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Long-term analysis of timber-concrete composite bridges

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Summary

The design of timber-concrete composite bridges is complicated due to time-dependent phenomenon like creep, shrinkage of concrete and effects of the varying temperature and moisture content. Unfortunately, at the moment, Eurocodes include very limited guidelines for designing such bridges. Existing guidelines and methods, time-dependent material models and effects of the environmental variations were studied for the long-term analysis. Based on the findings, a simulation tool for timber-concrete composite beam accounting the time-dependent phenomena was developed. Temperature and moisture content histories of the bridge components based on the existing weather data. The tool was used to simulate the effects over the service life in two cases; a bridge built using un-shored or shored construction method. In overall, wide agreement between the simulation and the approximate model was found.

Keywords: timber-concrete composite, bridges, long-term analysis, composite beam.

1. Introduction

Timber-concrete composite (TCC) bridges are affected by number of time-dependent phenomena, like creep, shrinkage of concrete and effects of varying temperature and moisture content. All these phenomena affect stresses and strains in the structure, and thus affecting deformations and load-carrying capacity of the bridge. At the moment, methods of analyzing the effects of aforementioned phenomena are not covered by the Eurocode standards, which makes long-term analysis of the bridges problematic in design practice. Due to quite intensive research on TCC structures in past few decades, some long-term analysis methods for TCC structures has been proposed, but mainly for building construction. The purpose of this paper was to investigate applicability of these existing methods for design of TCC bridges.

2. Time-dependent behavior of TCC bridges

Long-term behavior of a TCC bridge is affected by multiple time-dependent aspects, such as loads varying over time, different construction stages and time-dependent behavior of the bridge components.

2.1 Loads

A typical TCC bridge is subjected to various loads over the life span. In the construction phase, the structure is loaded gradually by self-weight of bridge components and construction loads like falsework, formwork, equipment, workers and machinery. After the construction is finished, the construction loads are removed. When the bridge is opened for traffic, it is mostly subjected to traffic loads and environmental variations (thermal and moisture content variations) besides the permanent loads (self-weight).

2.2 Construction method

Commonly two different construction methods are used for TCC structures cast on-site, (1) shored and (2) un-shored method. In the shored method, the structure is supported during the construction by intermediate supports, which are removed when the concrete is hardened enough. In the un-shored method, intermediate supports are not used. The clearest difference between the methods is that in the shored construction the self-weight of concrete and other components is transferred to composite section at support removal, while in the un-shored method self-weights are mainly carried by the timber sections. Whereas shored method applies composite section more effectively, un-shored method is particularly attractive due to its simplicity on site. Examples of Finnish TCC bridges built using un-shored method can be found in [1].

2.3 Time-dependent behavior of components

In addition to instantaneous behavior, timber, concrete and connectors display time-dependent behavior. The most notable time-dependent phenomena affecting: (1) timber are creep, mechano-sorptive creep, shrinkage/swelling and thermal strains, (2) concrete are creep, shrinkage and thermal strains and (3) connectors are creep and mechano-sorptive creep [2]. Over time, these phenomena will change stresses and strains [3], which will affect deflections and load-carrying capacity of the TCC beam. In addition, creep in composite structures is non-linear due to interaction between the components, which makes long-term behavior more complex.

3. Existing analysis methods

3.1 Eurocodes

The current version of the Eurocode standards include limited information about design of TCC structures. Only in EN 1995-2 [4] some guidelines for the structural behavior and the connector design are given, however long-term analysis of TCC bridges is not covered.

Nevertheless, the behavior of the individual materials is included in the Eurocodes. The creep in timber components is taken into account by using deformation factors (i.e. creep factors) k_{def} given in EN 1995-1-1 [5] and the effects of the creep on the structure are calculated applying effective modulus method (EMM). The factors are given in different service classes and for different types of wood products. While in the current version only thr final k_{def} values are given, the factors for intermediate duration were given in the earlier version of the standard (1994).

Methods of analyzing the effects of environmental variations in timber (thermal and moisture content) are not considered in EN 1995-1-1 or EN 1995-2. In general, guidelines in the Eurocodes are limited to thermal expansion factors for timber parallel and perpendicular to grain, which are given in EN 1991-1-5 [6].

Long-term behavior of the concrete is defined more explicitly. Standard EN 1992-1-1 [7] defines creep function $\varphi(t,t_0)$ depending on ambient relative humidity, dimensions of the element, strength class of the concrete and concrete age at loading as well as shrinkage $\varepsilon_{cs}(t)$ depending on ambient relative humidity, dimensions of the element, strength class of the concrete and concrete composition. The strains due to thermal variation should be determined by using linear expansion coefficient α_T given in the standard.

3.2 Finnish NCCI1 and NCCI5

Additional rules for timber bridges may be found in the national application documents, like Finnish Transport Agency's NCCI1 [8] or NCCI5 [9]. According to the NCCI5, the creep in TCC bridges may be taken into account by different modular ratios $n = E_c/E_{mean}$, where E_c is concrete modulus of elasticity and E_{mean} is timber mean modulus of elasticity, for short-term (n = 3) and long-term (n = 2) analyses. NCCI5 also gives expansion coefficients due to thermal and moisture content variation along different axes of the timber as well as variation range of timber moisture content for salt and creosote treated wood after the wood has reached its equilibrium moisture content. NCCI1 suggest that the thermal loads on the timber bridges should be defined from temperature distributions given for concrete bridges in EN 1991-1-5.

3.3 Methods proposed in literature

Intensive research on TCC structures has been conducted during the past few decades and some analysis methods has been proposed. Two of these will be discussed in this paper, namely methods proposed by Ceccotti [10, 11] and by Fragiacomo [3].

Ceccotti's approach considers simply supported TCC beam consisting of timber section and concrete slab connected by flexible connectors. Effects of the creep in timber, concrete and connectors is determined by using effective moduli for individual components; however, effects of inelastic strains due to concrete shrinkage and environmental variations are neglected. The total response of the structure is obtained by superimposing effects of individual external loads. It was later noted that Ceccotti's proposal leads to significant errors and un-conservative results due to neglecting inelastic strains in the analysis [12].

An extended version of Ceccotti's approach, a method including effects of the inelastic strains, was later proposed by Fragiacomo. In this approximate method, total effect S is obtained by superimposing effects of external loads, concrete shrinkage and inelastic strains due to environmental variations according to Eq. (1).

Effects of the permanent and imposed loads are obtained by superimposing effects of individual loads, which are calculated by using EMM with effective moduli according to Eq. (2). Effect of concrete shrinkage S_h^s is obtained by calculating effect of concrete shrinkage strain, $\Delta\varepsilon_{cs}(t) = \varepsilon_{cs}(t) - \varepsilon_{cs}(t_0)$, using effective moduli according to Eq. (3). Effects of inelastic strains S_{el}^y and S_{el}^d are both determined by applying elastic moduli according to Eq. (4) and applying yearly and daily inelastic strains according to Eqs. (5) and (6), respectively, as uniform strain loads on corresponding parts of the composite beam [3].

$$S = S_h^{G+Q} + S_h^s + S_{el}^y + S_{el}^d\,, \tag{1}$$

$$E_{c,eff}(t) = \frac{E_c(t_i)}{1+\phi_c(t,t_i)} \quad E_{t,eff}(t) = \frac{E_t}{1+\phi_t(t,t_i)} \quad K_{f,eff}(t) = \frac{K_f}{1+\phi_f(t,t_i)}\,, \tag{2}$$

$$E_{c,eff}(t) = \frac{E_c(\bar{t})}{1+\phi_c(t,t_0)} \quad E_{t,eff}(t) = \frac{E_t}{1+\phi_t(t,t_0)} \quad K_{f,eff}(t) = \frac{K_f}{1+\phi_f(t,t_0)}\,, \tag{3}$$

$$E_{c,eff}(t) = E_c(t_\infty) \quad E_{t,eff}(t) = E_t \quad K_{f,eff}(t) = K_f\,, \tag{4}$$

$$\Delta\varepsilon^{y}_{t_u}(t)=\alpha_{t_u}\left[u(t)-u(t_0)\right] \quad \Delta\varepsilon^{y}_{t_T}(t)=\alpha_{t_T}\left[T(t)-T(t_0)\right] \quad \Delta\varepsilon^{y}_{c_T}(t)=\alpha_{c_T}\left[T(t)-T(t_0)\right], \tag{5}$$

$$\Delta\varepsilon^{d}_{t_T}=\alpha_{t_T}k\Delta T_{daily} \quad \Delta\varepsilon^{d}_{c_T}=\alpha_{c_T}\Delta T_{daily}\ , \tag{6}$$

where S_h^{G+Q}, S_h^s, S_{el}^y and S_{el}^d are the effects of permanent and imposed loads, concrete shrinkage, yearly inelastic strains and daily inelastic strains, where indices h and el refer to hydroviscoelastic and elastic analyses. $E_{c,eff}$, $E_{t,eff}$ and $K_{f,eff}$ are effective moduli at time t for load applied at t_i, E_c, E_t and K_f are the elastic moduli, ϕ_c, ϕ_t and ϕ_f are the creep factors, where indices c, t and f refer to concrete, timber and connectors, respectively. Times t_0, $\bar{t}$ and t_∞ are the time when the concrete starts curing, the age of the concrete at shore removal and the age of the concrete at the end of the service life, respectively. $\Delta\varepsilon^{y}_{t_u}$, $\Delta\varepsilon^{y}_{t_T}$ and $\Delta\varepsilon^{y}_{c_T}$ are inelastic strains due to yearly moisture variation in timber, yearly temperature variation in timber and yearly temperature variation in concrete, where u and T are approximate histories of average moisture content and ambient temperature. $\Delta\varepsilon^{d}_{t_T}$ and $\Delta\varepsilon^{d}_{c_T}$ are inelastic strains due to daily temperature variations in timber and in concrete, where T_{daily} is average excursion of ambient temperature during the year and k is reduction factor accounting thermal inertia of the timber section.

CEB 90 [13] or B3 are suggested as material models for concrete and creep in timber is suggested to be modelled using Toratti's creep limit model B [14], which includes explicitly effects of mechano-sorptive creep. In the absence of experimental data, creep coefficient $\phi_f = 2\phi_t$ is recommended for the connectors [3].

Fragiacomo's proposal includes all the major time-dependent phenomena affecting TCC structures in outdoor environment, thus it was chosen as possible long-term analysis method for TCC bridges. Its applicability was studied by comparisons presented in the following sections. One drawback of the method is that analysis of structures built using un-shored method is not considered, but treatment of the case is discussed later in this paper.

4. Long-term simulation tool for TCC beams

4.1 General procedure

In the simulation, a time domain $t \in \left[t_0, t_\infty\right]$ is discretized into N+1 instances $\{t_0, t_1, \ldots, t_n, \ldots, t_N\}$, thus having N time steps, $\Delta t_n = t_n - t_{n-1}$. During the time step n, the structure and its components are subjected to strain increments $\Delta\varepsilon_n$ due to external loads, creep and inelastic strains. Then, general effect increments ΔS_n (strains, deformations, stresses, forces) due to the strain increments during the time step n are calculated. Environmental variations are input as discrete domains $\Delta T_n = T_n - T_{n-1}$ and $\Delta u_n = u_n - u_{n-1}$. In the beginning of the analysis, at $t = t_0$, all the effects $S_0 = 0$. Total general effect at time t_n is given by

$$S_n = S_{n-1} + \Delta S_n\,. \tag{7}$$

Depending on the construction stage history of analyzed the bridge, the structure may include only timber sections in the beginning of the simulation before the slab is cast, and may include intermediate supports (shored construction) during the analysis. Before the slab has cured, calculation model consists of timber section only, thus $S_c = S_f = 0$ (c = concrete, f = connectors). When the slab has cured, analysis model is switched to composite model and effects from the previous step with timber section only are taken as initial values for the composite model.

When the structure is shored, the analysis is carried in two stages, shored and un-shored. In the first stage, the beam is analyzed with intermediate supports. In the second stage, after the supports are removed, the model is switched to model without supports, intermediate support reactions are applied to the beam with opposite sign as external loads and all the effects from the previous step are taken as initial values for the un-shored model.

The calculation tool was implemented in Matlab 2015b and the analysis of stresses and strains during each time step was done by using DFC method [15].

4.2 Rheological models for timber, connectors and concrete

Time-dependent behavior of timber section was modelled in the analysis by using Toratti's creep limit model B [14], with two exceptions: elastic modulus's moisture content dependency and term $-b\varepsilon(t)$ in $\Delta\varepsilon_{t,u}$ were neglected. The latter change was proposed by Fragiacomo [2] due to bad compliance in TCC models. The strain increments were calculated adopting incremental formulation used by Toratti [14].

The model for the connector slip s_f according to Fragiacomo [2] and time-dependent strain in concrete was modelled according to CEB [13] model. Connector slip increments and concrete strains increments were calculated by adopting similar incremental formulation as presented for timber by Toratti [14].

4.3 Moisture and thermal variations

Moisture content and thermal variations in this study were obtained from time-history analyses based on weather history data. The weather data was compiled of Finnish Meteorological Institute's open data [16] from Kumpula weather station in Helsinki. Since only five full years of data was available, data from 1.5.2010 to 30.4.2015 was used and it was extended up to 50 years by repeating the same data. It is realized that this approximation may exclude peak values, which would exist if actual 50 years data were used. However, response of timber moisture content to ambient variation is slow, thus short peaks have limited effects on the moisture content history, thus having also small effect on the stresses. Effects on the thermal variation-induced stresses are higher due to shorter response time, but the error was considered acceptable for the study. The data included ambient temperature T_{amb} [°C], relative humidity RH [%] and cloud cover N [okta]. Thermal analysis required also data of solar radiation, which was obtained from Copernicus Atmosphere Monitoring Service [17].

Moisture content variation in the timber section were simulated based on Fick's II law using the model presented by Toratti [14]. Thermal variation in the composite section were simulated based on the Fourier's law considering effects of convection, solar radiation as well as radiation exchange with the sky and the environment. Surface structures were not included in the model, since their effect was noted negligible in preliminary studies. The analysis method is mostly adopted from [18], but effective sky temperature T_{sky} was determined from solar radiation and cloud cover data according to [19].

Both, thermal and moisture content analyses, were done as 2D analysis in Comsol Multiphysics (version 5.2.0.220). Thermal and moisture content variations over the section $T(y,z)$ and $u(y,z)$ histories, were transformed to equivalent uniform (T_u, u_u) and difference (T_{My}, u_{My}) component (see 4(3) in [6]) histories for the long-term analyses.

5. Comparison between simulation and existing method

Applicability of the approximate method proposed by Fragiacomo [3] was studied in two cases by comparing the results with results obtained from the simulation.

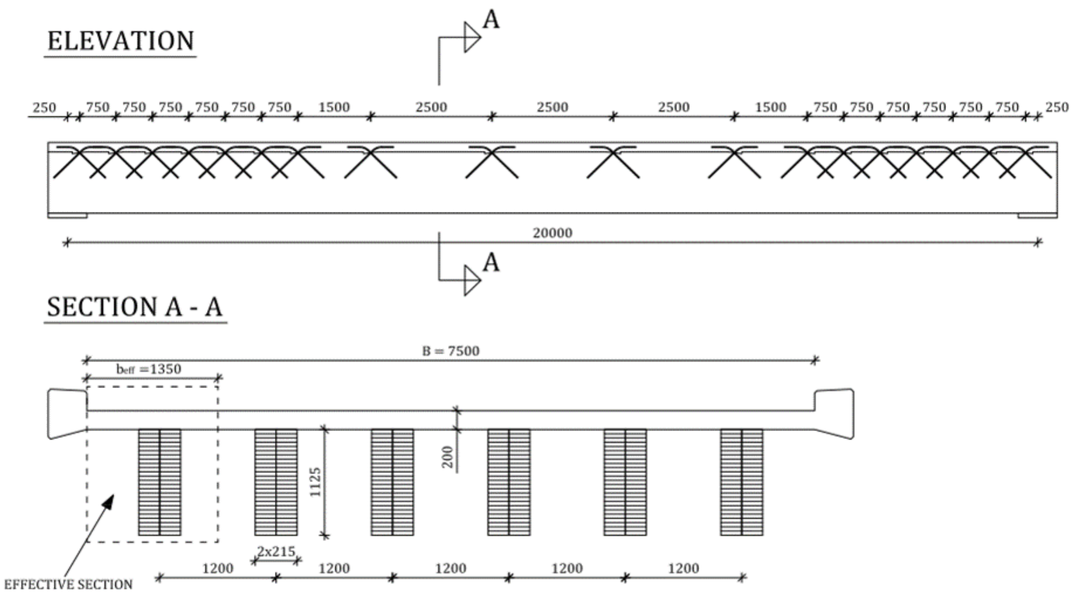

Figure 1. Elevation and cross-section of the case bridge.

5.1 Setup

A case bridge, two-lane road bridge with single span l = 20 m and free width of the deck B = 7.5 m was chosen for the case study. The bridge is illustrated in Figure 1. The dimensions and the material properties are summarized in the Table 1. They were chosen in order to reflect existing TCC bridges in Finland. The service life of the bridge in the comparison studies was 50 years.

Two different analysis cases were considered in the analyses; bridge built using shored or un-shored construction method. In the first case, the structure was supported at 1/3-points during the construction and the supports were removed after a hardening and in the second case, bridge had no intermediate supports during the construction. In the analyses, only effective section shown in Figure 1 was analyzed.

5.2 Loads

The investigated bridge is subjected to (1) external loads, (2) concrete shrinkage and (3) inelastic strains due to thermal and moisture content variations during its life.

The external loads consist of permanent loads (weights of timber sections, concrete slab, surface structures and railings), constructions loads (weight of scaffolding and formwork) and variable loads (traffic loads). The permanent loads were calculated based on the material densities and component geometries. The construction loads were approximated based on typical formwork and falsework structures used in the bridge construction. Traffic loads according to Finnish application document of EN 1991-2, NCCI1 [8], were used. Variability of variable loads were taken into account approximately by including effects of creep for portion $\psi_2 Q_k$ of the load and excluding effects of the creep for $(1 - \psi_2)Q_k$ of the load, where $\psi_2 = 0.3$ is combination factor for long-term loads in NCCI1. This way of accounting creep due to traffic loads is a crude approximation, but it was used due simplicity. The history of loads and construction stages is shown in Table 2. Portion of the total load acting on the effective section were determined by in each case by comparing mid-span deflections of the girders using cantilever rule or FEM model of the bridge depending on the construction stage.

The inelastic strains due to environmental variations were calculated from thermal and moisture content variation histories applying expansion coefficients α given in Table 1. It should be noted, that in this study initial moisture content was u_0 = 20%, while typically glued laminated components are delivered at $u \leq 12\%$. The shrinkage strains were calculated according to CEB.

Table 1. Dimensions and material properties of the case bridge.

Parameter	Value	Parameter	Value
Dimensions		**Timber section**	
Span length l	20 m	Strength class	GL30c
Timber section width b_t	0.43 m	Elastic modulus E_t	13000 MPa
Timber section height h_t	1.125 m	Creep model	Toratti [14]
Concrete slab effective width b_c	1.35 m	Thermal expansion coefficient α_T	5 x 10^{-6} / °C
Concrete slab thickness h_c	0.2 m	Moisture expansion coefficient α_u	5.25 x 10^{-5} / u-%
Concrete slab		**Connectors**	
Strength class	C30/37	Slip modulus K	1500 MN/m
Material model	CEB90 [13]	Creep model	Modified Toratti [1] [14]
Thermal expansion coefficient α_T	10 x 10^{-6} / °C		
(Mean) ambient relative humidity	80%		

1) With c_k = 2, according to [3].

Table 2. History of loads and construction stages in the case studies.

Event	Symbol	Un-shored	Shored
Timber beams installed	t_0	0 days	0 days
Formwork and falsework installed	t_1	3 days	3 days
Concrete slab is cast	t_2	7 days	7 days
Props removed	t_{sr}	- [1]	21 days
Formwork and falsework removed	t_3	28 days	28 days
Surface structures installed	t_4	42 days	42 days
Railings installed	t_5	45 days	45 days
The bridge opened for traffic	t_6	60 days	60 days
End of the service life	t_∞	50 years	50 years

1) No intermediate supports during the construction

5.3 Settings for approximate method

In the approximate method, same load histories, shrinkage and environmental histories as in the simulation were used to allow better comparison, even though Fragiacomo [3] suggest use of simplified moisture content and temperature histories.

Since un-shored construction was not considered in the approximate method, an extended method was used in the un-shored case. In the extended method, effects of the loads applied after the concrete slab has cured, are analyzed as in the shored case. The loads, which are applied before the slab has cured, analyzed using following procedure.

Before curing ($t \le t_c$), the effect is obtained by applying the load on the timber section only and taking into account the creep by using effective modulus for timber. After curing ($t > t_c$), total effect is obtained by superposing effects of (1) load applied on timber section only, (2) restrained load applied on the timber section and (3) restrained load with opposite sign applied on the composite section. The restrained load is equal to load, which is required to counter the creep deformation after the slab has cured.

The total effect in the latter approach can be calculated by

$$S(t) = \begin{cases} S_t(E_{t,eff}^{t_i}(t)) & ,t \le t_c \\ S_t(E_{t,eff}^{t_i}(t)) - \left[S_t(E_t) - S_{comp}(E_{c,eff}^{t_c}(t), E_{t,eff}^{t_c}(t), K_{f,eff}^{t_c}(t))\right] \cdot \dfrac{\left[\phi_t(t,t_i) - \phi_t(t_c,t_i)\right]}{1+\phi_t(t,t_i)} & ,t > t_c \end{cases} \quad (8)$$

where $S_t(\bullet)$ and $S_{comp}(\bullet)$ are the effects of the load on non-composite and composite sections, respectively, and values in the parenthesis $(\bullet)$ are moduli used to calculate the effects. $E_{t,eff}^{t_i}$ is effective modulus of timber at t for load applied at t_i, E_t is elastic modulus for timber and $E_{c,eff}^{t_c}$, $E_{t,eff}^{t_c}$ and $K_{f,eff}^{t_c}$ are effective moduli for concrete, timber and connectors at t for load applied at t_c (time, when the concrete starts curing).

5.4 Studied cases

The comparison was made for un-shored and shored cases, in which four separate load combinations were considered. The loads in the cases were: (C1) only external loads (permanent, construction and traffic loads), (C2) only concrete shrinkage, (C3) only inelastic strains due to temperature and moisture content variations and (C4) combination of loads from C1 to C3.

6. Results

The mid-span deflection w, stresses in the top fiber of the concrete slab $\sigma_{c,top}$, stresses in the bottom fiber of the timber section $\sigma_{t,bot}$ and connector forces nearest to support V_c were extracted from the analyses in each case. For the comparison, the numerical model results were assumed to be correct.

6.1 Un-shored case

Results from the un-shored case are displayed in Figures 2-5, where num. refers to simulation results and appr. to approximate method. In the case of external loads (C1), good overall agreement was found between the simulation and the approximate method results with differences < 5%. A good agreement (differences < 5%) of effects of the concrete shrinkage (C2) was also found, except for stresses in concrete $\sigma_{c,top}$, which display up to 150% overestimations. Effects of the inelastic strains (C3) had fairly good agreement with differences less than < 10%, except for $\sigma_{c,top}$, which is underestimated up to 50%. In the case including all the loads (C4) deflection w and stresses in timber $\sigma_{t,bot}$ display good agreement with differences < 5%. Stress in concrete $\sigma_{c,top}$ is underestimated by 7% and connector force V_c is overestimated by 11%. In overall, in the case C4 largest differences are around ±10%. Effects of the loads C2 and C4 were small compared to effects of the load C1, which is the reason for good agreement in the combined case.

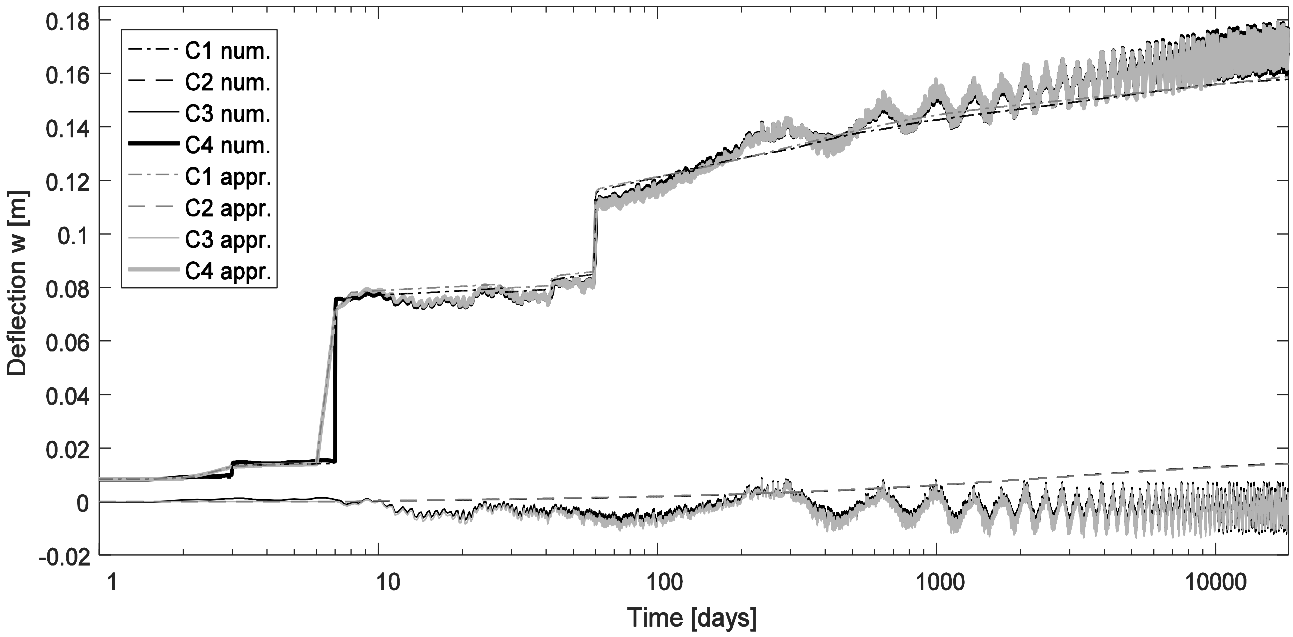

Figure 2. Deflections in the un-shored case.

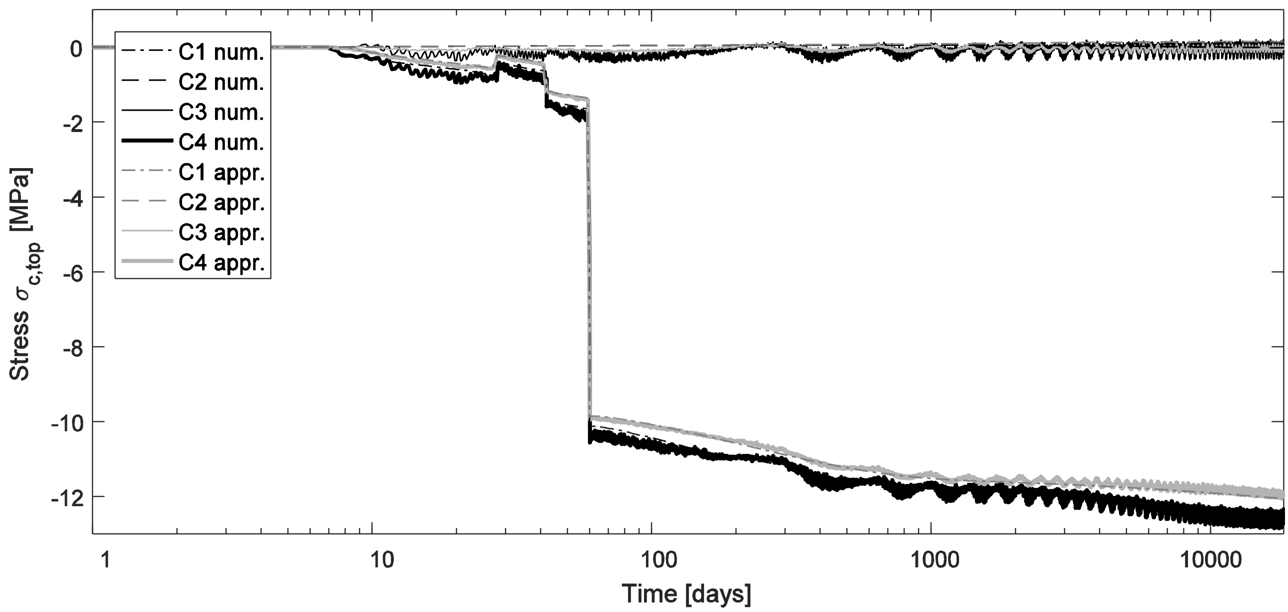

Figure 3. Stresses in top fibre of the concrete slab in the un-shored case.

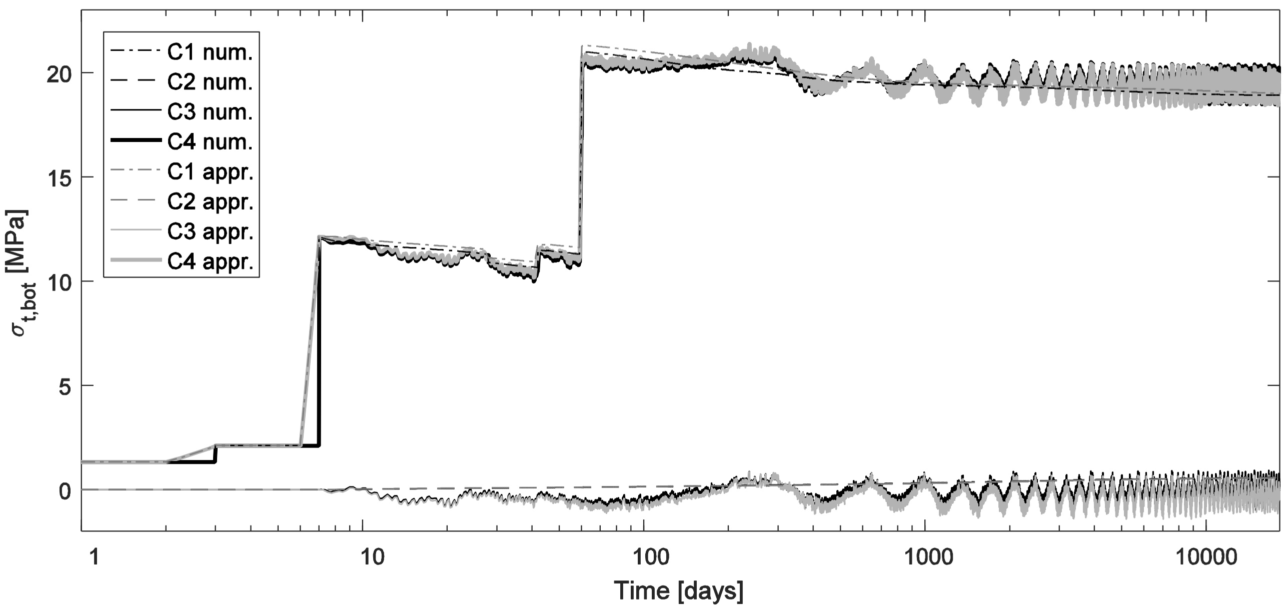

Figure 5. Stresses in bottom fibre of the timber section in the un-shored case.

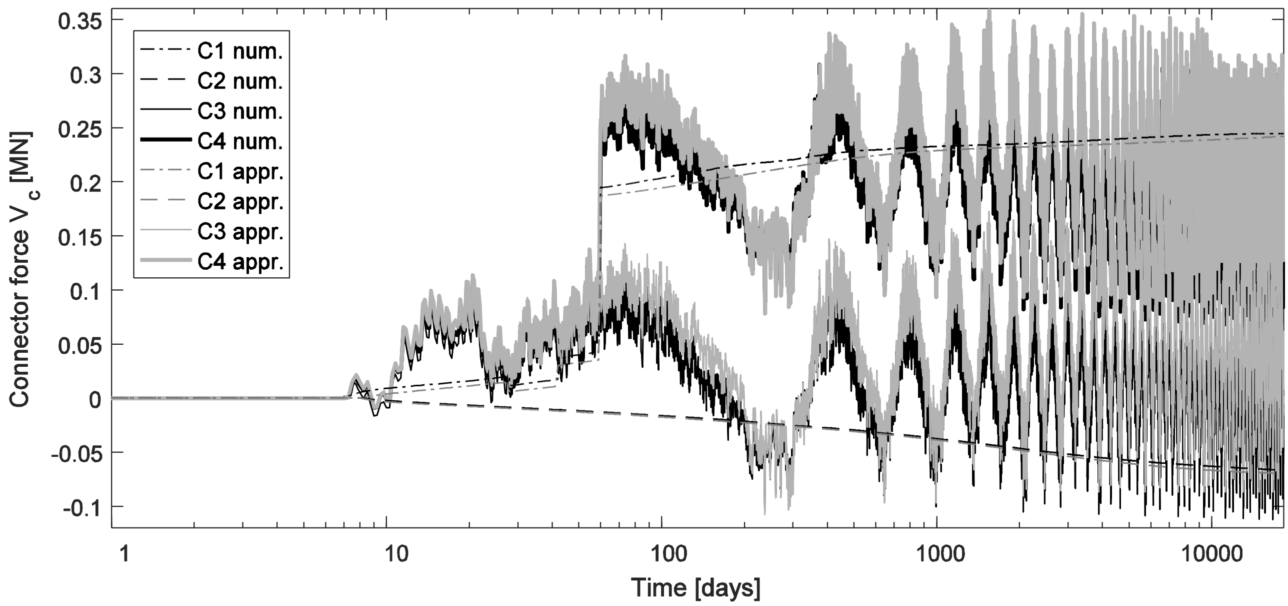

Figure 4. Connector forces in the un-shored case.

6.2 Shored case

Results from the shored case are displayed in Figures 6-9, where num. refers to simulation results and appr. to approximate method. In the case of external loads (C1), good overall agreement was found between simulation and simplified method results with differences < 5%. The effects of the concrete shrinkage (C2) are generally overestimated, displaying differences 5…25%, where highest differences are in concrete stresses and connector forces. The effects of the inelastic strains (C3) displayed poor agreement with the numerical results, except for deflection, which has differences < 5%. The differences in stresses in concrete, stresses in timber and in connector forces were around 20…120%, 25…35% and -5…40%, respectively. In the case including all the loads (C4) good agreement with < 5% differences is displayed, except for connector forces, which are overestimated by 11%. Similarly, as in the un-shored case, effects of the loads in cases C2 and C3 were small compared to effects in case C1, leading to good overall agreement in case C4.

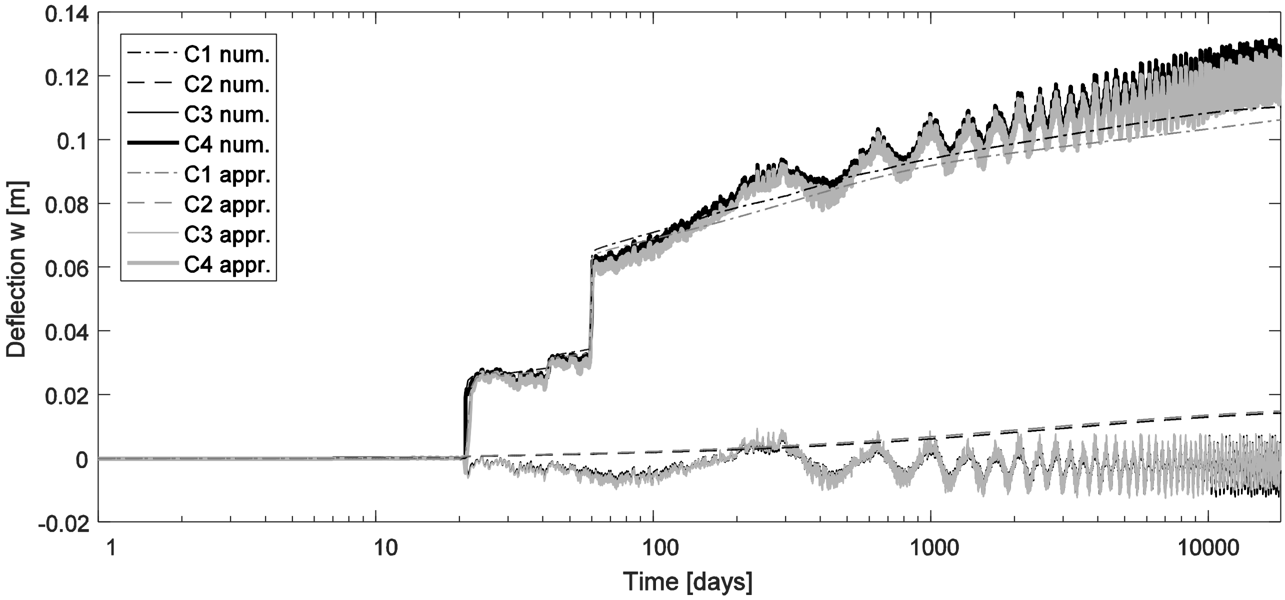

Figure 6. Deflections in the shored case.

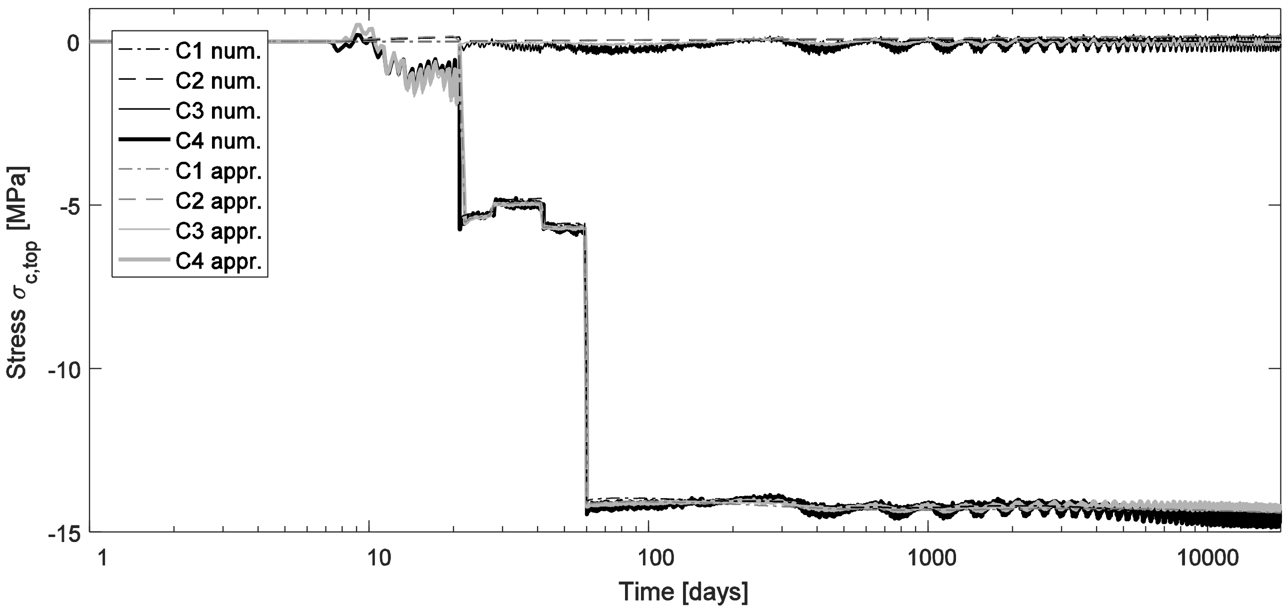

Figure 7. Stresses in top fibre of the concrete slab in the shored case.

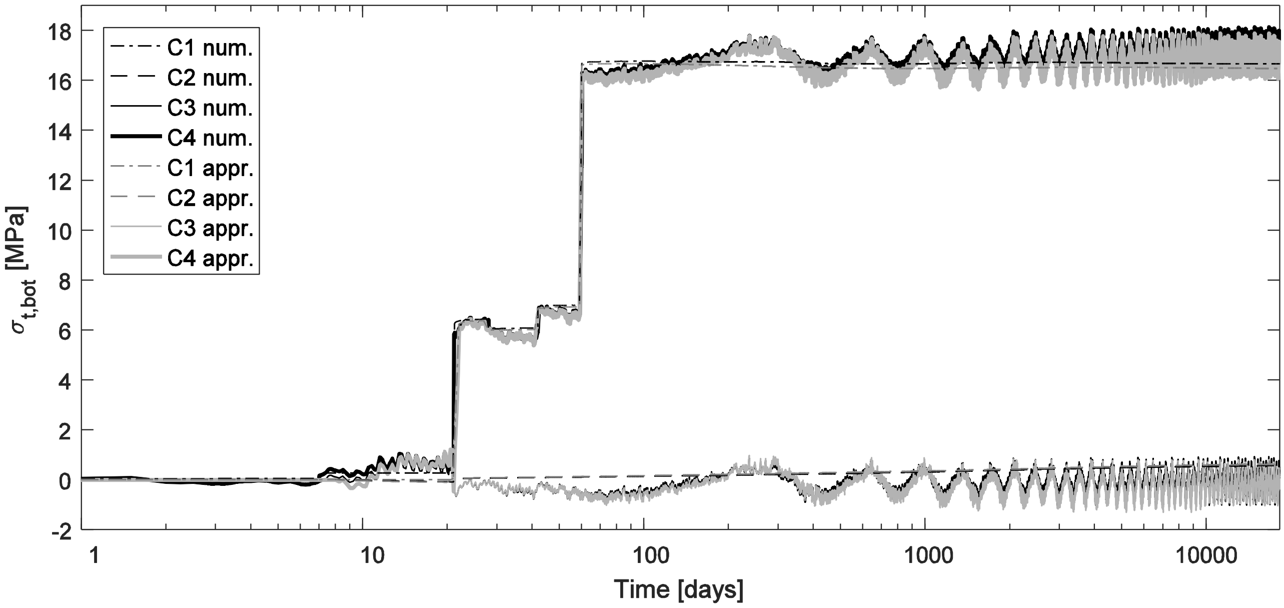

Figure 9. Stresses in bottom fibre of the timber section in the shored case.

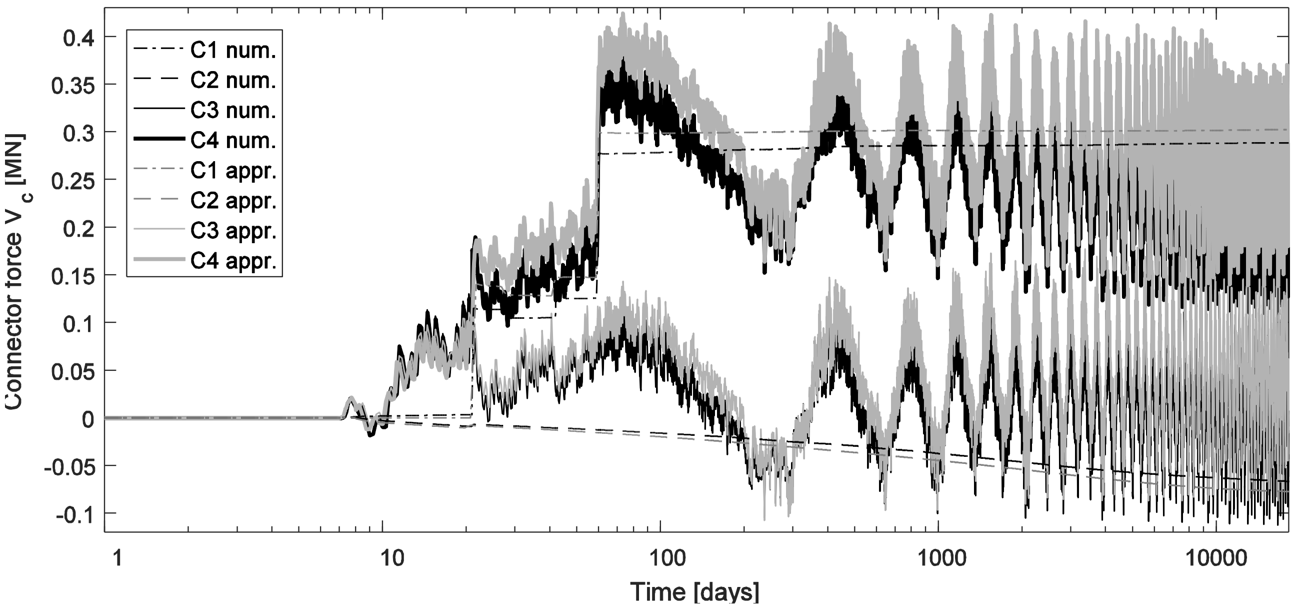

Figure 8. Connector forces in the shored case.

7. Conclusions

Based on the results, the approximate method seems to agree well with the simulation results when considering effects of the external loads in the shored case. Furthermore, the extension for the un-shored case showed a wide agreement. However, results of the extension are based only on this study, thus general applicability is uncertain. Using the simplified method in shored case in design of simple TCC bridges seems feasible for analyzing effects of the external loads. In the un-shored case, further studies should be done to ensure the applicability of the extension.

Weak agreement between the approximate model and the simulation was found, when considering effects of the concrete shrinkage and inelastic strains due to environmental variations. Even though the effects were rather small compared to effects of the total loads, analysis of these loads should be investigated further before applying them widely in the practice due to high differences that were found.

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