Calibration and verification of creep parameters for concrete

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Abstract. Concrete is a material which undergoes slow increasing deformation while subjected to persistent mechanical stress. This phenomenon is known as creep. In concrete material, creep occurs at all stress levels. Additional deformation of concrete structures at the end of their design working life caused by creep is usually two to three times of the immediate elastic deformation value, but might be even more in some cases. The value is dependent on many parameters, e.g. concrete grade, cement class, ambient environment relative humidity, geometry of the structure (drying surface of concrete in contact with air) and also the age of concrete at the time of loading. According to corresponding European standard, the effects of creep are evaluated using creep coefficient, and should be considered for verification of serviceability limit states, and if significant, also at ultimate limit states. In order to evaluate the creep effects in geometrically more complex structures, numerical finite element (FEM) analyses might be conducted. In commercially available software ANSYS, there is a library of several implicit creep equations, with several input parameters. These parameters need to be calibrated in order to match the assumptions of the creep effects over time in accordance with the corresponding European standard. In this study, calibration process of European standard concrete C35/45 parameters for selected implicit creep equation from ANSYS library is presented. The parameters are calibrated for two different ambient relative humidity (RH) levels, 78.8% and 90%, each for concrete loaded in 28 days (also 90 days for RH 78.8% and 50 days for RH 90%) after its casting, and suitable for finite element analysis of creep effects within the first year after loading of the concrete structure. The calibration process is split into two parts, analytical one conducted in table processor, where approximate estimations of suitable parameter values are determined. The second part consist of the subsequent optimization process in OptiSLang software, where the optimal parameter values are determined in order to achieve the best match between the time dependent Eurocode standard creep coefficient and the creep coefficient based on the results of one solid element uniaxial compression test in ANSYS finite element software. The obtained parameters are then verified on an analysis of a simply-supported concrete beam modelled of solid 3D finite elements. The

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values of selected creep equation parameters are summarized in the table, and might be used in the subsequent ongoing research.

1 Introduction

One of the significant material properties in concrete is the creep effect, which occurs at all the stress levels. Creep is a tendency of solid material to undergo certain amount of increasing deformation while subjected to persistent mechanical stress over long time. This rheological phenomenon is well described in detail e.g. by Bažant and Jirásek [1]. During the design process of structures, these long-time rheological effects of concrete should be considered. If not taken in account, the outcome might result into a structural failure. Insufficient prediction of creep contributed to collapse of Roissy Airport Terminal 2E in May 2004 [2] [3].

The effects of creep might be estimated in accordance with European standard [4], which defines creep coefficient as a function of time, dependent on many parameters, as concrete grade, ambient environment relative humidity (RH), drying surface of the concrete structure in contact with air and also the age of concrete at the time of loading. Numerical finite element analysis with consideration of the creep effects might be conducted for example in software ANSYS [5], which offers several creep equations to utilize. Analysis of creep effects using this software is described e.g. in a study by Daou et al. [6].

In this presented study, one of the creep equations from ANSYS library has been selected in order to calibrate the parameters of this equation to comply with the assumptions by the EC2 [4]. The calibration is done for specific conditions: grade C35/45 concrete beam of cross-section 150×200 mm, in two RH levels: 78.8% and 90%, loaded in 28 days and 90 days after casting (for the 78.8% RH), and in 28 days and 50 days after casting (for 90% RH). The parameters are calibrated to fit the EN estimations during the first year after the loading of the structure (with one batch of parameters suitable for analysis over first 10 years after loading).

The workflow of the parameter calibration is well described. In first step, approximate analytical estimation of the parameter values is done, which is subsequently refined by the optimization process conducted in the commercially available software OptiSLang [7].

The required parameters have been calibrated and are summarized. These parameters will be used for the subsequent research of the creep effects. The presented study however offers insight into the general workflow which might be later used for calibration of either the same creep equation parameters suitable for analysis of concrete structure under different circumstances (concrete grade, drying surface, RH, loading time, …), or while slightly modified for calibration of creep parameters for some other creep equation from the ANSYS library [5].

1.1 Eurocode standard assumptions

The time dependent creep strain is considered in accordance with the chapter 3.1.4. from EN 1992-1-1 [4]:

$$\varepsilon_{creep}(t) = \varphi(t,t_0) \cdot \varepsilon = \varphi(t,t_0) \cdot \frac{\sigma}{E} \tag{1}$$

where $\varphi(t,t_0)$ is the creep coefficient determined in accordance with Annex B of EN 1992-1-1 [4], E is elastic modulus, σ is compressive stress applied at time t_0, which should not exceed the value of 0.45 f_{ck} (characteristic value of concrete compressive strength) otherwise creep non-linearity should be considered.

An example of creep coefficient for concrete beam of rectangular cross-section of 150×200 mm, grade C35/45, loaded in t_0 = 28 days is depicted in the Fig. 1.

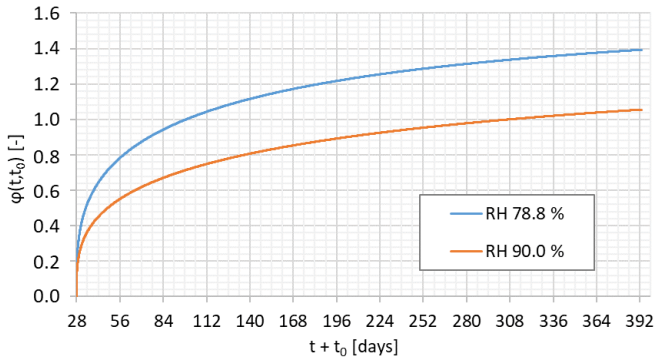


Fig. 1. Example of creep coefficient for two various relative humidity levels.

1.2 Considered ANSYS implicit creep equation

The creep strain might be incorporated into the finite element numerical analysis in ANSYS through several equations from the library [5]. For this study, the equation dependent on time t, thermodynamic temperature T and four parameters noted C_1 to C_4 has been considered:

$$\varepsilon_{creep} = \frac{C_1 \cdot \sigma^{C_2} \cdot t^{(C_3+1)} \cdot e^{-\frac{C_4}{T}}}{C_3+1} \tag{2}$$

Where the dependency on temperature has been neglected by considering the parameter $C_4 = 0$, hence simplifying the equation to:

$$\varepsilon_{creep} = \frac{C_1 \cdot \sigma^{C_2} \cdot t^{(C_3+1)}}{C_3+1} \tag{3}$$

As later noted, another simplification has been introduced, where parameter $C_2 = 1$. The objective of this study is to determine the values of parameters C_1 and C_3 for concrete grade C35/45 at the age at loading of 28 days after casting, under certain environment conditions (relative humidity levels), which would be suitable for finite element analysis of creep effects within the first year after the loading of the structure.

Note: parameter C_3 has no unit, as well as the parameter C_2. The unit of the parameter C_1 is rather complex, dependent on the previous parameter values. In this study, the unit derived from the basic SI units is considered, hence bas on Pascal and second. The unit of parameter C_1 is then $[s^{-(C3+1)} \cdot Pa^{-C2}]$, the dimension is defined by the corresponding C_3 parameter value ($C_2 = 1$).

2 Approximate estimation of creep parameters

2.1 Analytical approach

This chapter describes workflow of the approximate creep parameter calibration for certain inputs.

By logarithmization of the equation (3), the creep strain might be expressed as:

$$ln(\varepsilon_{creep}) = (C_3+1) \cdot ln(t) + ln(C_1) + ln(\sigma^{C_2}) - ln(C_3+1) \tag{4}$$

At the constant stress level σ, the relation between $ln(\varepsilon_{creep})$ and ln(t) might be expressed by linear polynomial:

$$ln(\varepsilon_{creep}) = (C_3 + 1) \cdot ln(t) + const \tag{5}$$

Equation (1) might be expressed in a logarithmic scale noted as:

$$ln(\varphi(t,t_0) \cdot \sigma / E) = f(ln(t)) \tag{6}$$

Example of the relation (6) is graphically depicted in the Fig. 2 for three different stress levels σ, considered as 0.45 f_{ck}, 0.30 f_{ck}, 0.15 f_{ck}, and creep coefficient $\varphi(t,t_0)$ for the relative humidity of 78.8% (Fig. 1). Material parameters for the concrete C35/45 are considered as f_{ck} = 35 MPa, and E = 34 GPa. The function domain ln(t) is considered with time t in seconds. Parameter C_3 is then obtained by the least square method (LSM) approximation of the relation (6) by linear function (5), and results in –0.7559. LSM is dome using discrete points of the function domain, which are equidistantly spaced each 3600 s, and the approximation is conducted within the time interval which corresponds to 365 days.

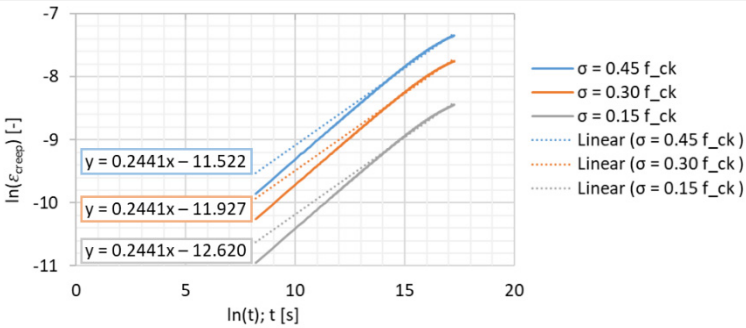


Fig. 2. Graphical determination of the parameter C_3.

The equation 3 might be also expressed in the form:

$$ln(\varepsilon_{creep}) = C_2\, ln(\sigma) + (C_3 + 1) \cdot ln(t) + ln(C_1) - ln(C_3 + 1) \tag{7}$$

When time t considering as a constant in simplified form:

$$ln(\varepsilon_{creep}) = C_2\, ln(\sigma) + const \tag{8}$$

The equation (1) might be expressed in a logarithmic scale as:

$$ln(\varepsilon_{creep}) = ln(\sigma) + ln(\varphi / E) \tag{9}$$

Comparing the equations (8) and (9), the approximate value of the parameter C_2 is determined as 1.0. For this value, it is possible to express the parameter C_1 based on equations (1) and (3) as:

$$C_1(t) = \frac{\varphi(t,t_0) \cdot (C_3 + 1)}{E \cdot t^{(C_3+1)}} \tag{10}$$

For the corresponding time dependent creep coefficient $\varphi(t,t_0)$ (Fig. 1), Elastic modulus E and C_3 parameter, the equation (10) is graphically depicted in the Fig. 3. In order to estimate the approximate constant value of the parameter C_1, the averaged value is proposed as 1.5383E–13.

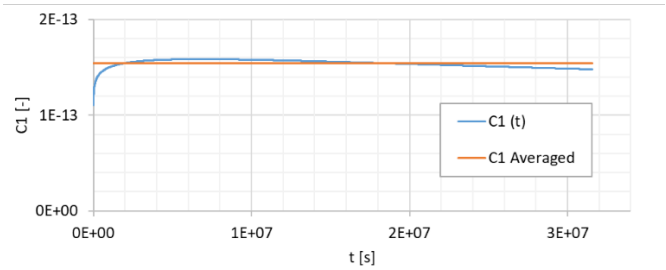


Fig. 3. Graphical depiction of the parameter C_1.

Analogical workflow presented in this chapter is used also for the determination of C_1 and C_3 parameters for concrete in the environment of 90% relative humidity.

It is important to note, that the approximate estimation of the C_3 parameter (Fig. 2) is dependent on the considered interval of the function domain ln(t), and the distance of the points for the LSM. In case the interval is considered to be first 10 years after concrete casting, with the points of the function domain for the LSM approximation equidistantly spaced 1 day, the change in the graph for stress level $\sigma = 0.45\, f_{ck}$ is depicted in the Fig. 4. In this case, the C_3 parameter would result into –0.8786, and the averaged C_1 parameter (interval 10 years, points each 1 day) as 5.7950E–13. Hence, the approximate values of these parameters always needs to be determined with respect to the considered time interval the concrete structure is being analyzed.

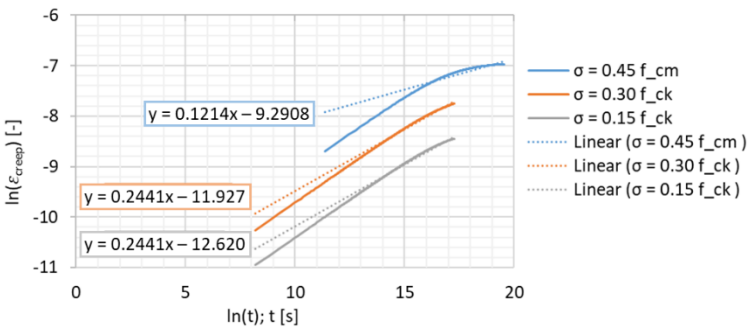


Fig. 4. Graphical determination of the parameter C_3 – change in considered interval of function domain.

2.2 Time dependency of the elastic modulus

In order to determine the suitable creep parameters for concrete loaded at later time then 28 days, e.g. at the age of 90 days after casting, the time dependency of the Elastic modulus should be considered. This might be estimated based on CEB-FIP assumptions [8], which were utilized also in study by Singh et al. [9]:

$$E_c(t) = \beta_E(t) \cdot E_c \tag{11}$$

where E_c is the elastic modulus at the age of 28 days, and the time-dependent parameter $\beta_E(t)$ is defined as:

$$\beta_E(t) = \sqrt{exp\left\{ s \cdot \left[1 - \sqrt{\frac{28}{t/t_1}} \right] \right\}} \tag{12}$$

where t is the age of concrete after casting in days, t_1 is 1 day, s is the coefficient which depends on the type of cement aggregate, 0.38 for slowly hardening cements, 0.25 for rapid and normal hardening cements, and 0.2 for high strength rapid hardening cements. In this study, normal hardening cement is considered, and for concrete C35/45, the example of time-dependent elastic modulus is depicted in the Fig. 5.

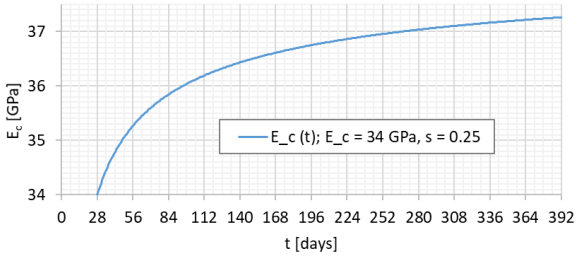


Fig. 5. Example of time-dependent E modulus for concrete C35/45

2.3 Verification by numerical analysis of one element in uniaxial compression

The approximate values of parameters C_1 and C_3 are verified in two ways: analytically by graphical depiction of the equation (3) with the corresponding parameter values in table processor (MS EXCEL), and also based on the results of numerical analysis of uniaxial compression of one element test in ANSYS software [5]. For this purpose, 8-nodal solid element (SOLID185) in a shape of cube with edge size of 0.1 m has been considered. Boundary conditions are set to simulate uniaxial compression in the local x-axis (lateral deformations in y and z directions are constrained at the nodes of corresponding planes). The finite element is axially loaded by constant forces in the 4 nodes of the upper x-plane. Values of the forces are set in order to achieve the stress value of $\sigma = 0.45\, f_{ck}$. Creep strain is being monitored, and the creep coefficient $\varphi(t,t_0)$ is determined as:

$$\varphi(t,t_0) = \frac{\varepsilon_{x,creep}(t)}{\varepsilon_{x,el}(t_0)} \tag{13}$$

where $\varepsilon_{x,el}(t_0)$ is the elastic strain in the corresponding direction at the time of loading (first step of the numerical analysis). Note: for numerical analysis purpose, the time t_0 is considered by small value, e.g. 1E–12 s, and the corresponding value of the time t_0, either 28 or 90 days, is managed in the graphical post processing only. For the verification numerical static structural analysis, two various time steps dt have been considered: 1 hour and 1 day. The comparison of the time-dependent creep coefficient $\varphi(t,t_0)$ in accordance with EC2 (the "EN creep curve") with the verification results is depicted in the Fig. 6. The differences between analytical verification conducted in MS-EXCEL with the results based on numerical analyses are negligible, depending on the time step dt of the analysis. It might be concluded that time step of 1 day is sufficient enough (difference in creep coefficient with respect to analytical verification is smaller than 0.001 – see Fig. 6, right zoomed part).

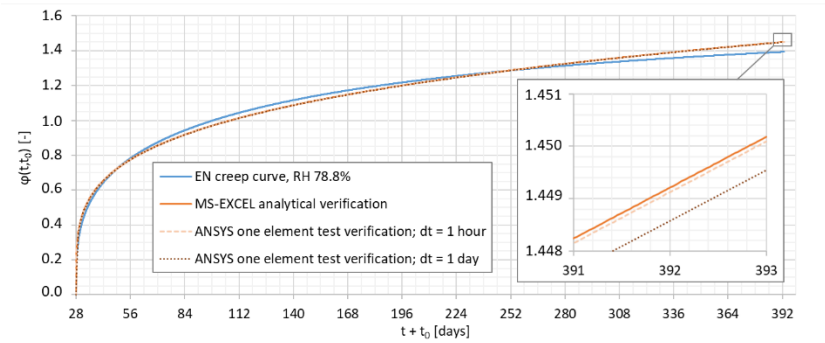
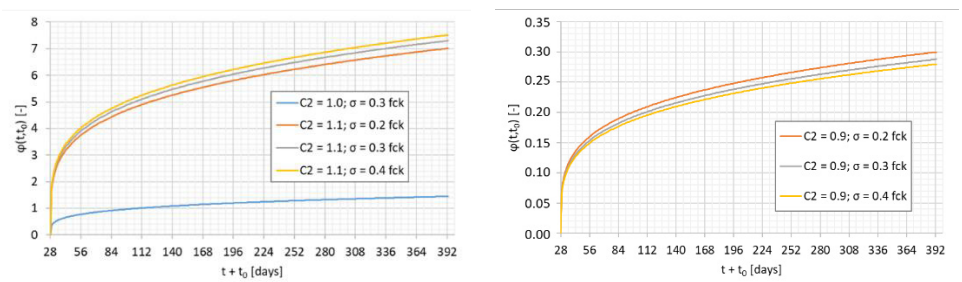


Fig. 6. Verification of the approximately determined creep parameters.

2.4 Test of parameter C_2 change

In order to evaluate the influence of the parameter C_2, 6 one element tests have been conducted in ANSYS (as described in the previous chapter), and the results (time-dependent creep coefficient) are summarized in the Fig. 7. The values of parameters C_1 and C_3 are the same for all these 6 cases (1.5383E–13 and –0.7559 respectively). Three various constant stress loadings are considered $\sigma = 0.2\ f_{ck}$, $\sigma = 0.3\ f_{ck}$ and $\sigma = 0.4\ f_{ck}$. When the parameter $C_2 > 1.0$, the creep coefficient results in larger values for more loaded elements (Fig. 7 a), and when the parameter $C_2 < 1.0$, the creep coefficient is smaller for more loaded elements (Fig. 7 b). This response is in match with expectations (see Equation 3)



(a) Test of C2 > 1.0 (b) Test of C2 < 1.0

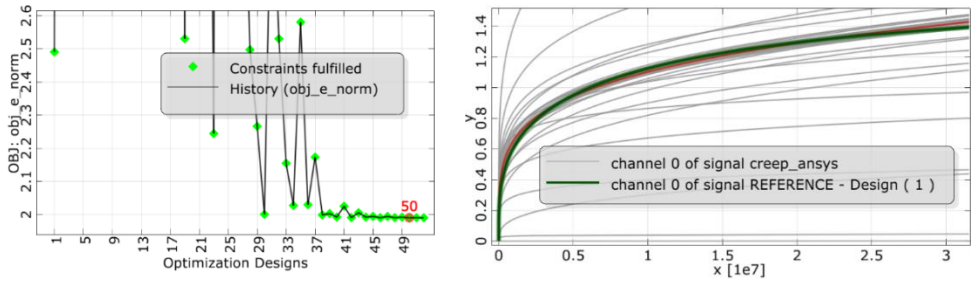
Fig. 7. Test of parameter C_2 response.

3 Optimization of the creep parameters

3.1 Optimization process

In order to achieve the best match between the EN creep curve and the time-dependent creep coefficient based on numerical analysis of one element test in uniaxial compression (determined by Equation 13), subsequent optimization analysis has been conducted using the software OptiSLang [7]. The objective of the optimization analysis is to minimize the difference between EN creep curve (noted as the reference) and the time-dependent creep coefficient curve obtained from the numerical analysis. This difference is defined as the Euclidean norm which is evaluated in equidistant points of the function domain with time interval span of 1 hour. The time step *dt* during the numerical analyses was also considered as 1 hour for the optimization purpose. Simplex optimization algorithm [7] has been selected

for the process, with the initial parameter values of C_1 and C_3 determined based on the approximate estimation (1.5383E–13 and –0.7559 respectively). The parameter C_2 is not optimized, but considered as constant 1.0, as for the future utilization of these parameters in the subsequent research, the effect of creep coefficient stress dependency is not desired. The ranges of C_1 and C_3 within the Simplex algorithm are set as (1E–16; 1E–12) and (–0.9; –0.1) respectively. The objective history progress is depicted in the Fig. 8 a – where the x-axis denotes the number of design, and y-axis the value of the objective (Euclidean norm).



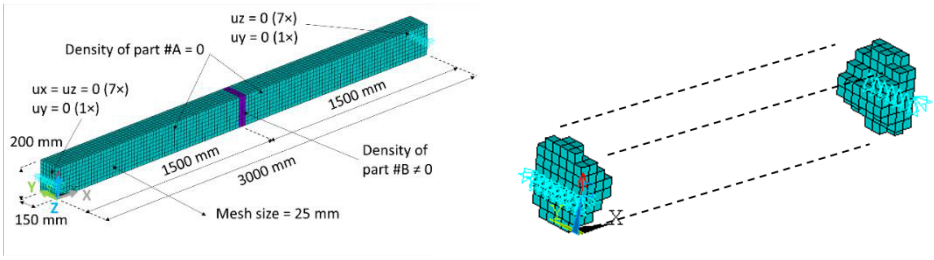
(a) Optimization: Objective history

(b) Creep curves during the optimization process

Fig. 8. Optimization process of creep parameters C_1 and C_3.

Fig. 8 b depicts the reference EN creep curve (green colour), creep coefficient curves of the optimization designs (grey colour), and the best design (number 50) – the one with the smallest value of the objective. The values of C_1 and C_3 parameters of this design number 50 are 1.94E–13 and –0.77497 respectively. Approximately 20% decrease of the objective value (Euclidean norm) has been achieved (from initial 2.5 to 2.0 – Fig. 8 a).

3.2 Verification by Numerical Analysis of a Simply Supported Beam



(a) Numerical model geometry

(b) Selection of Finite elements in regions out of area feasible for monitoring of the creep coefficient

Fig. 9. Parameter verification on a simply supported beam

The verification of the optimized C_1 and C_3 parameters has been conducted on a numerical model of a simply supported beam, where the performance of the approximately determined parameters is also compared. The geometry and the boundary conditions of this numerical model is described in the Fig. 9 a. The boundary conditions are applied on the nodes in the mid-height of the cross-section. The beam is loaded by a constant "force" of 17 kN located in the mid-span. This force results in compressive stress equal to circa $\sigma = 0.364\ f_{ck}$ in the mid-span upper compressed surface. In order to redistribute this force evenly through all the

finite elements in the mid-span cross-section, the loading force is considered as volumetric load (through acceleration), and the density of the material in the mid-span area (Fig. 9 a – density of part #B) is calibrated, so the desired resultant force of 17 kN is achieved. The density of the rest of the beam finite elements is considered as 0 (Fig. 9 a – density of part #A). Otherwise the material properties of the finite elements in the part #A and #B are the same (concrete C35/45, elastic modulus of 34 GPa, poisons ratio of 0.2).

For the analyzed numerical model of the simply supported beam, the creep coefficient determined based on the Equation 13 might be obtained from 5760 finite elements. The results are however slightly different for each finite element. For the analysis conducted with the optimized parameters C_1 and C_3, the creep coefficient $\varphi(t,t_0)$ has been calculated in the last step of the analysis (time t = 1 year) for each of the total 5760 finite elements. The averaged value of the creep coefficient $\varphi(t=1y,t_0)$ from all the finite elements is 1.45124, with the standard deviation of 0.368231. In next step, those finite elements are excluded from this evaluation, for which the creep coefficient $\varphi(t=1y,t_0)$ does not fit within the interval (1.4; 1.5). There were 232 of such finite elements – and these are depicted graphically in the Fig. 9 b. If these particular finite elements are excluded from the average evaluation of the $\varphi(t=1y,t_0)$, the average value of the creep coefficient at the time of 1 year is 1.42668, with standard deviation of 0.00571. The standard deviation value of the creep coefficient based on the set with exclusion of these elements (Fig. 9 b) is much smaller than from the whole set of finite elements of the beam.

Apparently there are areas of the numerical model where the elements are not suitable for the evaluation of the creep coefficient, and those areas are in close distance to the applied boundary conditions (Fig. 9 b). For the further evaluation of the time-dependent creep coefficient $\varphi(t,t_0)$, the averaged value out of the finite elements from the middle 2/3 length of the beam is considered (the areas within 0.5 m from the supports are excluded for the averaging). These creep curves out of the averaged values are depicted in the Fig. 10. The standard deviation is provided only for the last data-point – for the value of $\varphi(t=1y,t_0)$.

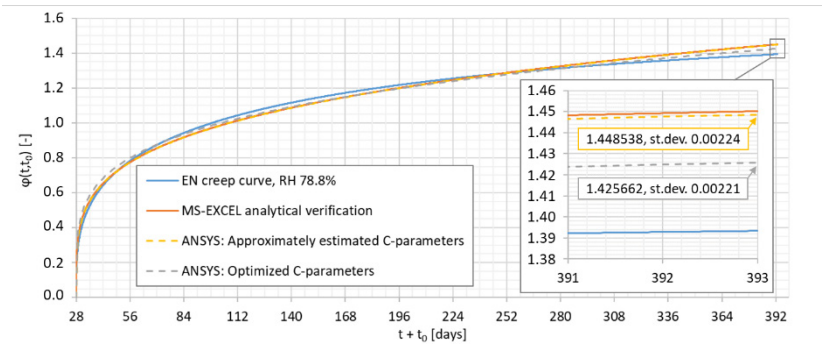


Fig. 10. Verification of the C-parameters by simply supported beam analysis

4 Summary of the calibrated creep parameters

The workflow of the parameter calibration along with the verification process has been provided in the previous chapters, with example of the creep parameters suitable for numerical analysis during the first year after loading of the concrete C35/45 beam of considered cross-section (150×200 mm) loaded in 28 days after casting in the environment with the relative humidity of 78.8%. Analogically to the presented workflow, the parameters are derived for the same structure loaded in 90 days after casting in relative humidity of 78.8%, and afterwards loaded in 28 and 50 days after casting in the relative humidity of 90%. For these second cases, the optimization was not conducted, as the difference in performance

between the analytically estimated parameters and the optimized ones are rather negligible (similar to what is presented in Fig. 8). The calibrated creep parameter values are summarized in the matrix depicted in the Fig. 11. The positions marked by "x" have not been determined, as these were not required for the subsequent research. Note: C_3 parameter has no unit dimension, C_1 values are presented in rather complex unit [$s^{-(C3+1)} \cdot Pa^{-1}$]. Unit transfer to "days" is then: 1 $s^{-(C3+1)} \cdot Pa^{-1} = 86400^{(C3+1)}$ $days^{-(C3+1)} \cdot Pa^{-1}$.

suitable for numerical analyses over time	accuracy	relative humidity RH [%]	78.8		90.0	
		loading time - t_0 [days]	28	90	28	50
1 year	estimation	C_1	1.5383E−13	1.47E−13	8.59E−14	7.28E−14
		C_3	– 0.7559	– 0.77486	– 0.7350	– 0.7355
	optimization	C_1	1.94E−13	x	x	x
		C_3	– 0.77497	x	x	x
10 years	estimation	C_1	5.795E−13	x	x	x
		C_3	– 0.8786	x	x	x
Note: Values are valid with parameter C_2 = 1.0 for all the above mentioned cases						

Fig. 11. Summary matrix of the calibrated creep parameters

5 Discussion

The calibrated values of the creep equation (2) parameters (C_1 and C_3) are dependent on time over which the subsequent numerical analysis will be conducted (see Fig. 2 and Fig. 4). Different values have been calibrated for the analysis of the same concrete structure (loaded in the same time after concrete casting) during the first year after loading, and different in 10 years after loading (Fig. 11). This is a result of slightly different shape of the creep curve defined by the European standard [4] and the shape of the curve that might be achieved by the calibration of the Equation (2). The pure time-dependency of the creep coefficient achieved by the Equation (2) and (13) might be expressed as:

$$\varphi(t) = a \cdot t^b \tag{14}$$

where a and b, are variables (functions) not dependent on the time after loading of the structure t. The pure time-dependency of the creep coefficient determined in accordance with Annex B of EN 1992-1-1 [4] might be expressed as:

$$\varphi(t) = c \cdot \left(\frac{t}{t+d} \right)^{0.3} \tag{15}$$

where c and d, are variables (functions) not dependent on the time after loading of the structure t. Apparently these two Equations (14) and (15) will result for slightly different shapes of the $\varphi(t)$ over the considered time interval. Hence, for each analysis, the unique calibration to achieve the best fit between creep curve based on EC2 [4] and creep curve based on Equation (2) is required. This would be similar for any other creep equation available from the ANSYS library [5].

The creep coefficient based on the approximately determined creep parameters have resulted in a good match with the creep curve based on EN (Fig. 6). Subsequent optimization process has not resulted in a significantly better match between the creep curve based on the optimized C_1 and C_3 parameter values and the EN creep curve (Fig. 8). Although the decrease of the optimization objective, the Euclidean norm of the curve differences, was 20%, the Euclidean norm of the initial design (which uses the approximated parameters) was already small. Hence there was no much space for further optimization. The comparison of performance between the analytically approximated parameters and the optimized ones is conducted on a verification test of a simply supported beam (Fig. 10 – The optical difference

between the two dashed curves is rather negligible). Hence, it appears that the analytically derived parameters are good enough for the subsequent utilization in a numerical analyzes – further optimizations have not been conducted (summary in the Fig. 11).

6 Conclusion

In order to incorporate the creep effects of the concrete material in accordance with European standard into the numerical analysis in ANSYS [5], calibration of the selected implicit creep equation is required. In this study, the calibration of the Equation (2) has been conducted, with the parameter C_2 considered as 1.0, in order to avoid the dependence of the creep (relatively expressed by the creep coefficient) on the stress level – which is similarly assumed in the corresponding Eurocode [4].

In this study, creep parameters suitable for numerical analysis over the first year after the loading of specific concrete beam have been determined (for comparison one set of parameters is determined for the analysis over first 10 years). These parameters are valid for the concrete beam of cross-section 150×200 mm, grade C35/45, in two relative humidity (RH) levels (78.8% and 90%), loaded in 28 and 90 days (for the RH 78.8%) and 28 and 50 days (for the RH 90%) – values of the parameters have been summarized in the matrix depicted in the Fig. 11. Units derived from the basic SI units are considered.

The workflow of the parameter determinations is provided in detail. In first step, the analytical approximate determination is done, and in the second step, subsequent optimization of these approximate parameters is conducted. It appears that the values of the approximate estimation are exact enough, and the subsequent optimization does not improve the performance significantly, at least in case of the considered conditions. Perhaps for the different conditions (RH level, concrete grade, time of the analysis the parameters are suitable for), the optimization might result in more significant improvement.

The values of these parameters will be used for the subsequent research of the creep effects.

Acknowledgments

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