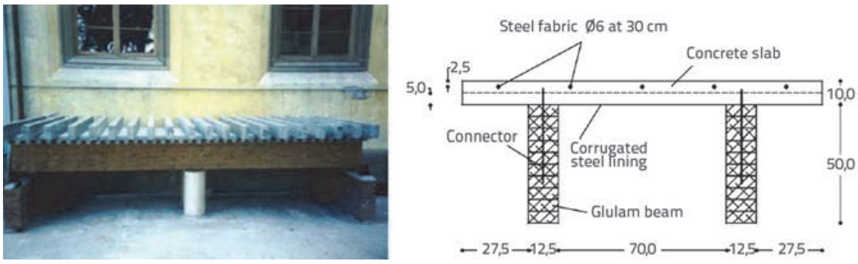

Figure 5. Composite beam during testing with cross-sectional dimensions in cm [11]

i.e. irreversible deformation amounting to 20 % of the long-time deflection. Deformation factors significantly greater that the ones prescribed in EC5 [2] were registered. The difference in girder stiffness prior to and after 411 days was reduced by 20 % with regard to initial stiffness, while the initial slip modulus was reduced by two times.

Ceccotti et al. [11] experimentally observed behaviour of a 6-m beam subjected to long-term load (Figure 5). The composite action was realised via glued-in steel rods, and the composite was exposed to constant load, and to continuous time changes over a five year period.

Based on frequent moisture measurements, the wooden element was classified into class 2 according to EC5 [2], as the moisture content was always lower than 18 %. On the contrary, the relative air humidity was about 85 percent, according to which the wooden element should be classified into serviceability class three. Deformations of the composite itself greatly depended on weather changes, and so the deformation of the composite was greater in case of greater relative air humidity values. Displacements measured during the first two years of the experiment were very high, but the final deflection value after five years was significantly lower than the values specified in EC5 [2]. The slip at connection was not significant even after five years. Both characteristics fluctuated considerably at the annual and even daily levels, which is due to differences in weather conditions. After five years, the beam was tested until failure. The characteristics of the connection itself were derived experimentally, rather than analytically according to EC5 [2], as the latter specifications are considered as being highly conservative and as they greatly underestimate the stiffness and bearing capacity of the wood and concrete connection. After comparison of experimental and analytical solutions, it was concluded that the composite has to be included in class three, although the moisture content in wood was always below 20 percent.

In the same year, Fragiacomo and Ceccotti [9] suggested a simplified analysis of the long-term behaviour of wood-concrete composites, as based on the research and recommendations from 1995 (Ceccotti [3]). The composite design also has to meet the ultimate limit state requirements (as proven by calculation of maximum stress of composite components (concrete, steel, wood) according to elastic analysis) and the serviceability limit state requirements (maximum deformations are proven for both the short term and long term actions). Simplified design models were presented even before 2006, but subsequent investigations have revealed that some occurrences (such as concrete shrinkage) were taken too lightly. Kuhlmann [20] and Shanzlin [21] proposed that the effective creep and shrinkage values of all materials be taken into account in the calculation. Fragiacomo [15, 22] proposed a simplified Ceccotti's approach so as to take into account the influence of concrete creep and inelastic stress/strain due to climatic variations in air humidity and temperature. All these models may cause composite dimensioning errors precisely because of simplified behaviour assumptions. In earlier models, the direct link between the creep and changes in relative air humidity did not exist, and so Ceccotti and Fragiacomo [9, 10] attempted to establish this link through a unified creep coefficient dependent on serviceability class. A new design model was proposed and compared to the EC5 model and numerical simulations. Basic conclusions of this research are: Toratti's rheological model [7] is greatly dependant on annual changes in relative air humidity; b) the deformation coefficient of the connection, which is assumed in EC5 [2] as being two times greater than the deformation coefficient for wood, is overestimated and excessively high; c) the use of the effective elastic modulus method provides accurate results; d) the concrete shrinkage effect can be calculated very accurately using the formula (for elastic area) of the composite with ductile connectors; e) the same assumption is valid for the shrinkage/swelling due to climatic variations (temperature changes in concrete and wood are equivalent to temperature changes in air; moisture changes in wood are assumed to be constant in each point and equal to an average value in cross section); f) numerical-analytic verifications show that this calculation results in accurate stress and strain values; g) type of environment (interior space, exterior space, heated space) does not exert a great influence on the behaviour of the composite.

Fragiacomo [14, 15] published an extensive study on the composites behaviour when subjected to long term load. In this analysis, he evaluated the simplified analysis method through numerical studies. The model takes into account all rheological indicators and hence results in rigorous formulas. The following rheological indicators are included in the design: creep of wooden element and connection, creep of concrete, shrinkage of concrete, and change in the relative air humidity and temperature. The creep is taken into account through a modified elastic modulus. The distribution of moisture in wood along the cross section is evaluated using the diffusion problem solving procedure. The reliability of the proposed method is checked by numerical analyses. The traditional approach according to EC5 [2] is based on formulas for ductile connections (Mohler [23]). The creep effect is taken into account through the effective modulus method (Chiorino [24]). The model is the combination of superposition of the load and concrete shrinkage effects, with the effects caused by changes in humidity and temperature on the annual and daily bases. Three basic ways in which the long term load is applied on the composite are defined in the conclusion of experimental and numerical tests: permanent load and service load, concrete shrinkage, and inelastic deformations due to weather changes in the environment. Each load is considered separately and is then superposed with other loads. The concrete shrinkage effect resulting in an increase in deformations is very significant; the creep greatly increases the deformations and slip due to load. The slip and internal forces also vary greatly and can attain very high values, especially if exposed to external environment. The accuracy of the proposed calculation method, especially in the calculation of deformations and deflection that are the basic factors for behaviour under a long-term load, is confirmed by comparison with numerical simulations. The use of the deformation coefficient according to EC5 [2] for external conditions provides, in all simulations, the values that are more conservative than the ones proposed by numerical simulations. The comparison with traditional design methods that take into account the permanent load and service load only shows that the effect of other indicators has been underestimated. The calculation model is presented in the following formulas.

$$V_{max} = V_{max,full} \cdot \gamma_v \tag{17}$$

$$v_{max,full} = \frac{\Delta\varepsilon_n}{H}\cdot\frac{(EI)_{full}-(EI)_{abs}}{(EI)_{full}}\cdot\frac{L^2}{8} \tag{18}$$

$$\gamma_v = 1-\frac{8}{(\alpha L)^2}\cdot\left[1-\frac{1}{\cosh(0.5\alpha L)}\right] \tag{19}$$

$$s_f(x) = s_{f,max,abs}\cdot\gamma_s(x) \tag{20}$$

$$s_{f,max,abs} = -\Delta\varepsilon_n \frac{L}{2} \tag{21}$$

$$\gamma_s(x) = \frac{1}{0.5\alpha l}\cdot\left[\tanh(0.5\alpha L)\cdot\cosh(\alpha x)-\sinh(\alpha x)\right] \tag{22}$$

$$E_f(x) = k_f s_f(x) \tag{23}$$

$$N_w(x) = -N_c(x) = N_{w,max,full}\cdot\gamma_\vartheta(x) \tag{24}$$

$$M_i(x) = M_{i,max,full}\cdot\gamma_\vartheta(x) \quad i = c,w \tag{25}$$

$$N_{w,max,full} = \frac{\Delta\varepsilon_n}{H}\cdot\frac{(EI)_{full}-(EI)_{abs}}{(EI)_{full}}\cdot\frac{(EI)_{abs}}{H} \tag{26}$$

$$M_{i,max,full} = \frac{\Delta\varepsilon_n}{H}\cdot\frac{(EI)_{full}-(EI)_{abs}}{(EI)_{full}}\cdot E_iI_i \tag{27}$$

$$\gamma_\vartheta(x) = 1 + \tanh(0,5\,\alpha L)\cdot\sinh(0,5\,\alpha x) - \cosh(0,5\,\alpha x) \tag{28}$$

$$\Delta\varepsilon_n = \Delta\varepsilon_{wn} - \Delta\varepsilon_{cn} \tag{29}$$

$$(EI)_{abs} = E_cI_c + E_wI_w \tag{30}$$

$$(EI)_{full} = (EI)_{abs} + (EA)^*\cdot H^2 \tag{31}$$

$$(EA)^* = \frac{E_cA_cE_wA_w}{(EI)_{abs}} \tag{32}$$

$$\alpha = \sqrt{\frac{k_f}{i_{f,ef}(EA)^*}\cdot\frac{(EI)_{full}}{(EI)_{abs}}} \tag{33}$$

$$s_{f,ef} = 0,75\cdot s_{f,min} + 0,25\cdot s_{f,max} \tag{34}$$

Where:

v - deflection

L -beam length

Δe_n - difference between the inelastic stress in wood Δe_{wn} and concrete Δe_{cn}

(EI) - stiffness

E, A, I - Young's modulus, the area and 2nd moment of inertia for each cross section (wood and concrete)

k_f - connection stiffness

$s_{f,max}, s_{f,min}, s_{f,ef}$ - maximum, minimum and effective connector spacing

H - distance between the centres of gravity of the wooden part and concrete part

F_f, s_f - shear force at the connection, relative slip between concrete slab and timber beam

N, M - axial force, bending moment

v, x - deflection along the x axis

Indices:

abs i ful - no connection and rigid connection

max - maximum value along the beam axis

c, w, f - concrete, wood, connector.

The coefficients $\gamma_s(0)$ and $\gamma_u(l/2)$, which take into account maximum effects along the main axis of the beam, are assumed based on the following values:

$$\gamma_s(0) = \frac{\tanh(0.5\alpha l)}{0.5\alpha l} \tag{35}$$

$$\gamma_\vartheta(l/2) = 1-\frac{1}{\cosh(0.5\alpha l)} \tag{36}$$

Kavaliauskas et al. [25] observed behaviour of composite systems subjected to long-term load, and tried to evaluate the long-term behaviour, and to compare it with some wood-creep models. They have shown through calculation that the stresses and deflections change considerably during the first 180 days, and that subsequent changes are very small. The following model was used to calculate creep deformation for wood:

$$\varepsilon(t-t_0) = \frac{\sigma}{E}\left[1+0,65\left(1+0,65\left(1-e^{-(t-t_0)}\right)\right)\right] \tag{37}$$

$$\varepsilon(t-t_0) = \frac{\sigma}{E}\left[1+0,3\left(1+0,3\left(1-e^{-(t-t_0)}\right)\right)\right] \tag{38}$$

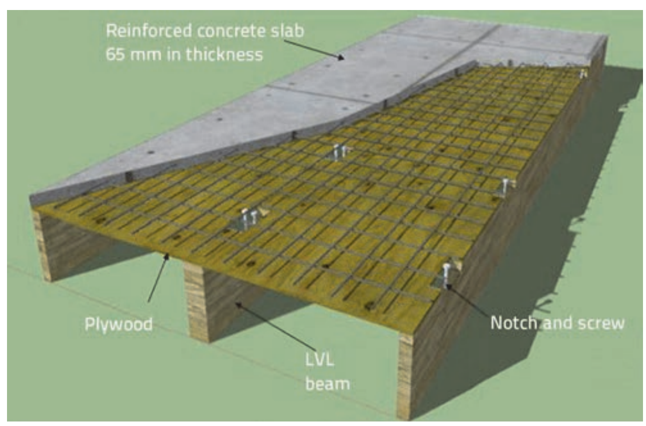

Figure 6. System tested by Yeoh et al. [26]

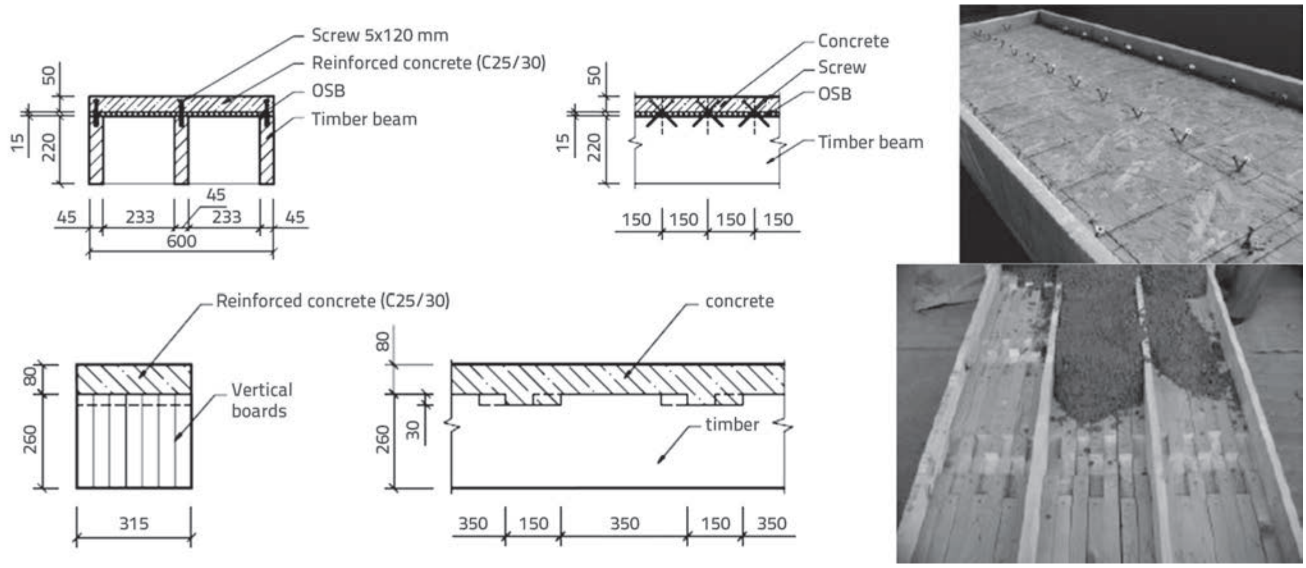

Figure 7 Geometry and fabrication of composite beams tested by Kanocz and Bajzecerova [27]

A two times greater initial deflection value was obtained using the above wood element creep formulas, while the final deflection was 1.5 times greater compared to the values obtained by the method proposed in EC5 [2]. The behaviour of composite concrete and LVL beams under a long-term load was also studied by Yeoh et al. [26]. Three 8-m beams were placed as a garage ceiling, and were then subjected to additional permanent load, as shown in Figure 6:
All significant parameters were measured continuously for four years. Weather conditions present from the beginning to the end of the measurement were characterized as the periods with low temperature and high relative air humidity, or periods with high temperature and low relative air humidity, and so the composite was included in class three according to EC5 [2]. The basic conclusions reached during the testing are:

a) Very high deflection values occur during cold and wet weather periods.
b) The deflection was by 15 percent smaller in case of beams built from low shrinkage concrete.
c) Significant portion of deflection occured already after three months.
d) The final deflection after four years is by five times greater compared to the short deflection.
e) The mid-span deflections were extrapolated to fifty years, and the value greater than the usually acceptable one was obtained (L/200).

The theoretical and experimental testing of composite wood-concrete beams subjected to long-term loading, and the influence of rheology on the bearing capacity of such beams, was presented by Kanocz and Bajzecerova [27]. The analytical calculation model based on annex B from EC5 [2] was presented. The viscoelastic creep of concrete from EC2 [6] was included in the effective stiffness calculation.
Experimental tests were conducted on two types of 5-m composite beams, as shown in Figure 7.
The beams were subjected to bending load for five years in a confined space where changes in the relative air humidity and temperature were continuously measured. Experimental results were compared with the analytical model (Figure 8). The contribution of different rheological phenomena to the total deflection is shown in Figure 9.

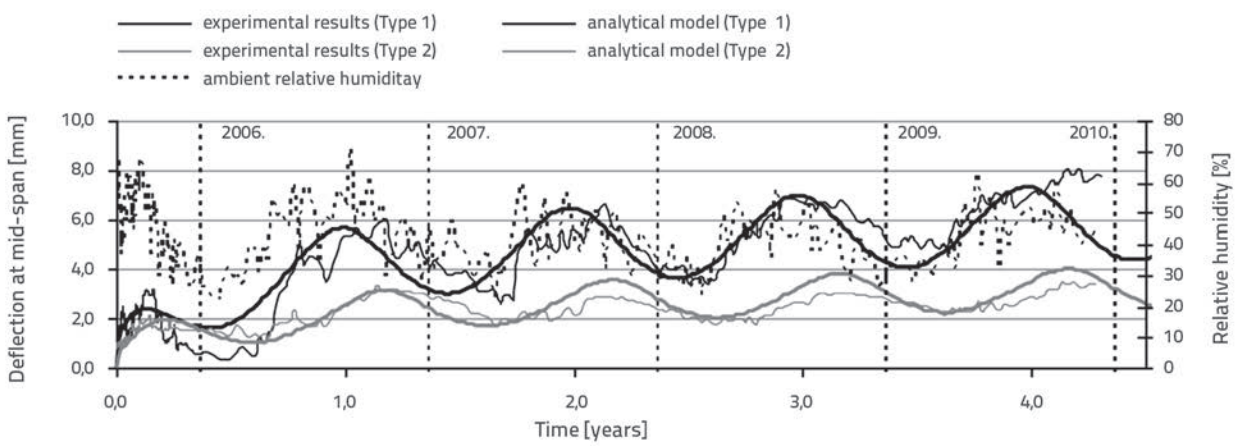

Figure 8. Comparison of experimental and theoretical mid-span deflection in time [27]

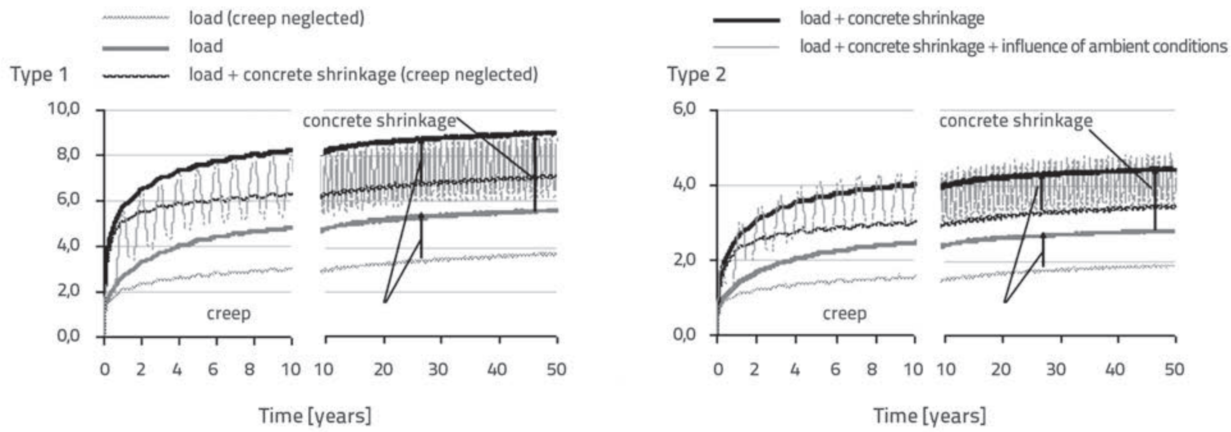

Figure 9. Contribution of various rheological phenomena to total deflection for beam types 1 and 2 [27]

The increase and decrease in deflection was followed by changes in air humidity: in winter months the relative humidity was lower and, consequently, the deflection in beam centre was also lower. The concrete shrinkage greatly contributes to the total deflection (20 %), while the wood shrinkage increases the deflection by 37 percent, with respect to the external load. It was concluded after the testing that rheological factors greatly influence final deformations and that, therefore, they must not be neglected in the design. Measured annual variations in deflection, as a result of changes in relative humidity and temperature, show changes of up to 44 percent with respect to the expected final deflection. The influence of the relative air humidity is greater than that of the change in temperature.

The behaviour of composite floors made of wood and lightweight concrete was studied during 600 days by Jorge et al. [18]. Three 4-sample series were tested in order to determine development of creep coefficient over time (Figure 10). The measured creep coefficient was calculated according to the following equation:

$$\varphi(t=t_i)=\frac{w_{(t=t_i)}-w_{(t=t_0)}}{w_{(t=t_0)}} \qquad (39)$$

where $w_{(t=t0)}$ and $w_{(t=ti)}$ istand for the initial and final slip. The initial slip is the slip assumed after ten minutes of loading.

The results show that more than fifty percent of expected creep occurred at the shear connector already after 600 days. When comparing test results with mean values calculated using the method contained in EC5 [2], we can notice considerable differences that should not be neglected. The deflection obtained according to EC5 [2] for the 10-year period was attained already after 150 days; the deflection expected after fifty years according to EC5 [2] was attained already after 230 days.

These differences are due to the following points that are neglected in the structural design according to EC5:
- Shrinkage of both materials.
- Influence of composite action on effective creep coefficients that should take into account the redistribution of stress in the composite system.
- Different temporal development of the creep and shrinkage strain.

Taking into account the fact that a considerable amount of data is needed in numerical modelling, and that the process is time consuming, the authors have concluded that the procedure proposed in EC5 [2] can be used, but subject to some corrections.

Van de Kuilen and Dias [28] studied the long-term behaviour of composite wood-concrete systems with rod connectors. The total of seven series with different samples were tested (40 samples in total). The samples varied either by the material itself or by the connection devices that were used for linking the concrete and wood together. The main objective for studying the long term behaviour was to define the creep properties of the connecting device (in controlled and uncontrolled conditions). The samples are shown in Figure 11.

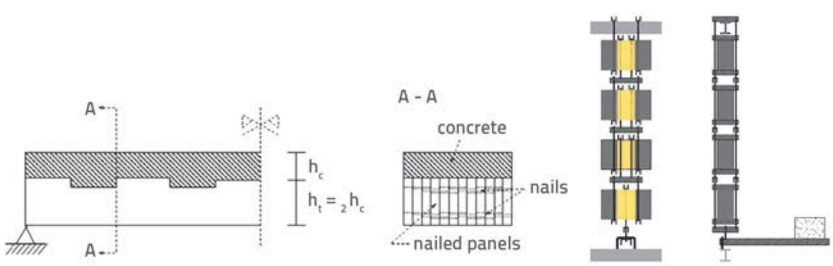

Figure 10. Floor and croos section of the case study by Jorge et al.; Samples ready for long-term testing [18]

The duration of testing was not uniform for all samples, i.e. it varied from 655 to 1160 days. As analytical models for predicting long-term behaviour of composite wood-concrete systems do not exist, the models used for the behaviour of wood-wood connections are often used as an analogy (van de Kuilen [29]). The authors assumed that the long-term behaviour of connections can very well be described through non-linear Maxwell elements

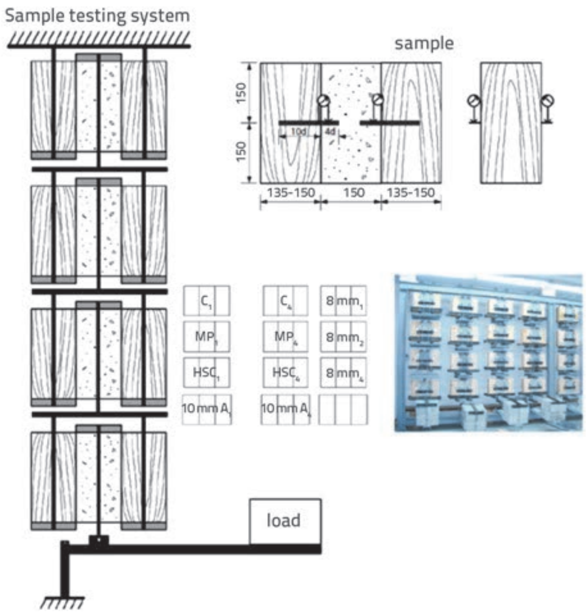

Figure 11. Test setup used by van de Kuilena & Dias [28]

with the stress of up to $d\varepsilon_{el,i}/dt$, which denotes elastic behaviour of materials, and with $d\varepsilon_{n,i}/dt$, which denotes the viscoelastic stress. The sum of these factors represents the slip:

$$\frac{d\varepsilon_i}{dt} = \frac{d\varepsilon_{el,i}}{dt} + \frac{d\varepsilon_{v,i}}{dt} \quad (40)$$

A reasonable slip-model solution can be obtained if the following hypotheses are adopted:

- Wood behaviour can be described by a single nonlinear Maxwell element;
- Elements are subjected to constant load;
- The creep time is sufficiently long and so that the coefficients C1 and C2 from the next equation are not influenced before the steep part of the creep curve (Figure 12).

The slip modulus is then calculated according to the following equation:

$$\varphi = \frac{\delta_\infty - \delta_{inst}}{\delta_{inst}} = C_1 \ln(1 + C_2 T) \quad (41)$$

where δ_{inst} is the initial slip of the connection, δ_∞ is the long-term slip of the connection, T is the time, and the values of C_1 and C_2 can be taken and calculated, because of their complexity, through test results.

Principal conclusions made by the authors are that the creep of the composite greatly differs depending on the connector that

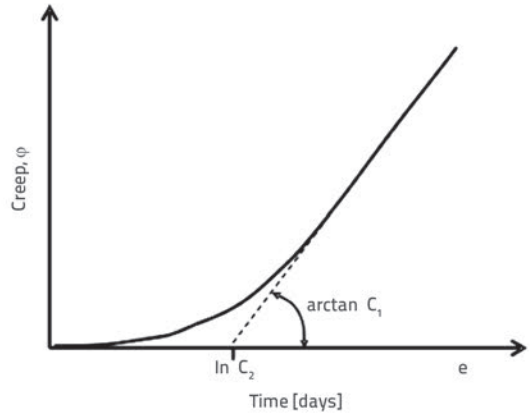

Figure 12. Parameters C_1 and C_2 and the relationship between creep and time [28]

is used for connecting concrete with wood. Similarly, as the samples were tested in controlled and uncontrolled conditions, it was concluded that the creep in the service class 2 is almost two times greater than the creep in the service class 1. The authors conclude that the method given in EC5 [2] can be acceptable for the use of wood-concrete connections for the service class one, while the values obtained for the class two lead to un-conservative and inacceptable solutions during the long-term load.

Manthey et al. [30] studied behaviour of the SBB composite connection (connection developed in the French company AIA Ingeniere, Figure 13) when subjected to monotonous and cyclic loads. The monotonous load results in an excellent ductile behaviour of the connection, which gives a competitive advantage

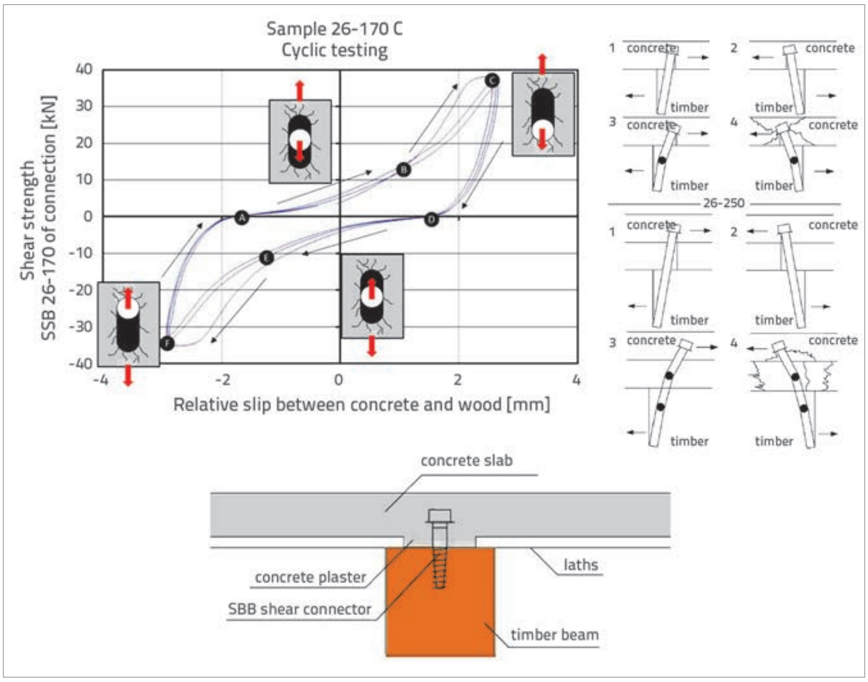

Figure 13. Behaviour of cyclically loaded connection with SBB connector (3 cycles) tested in the study presented by Manthey [30]

to this system for installation into systems that are built in seismically active areas. In case of cyclic testing, the behaviour was once again very ductile, without reduction in shear strength at greater deformations. According to EC8 [31], this connection can be considered as energy dissipative, and can be used without risk of brittle facture occurring at the beam and slab connections. A comparative study of analytical modelling of the composite wood-concrete structures was presented by Khorsandnia et al. [32]. The long-term behaviour of such connections is represented in many standards and regulations, and is based on the creep of three materials. The most extensive regulations are given precisely in EC5 [2] where the long-term deformation of the composite is calculated with the double coefficient of deformation k_{def} of the connection itself. Although the wood exhibits linear behaviour at a short-term testing, this behaviour becomes quite nonlinear at the long-term load, which is due to influence of weather conditions the wood is susceptible to. When stresses in wood amount to less than 35 percent of the short-term strength, the wood can be characterized as a linear-viscoelastic material in the environments where there are no excessive deviations in the relative air humidity and temperature. However, if factors such as the temperature and relative air humidity are variable, one may say that the behaviour of wood becomes nonlinear. The behaviour of wood over a long period of time can be defined as a complex function of ambient conditions and rheological characteristics of the material itself. A parallel can also be drawn when we discuss composite wood-concrete systems, in which case the situation is even more complex because all three materials reveal changes of properties and redistribution of stress and strain at the change of weather conditions.

5. Conclusion

Although wood-concrete composites make good use of favourable mechanical properties of the wood in tension, and of the concrete in compression, an efficient connection or connector of these two materials is needed to ensure an efficient behaviour of the composite: this connector must transfer the load from one material to the other, and ensure minimum slip between the two materials. The wood-concrete composites must be designed in such a way to meet ultimate limit states and serviceability limit states both at the short-term and long-term loading. The attention should be paid to two specific problems:

1) The connection ductility by which the composite action is defined.
2) Suitable long-term behaviour of materials the system is made of, especially with regard to changes in the relative air humidity, temperature, load, and moisture of materials themselves.

The first problem is currently solved using two design models: the linear-elastic method (Ceccotti [3] and the elastoplastic method (Frangi [4]).

The linear-elastic method is based on the assumption that all materials remain in the linear-elastic range until the failure of one of the components (most often the wooden element or connector). This method is very suitable for the highly stiff wood and concrete connections, such as those with notches in the wood and steel bolts. Basic assumptions adopted in the design are that the connector behaviour is perfectly elastic, and that the wood attains its limit bending strength. The tensile strength of concrete is neglected. The method is mostly used for short-term verifications and is based on the γ method recommended in the EC5 [2]. According to this design model, the effective stiffness is used to calculate yield of the shear connection itself. The effective stiffness is calculated using the yield coefficient γ varying from 0 (no composite action) to 1 (full or rigid composite action). Various slip moduli (K_u and K_{ser}) are used for various limit states. These moduli are obtained experimentally as specified in EN 26891 [33].

The elastoplastic method is proposed for specific cases when the composite yields following a strong plasticisation of the connector. Such cases are frequent when the steel connections characterized by low strength and high ductility are used. The yield limit is obtained under assumption that the connector behaviour is perfectly plastic.

The Effective Modulus Method proposed by Ceccotti [3] is the most often used long-term analysis method that takes into account the creep of all three materials.

Based on the Ceccotti's model [3], Fragiacomo [15] presented an extensive study of the behaviour of composites subjected to long-term load in which he evaluated, via numerical studies, the Ceccotti's simplified design method. The following rheological factors were included in the calculation: creep of wooden element and mechanical connector, creep of concrete, shrinkage of concrete, and change in the relative air humidity and temperature. The effects of load, concrete shrinkage, and inelastic stress due to environmental influences, were each evaluated separately by approximation formulas, and were then superposed. The creep was taken into account via the modified elastic modulus. Although the model takes much more variables into account, smaller deformation values are obtained when compared to the deformation coefficient for external influences as given in Eurocode 5 [2]. This shows that the deformation coefficient presented in EC5 [2] is always conservative.

Over the years many researchers have studied behaviour of composite wood-concrete systems. As each composite is different, it is difficult to define a universally acceptable calculation for composite systems [35, 36]. The basic conclusion is that the method recommended in EC 5 [2] can safely be used only for composites that will behave exclusively in the linear-elastic manner. The calculation defines very well the serviceability limit states, although sometimes the slip modulus has to be obtained experimentally.

In composite systems, different shrinkage due to change in moisture in wood and concrete leads to and causes additional internal forces and deformations. The concrete shrinkage leads

to lower resulting stress values and consequently, to lower efficiency of concrete itself. For that reason, the wooden part of cross-section assumes additional stresses. Creep is the next phenomenon that changes the amount of stress along the cross-section of composite systems. The part with a lower creep coefficient assumes greater stress because the stress is reduced in the other part of the cross-section (stress relaxation effect). A simple creep coefficient can not be taken into account in composite systems as it assumes constant elastic stresses. Many researchers have come to the conclusion that the creep and deformations in composite systems can not be observed in the initial point ($t = 0$) and end point ($t = \infty$) only, as some other points in time between these end values can also be critical. This especially concerns the time period from the first three to seven years as in this period the concrete shrinks much more than the wood. Thus stresses in concrete decrease while those in the wooden part of the cross-section actually increase. Empirical equations for calculation of this behaviour are very complex and demanding, and are thus largely unsuitable in practical engineering situations. Creep coefficient values recommended in the dissertation prepared by Schanzlin [34] are very often used as an aid in the design of composite systems [34].
As the field covering the issue of concrete and wood connections is very wide, and as the very design of these composites according to applicable regulations is rather incomplete in some segments, there is an ample room for improvement and study of new connection systems, and hence also for further improvement of the existing standards and regulations.

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