Jordan Journal of Civil Engineering, Volume **15**, No. **1**, **2021**

Comparison between Various Creep Calculation Methods for the Time-dependent Analysis of Terminal 2E at Roissy

Hikmat Daou [1] ***and Wassim Raphael*** [2]

[1] Ph.D. Researcher, Civil Engineering Department, Saint Joseph University of Beirut, Beirut 17-5208, Lebanon. E-Mail: hikmat.daou@net.usj.edu.lb
[2] Professor, Civil Engineering Department, Saint Joseph University of Beirut, Beirut 17-5208, Lebanon. E-Mail: wassim.raphael@usj.edu.lb

ABSTRACT

Creep affects the concrete structural parts existing in various buildings and bridges, such as beams, columns and walls. Understanding the impact of creep on structural components over time is critical to develop a safe and efficient structure. Creep is considered as one of the causes of structural failure, such as the collapse of Terminal 2E at Roissy at Charles de Gaulle Airport in Paris, France. Therefore, the accurate calculation of the creep effect is very meaningful. In this paper, detailed implementation calculations based on viscoelastic and creep models are described using ANSYS. The parameters of the Prony series and the constants of the modified time hardening creep model present in ANSYS are evaluated according to Eurocode 2 creep model. A nonlinear model of Terminal 2E is carried out using ANSYS, then nonlinear analyses are performed. Finally, the results of time-dependent analyses are compared and discussed.

KEYWORDS: Creep, Effective modulus, Age-adjusted effective modulus, Prony series, Modified time hardening model, ANSYS.

INTRODUCTION

Concrete is a composite construction material consisting of aggregates and hydrated cement paste with or without admixtures. Generally, concrete can be classified to be of low, moderate or high strength based on its strength. Concrete strength is highly affected by many factors. High water temperature used in concrete production (Naganathan and Mustapha, 2015) or increasing the temperature and heating time (Toumi et al., 2009) may reduce the strength of concrete, while remixing (Alnaki et al., 2014) may improve it. Due to being highly durable against the influence of water, easy to manufacture in various shapes and relatively the cheapest material available to an engineer, concrete is one of the most widely-used construction materials.

Terminal 2E at Roissy at Charles De Gaulle Airport is a reinforced concrete complex structure consisting of three main parts: a main building, a boarding area and an isthmus linking these two buildings. The boarding area is formed by ten shells with a length of 650 meters. The shells are stiffened by curved steel ties which are braced to the two sides and held away from the shell by regular steel struts. Many incidents have appeared during construction, such as cracks in columns and near the fixation plates of the footbridges, spreading of the shell. Faddoul et al. (2013) proposed an approach for the optimization of inspection and maintenance for civil engineering projects. Part of Terminal 2E in the boarding area collapsed in 2004 and left four casualties after eleven months of its inauguration. The National Investigation Committee found that the load applied at the ultimate limit state was 4.5 times greater than the maximum permissible load. The Committee also reported the hasty way of construction, especially that the construction phase of the project was delayed for a month because of technical problems due to non-compliance with the normal construction rules. Therefore, according to the Committee, the failure was due to a lack in structural design and construction. Daou et al. (2019a) performed a reliability analysis of the

Received on 6/10/2020.
Accepted for Publication on 12/11/2020.

terminal and showed that the terminal represented deficiencies and was prone to failure in terms of long-term conditions. Moreover, the results of the probabilistic and reliability analysis performed by Daou et al. (2019b) showed that the required reinforcement ratio is greater than the existing ratio in the shell and the long-term deflection exceeds the admissible value. Therefore, the structure was not safe and presented deficiencies in terms of moment and long-term deflection. Kaljas (2017) demonstrated that the external tensile reinforcement geometry was ineffective because of its geometry, inadequate tensile side reinforcement placement and lack of strength and shear stiffness between tensile and compressive sides. Raphael et al. (2012a) also investigated the real reasons for the terminal collapse by performing a deterministic analysis using the ST1 software. The results showed that an inadequate modeling was made during the design phase, where the terminal's model was not detailed enough to be faithful to reality, especially about the non-classic block from the structural or architectural viewpoint and the calculations made have not taken the long-term effects of materials into account, such as creep, shrinkage and relaxation. The creep of concrete caused unexpected excessive deformations by the design office. El Kamari et al. (2015) modeled the terminal using ANSYS software and simulated a progressive collapse by reducing the rigidity of the yielded elements to explore the terminal's collapse. They obtained that the failure was due to the improper design of the terminal and insufficient prediction of creep.

Concrete creep and shrinkage play a significant role in the long-term performance of concrete structures (Barthélémy et al., 2015; Luzio et al., 2015; Raphael et al., 2012b, 2018; Zhu et al., 2020). Therefore, it is required to predict creep accurately to prevent such failure. There are many theories to explain the phenomenon of concrete creep, like viscoelasticity theory, seepage theory, viscous flow theory, micro-fractures theory and internal forces balance theory. At initial loading, the creep rate will gradually decrease over time, producing an elastic aftereffect after unloading and this can be explained by the viscoelasticity theory and viscous flow theory. The seepage theory explains the generation of the irreversible creep after unloading. When the loading stress exceeds the normal working stress range, the creep rate increases rapidly again with a nonlinear relationship of stress-strain. This can be explained by the plasticity theory and micro-cracks theory (Liu, 2014). This paper presents various methods used in ANSYS to take the effect of creep of concrete into consideration, applied to Terminal 2E. Creep methods presented in this paper are calculated for Terminal 2E, with a time frame of 365 days, exposed to a constant temperature and stresses within the elastic range.

The objective of this paper is to compare various creep calculation methods used to perform a time-dependent analysis of Terminal 2E using ANSYS. Methodologies of the linear and nonlinear viscoelastic theory and modified time hardening model are developed. Viscoelastic and creep models are calculated and assigned to the material properties. Therefore, a nonlinear finite element model of the terminal is carried out using ANSYS and time-dependent nonlinear analyses are performed.

NUMERICAL MODELING OF TERMINAL 2E

Overview of the Terminal

Terminal 2E at Roissy at Charles De Gaulle Airport is designed to handle more than 10 million passengers annually. The terminal consists of three buildings: the main building, the boarding area and the isthmus connecting these two buildings. The boarding area, where the collapse occurred, consists of 10 shells providing access to aircraft through the nine gates. Each shell is divided into 4 meters wide interlocking precast concrete arches of 30 cm thickness, 30 meters width and 26.2 meters span. The shell is stiffened with ties kept out through struts. The boarding area is surrounded by glass that provides natural light and is connected to the central area of the terminal by footbridges (see Fig. 1a).

On May 23, 2004, six arches from the boarding area suddenly collapsed leaving four casualties (see Fig.1b).

ANSYS Terminal 2E Model

Modeling a structure properly and realistically has always been a challenge facing designers and engineers. Nowadays, it gets easier due to the availability and development of finite element software, like ANSYS. ANSYS provides an accurate prediction of the component response that is subjected to different structural loads based on a finite element analysis. It is used for modeling composite concrete structures such as nonlinear behavior modeling of reinforced concrete members, which is very complicated due to nonlinearity of material or/and geometry. The nonlinearity of concrete is difficult to be truly modeled because of its complex stress-strain behavior (Avci and Bhargava, 2019). The geometric nonlinearity is encountered in the change of geometry in the elements during loading, such as slender members.

Nine arches including the collapsed ones are modeled using ANSYS taking into consideration the structure complexity, material nonlinearity, holes in the shell, asymmetry of the structure and applied loads (see Fig. 2). The terminal shell is modeled using the SHELL181 element. SHELL181 is suitable for analyzing thin to moderately-thick shell structures. The four-node shell element is based on Bathe-Dvorkin assumed transverse shear treatment, coupled with uniform reduced integration or full integration with enhancement of membrane behavior using incompatible modes. Several elastoplastic, hyperelastic and viscoelastic material models can be employed (Bhashyam, 2002). SHELL181 is well-suited for linear, large rotation and/or large-strain nonlinear applications. Struts and ties are modeled using the BEAM4 element. The loads considered in this analysis are self-weight, glazed roof and footbridges.

Materials' Properties

Concrete exhibits different behaviors in compression and tension. Modulus elasticity of concrete and tensile strength are calculated according to Eurocode 2, EC2 (CEN, 2004). Poisson's ratio is 0.2. The compressive uniaxial stress-strain behavior for concrete is considered as an elastoplastic model followed by a perfectly plastic response terminated at the onset of crushing (Shakir, 2016). The stress-strain relationship for concrete is calculated according to EC2, as shown in Fig.3. Concrete material properties are shown in Table 1. The steel has been assumed to be an elastic-perfectly plastic material and identical in compression and tension. Therefore, the stress-strain relationship adopted for steel bars is assumed to be elastic up to the steel yield stress, f_y, followed by linear hardening up to the steel ultimate, f_u. Poisson's ratio is 0.3 and the elastic modulus is equal to 210 GPa. The steel properties are described in Table 1.

Creep Modeling

Creep modeling aims to reflect basis features of creep in structures, including the evolution of inelastic deformations, redistribution of stresses, relaxation and local reduction of material strength. To consider the creep process, a specific constitutive model should be incorporated into the finite element software, thus the long-term structural behavior can be predicted and the critical zones of creep failure can be analyzed (Altenbach et al., 2007).

Viscoelastcicty Theory

The behavior of a viscoelastic material is represented by hypothetical models composed of viscous and elastic elements (Slanik et al., 2000). For stresses up to about 40% of the concrete strength, concrete can be described as a material with a linear viscoelastic behavior (Creus, 1986). In this case, creep generated from a constant load is a linear function of stress and the superposition principle may be applied (Veglianti and Sgambi, 2003; Wu et al., 2014).

(a) (b)

Figure (1): (a) View of the terminal and (b) Collapsed area of the terminal (El Kamari et al., 2015)

The creep analysis of concrete structures is sanctioned by different design code recommendations. The creep properties are defined by combining the creep coefficient, φ(t,t$_0$), with the elastic modulus of concrete (Bažant and Buyukozturk, 1988). The Effective Modulus Method (EMM) and Age-Adjusted Effective Modulus Method (AEMM) are computational methods that use the superposition principle. They are suitable for programming and provide sufficient accuracy.

- **Effective Modulus Method (EMM)**

The strain increment produced by creep is given by:

$$\Delta_{(i,,i-1)} = \frac{\Delta\sigma_{(i,i-1)}}{E_{c(i-1)}}\left(1+\varphi_{(i,i-1)}\right) + \sum_{j=1}^{i-1}\frac{\Delta\sigma_j}{E_{c(j)}}\left(\varphi_{(i,j)}-\varphi_{(i-1,j)}\right) \quad (1)$$

where (i,i-1) is the i time intervals, $\Delta\sigma_{(i,i-1)}$ is the stress increment of the i time intervals, $\varphi_{(i,i-1)}$ is the creep coefficient calculated according to EC2 and $E_{c(i-1)}$ is the elastic modulus of concrete at the i-1 time.

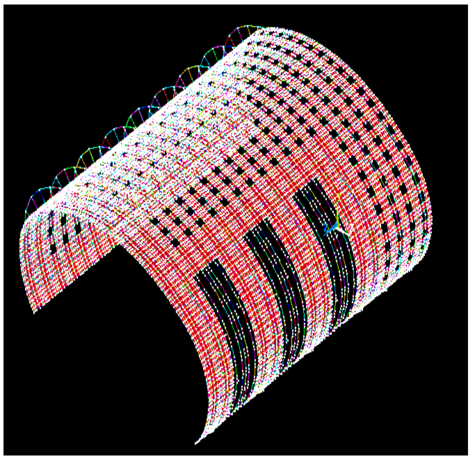


Figure (2): 3D view of ANSYS terminal model

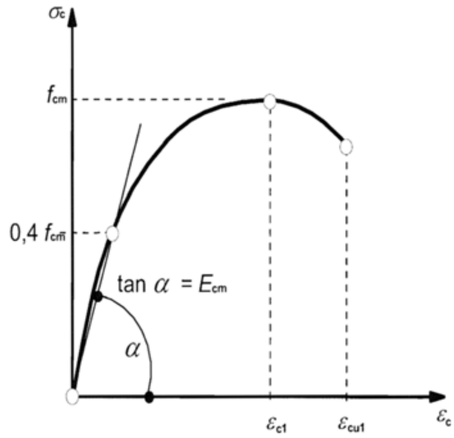


Figure (3): Schematic representation of the stress-strain relation for structural analysis (CEN, 2004)

Table 1. Properties of materials used in this study (Raphael et al., 2012a)

Concrete	Density	2.5 t/m^3
	Compressive strength	40 MPa
	Thermal expansion coefficient	10^{-5} K^{-1}
	Poisson's ratio	0.2
Steel	Density	7.85 t/m^3
	Yield stress	460 MPa
	Thermal expansion coefficient	10^{-5} K^{-1}
	Young's modulus	210 GPa
	Poisson's ratio	0.3

The effective modulus of elasticity, $E_{c,eff}$, takes the impact of the creep on the total relative strain into account. $E_{c,eff}$ is used instead of the modulus of elasticity, E_c and calculated using the following equation:

$$E_{c,eff\,(i)} = \frac{E_{c\,(i-1)}}{1+\varphi_{(i,i-1)}} \quad (2)$$

$$\eta_{(i,i-1)} = \frac{E_{c,eff(i)}}{E_{c(j)}}\left(\varphi_{(ij)}-\varphi_{(i-1,j)}\right); \quad j = 1, i-1 \quad (3)$$

where $\eta_{(i,i-1)}$ is the relaxation ratio.

For an element e with nodes a and b and length L in the i time interval, the node forces generated by creep are given in the following equations.

$$\Delta \boldsymbol{N}_{e(i,i-1)} = \sum_{j=1}^{i-1} \boldsymbol{\eta}_{(i,j)} \Delta \boldsymbol{N}_{e(j)} \quad (4)$$

$$\Delta M_{e(i,i-1)} = \sum_{j=1}^{i-1} \eta_{(i,j)} \Delta M_{e(j)} \quad (5)$$

$$\Delta V_{e(i,j)} = \frac{\Delta M_{a(i,j-1)} + \Delta M_{b(i,j-1)}}{L} \quad (6)$$

The final equilibrium equation of creep is:

$$[K_\varphi].\{\Delta\delta_\varphi\} = \{\Delta F_\varphi\} \quad (7)$$

where $[K_\varphi]$ is the creep stiffness matrix of the creep system, $\{\Delta\delta_\varphi\}$ is the creep displacement increment vector of solution and $\{\Delta F_\varphi\}$ is the node force vector of the creep system.

The solution process of Eq. 7 is carried out using ANSYS and the creep displacement increment and internal force increment are obtained at any time interval. The final value of the node forces and node displacements at the end of each time interval is the sum of the increments and the node force and node displacement at the beginning of this time interval. Accordingly, the following time interval is calculated based on linear superposition of the linear creep theory (Ge and Zhang, 2011).

- **Age-adjusted Effective Modulus Method (AEMM)**

AEMM is similar to EMM, but the strain increment produced by creep in this method is given by:

$$\Delta_{(i,i-1)} = \frac{\Delta\sigma_{(i,i-1)}}{E_{c(i-1)}}\left(1 + \chi_{(i,i-1)}.\varphi_{(i,i-1)}\right) + \sum_{j=1}^{i-1} \frac{\Delta\sigma_j}{E_{c(j)}}\left(\varphi_{(i,j)} - \varphi_{(i-1,j)}\right) \quad (8)$$

where $\chi_{(i,i-1)}$ is the aging coefficient which ranges between 0.3 and 1.5. For an approximate calculation, when the composition of concrete is not experimentally verified, one can take a value of 0.8 (Tvrdá and Drienovská, 2017).

AEMM defines an efficient concrete module dependent on the age, $E_{c,adj}$ and calculated as follows:

$$E_{c,adj(i)} = \frac{E_{c\,(i-1)}}{1 + \chi(i,i-1).\varphi(i,i-1)} \quad (9)$$

The relaxation ration is thus defined by:

$$\eta_{(i,i-1)} = \frac{E_{c,adj\,(i)}}{E_{c\,(j)}}\left(\varphi_{(i,j)} - \varphi_{(i-1,j)}\right); \quad j = 1, i-1 \quad (10)$$

The calculations of the node force vector of the creep system and the final equilibrium equation of creep are the same as shown in EEM (Eqs. 4-7).

The viscoelastic behavior for concrete has been investigated in several studies (Choi et al., 2010; Veglianti and Sgambi, 2003) and the long-term viscoelastic behavior of concrete, such as stress relaxation and creep, has been investigated for different types of concrete (Fan et al., 2013). Nonlinearity in the viscoelastic behavior of concrete may be due to high stresses or due to partial unloading. This type of behavior represents a transition between viscoelastic and plastic flow and should be taken into account in problems, such as creep-buckling, stress concentration and rupture under high dynamic loads (Creus, 1986). Viscoelasticity model implemented in ANSYS is a generalized integration form of Maxwell model, in which the relaxation function is represented by a Prony series. There are three sets of Prony progression model in ANSYS, including: shear response, volumetric response and shift function. The shear module and volumetric module in terms of Prony progression are expressed as:

$$G(t) = G_0\left[\alpha_\infty^G + \sum_{i=1}^{n} \alpha_i^G e^{-t/\tau_i^G}\right] \quad (10)$$

$$K(t) = K_0\left[\alpha_\infty^K + \sum_{i=1}^{n} \alpha_i^K e^{-t/\tau_i^K}\right] \quad (11)$$

where G_0 and K_0 are the instantaneous modulus of viscoelastic material, α_i^G and α_i^K are the relative modules, t is the time and τ_i^G and τ_i^K are the relative relaxation time of each Prony progression increment (Huanyun and Yang, 2012).

Any deformation (strain state) of a solid body can be divided into two parts: the volume-preserving part (incompressible) and the volume-changing part (volumetric). The shear modulus relates to the incompressible strains and the bulk modulus is related to the volumetric strains.

DETERMINING PARAMETERS OF PRONY SERIES

Prony series shown in Eq.11 and Eq.12 are calculated to accurately predict the viscoelastic behavior of concrete. The shear modulus, G, is calculated as a function of the modulus of elasticity, E and Poisson's ratio, υ, as shown in Eq.13.

$$G = \frac{E}{2(1+\upsilon)} \quad (13)$$

Prony series with three, five and seven parameters are defined for the shear modulus, G. The parameters α_i and τ_i are calculated using the Levenberg-Marquard algorithm. Fig. 4 shows the values of the shear modulus of the Prony series with 3, 5 and 7 parameters. It is shown that the Prony series with 5 parameters describes more successfully the shear modulus of concrete. Therefore, the Prony series used in this study for the shear modulus is defined in Eq.14.

$$G(t) = G_0\left(0.4 + 0.42e^{-\frac{t}{10.27}} + 0.18e^{-\frac{t}{136.18}}\right) \quad (14)$$

The bulk modulus, k, is calculated as a function of the modulus of elasticity, E and Poisson's ratio, υ, as shown in Eq.15.

$$K = \frac{E}{3(1-2\upsilon)} \quad (15)$$

K can be expressed as a function of the shear modulus, G, as follows:

$$K = \frac{2G(1+\upsilon)}{3(1-2\upsilon)} \quad (16)$$

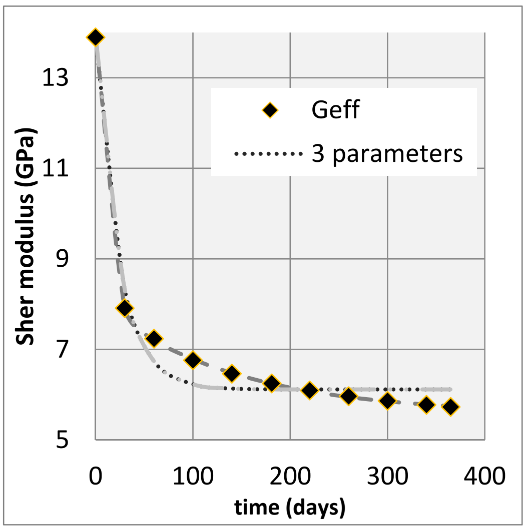


Figure (4): Shear modulus of Prony series as a function of time

Accordingly, the Prony series used in this study for the bulk modulus is defined in Eq.17.

$$K(t) = K_0\left(0.4 + 0.42e^{-\frac{t}{10.27}} + 0.18e^{-\frac{t}{136.18}}\right) \quad (17)$$

Creep Material Model

ANSYS creep law is an effective tool to take the effect of creep into account and is used in many studies to perform time-dependent analyses (Asraff et al., 2010, 2016; Minhas and Qin, 2013). ANSYS provides 13 creep equations to simulate the concrete creep effect through nonlinear material properties (Ge and Zhang, 2011). Fig.5 shows the three stages of creep strain due to a constant applied stress. The first time interval is the primary creep interval characterized by large deformation. In the second interval, there is a quasi-constant rate of deformation called secondary creep. Under large loads, creep crack occurs, which is in the third creep interval. ANSYS analyzes creep using two time integration methods: the implicit creep method and the explicit creep method.

The implicit creep method is fast, accurate, robust and recommended for general use. The explicit creep method is useful for cases where very small time steps are required (Wang et al., 2011). Therefore, libraries of creep strain rate equations are found in ANSYS under the implicit creep equations and explicit creep equations.

In this study, creep is calculated according to EC2 creep model over 365 days. Fig.6 shows the results of creep strain calculation for a specimen with a volume-surface ratio equal to the terminal volume-surface ratio, compressive strength of 40 MPa, age at loading of 28 days and stress of 40% of the compressive strength according to EC2 over 2000 days. As shown in Fig.6, it can be assumed that creep is under the first stage within 365 days. Moreover, the implicit creep method is used, since it is recommended for general use, especially with problems involving large creep strain and large deformation. The implicit method is also more accurate and efficient than the explicit method, because creep and plasticity are modeled simultaneously (no superposition). For the case when the stress is close to a steady-state, a time hardening rule is used (Kodur and Dwaikat, 2010; Li and Zhang, 2012). Therefore, the modified time hardening model (MTHM) (see Eq.18) is used for the calculation of the primary creep of Terminal 2E during 365 days.

$$\varepsilon = C_1 \sigma^{C_2} t^{C_3+1} e^{-\frac{C_4}{T}} / (C_3 + 1) \quad (18)$$

where ε is the creep strain, σ is the constant stress, t is the time and T is the temperature.

As the concrete is an isotropic material, the von Mises potential is used for creep analysis and the based solution technique used is the initial-stiffness Newton-Raphson method.

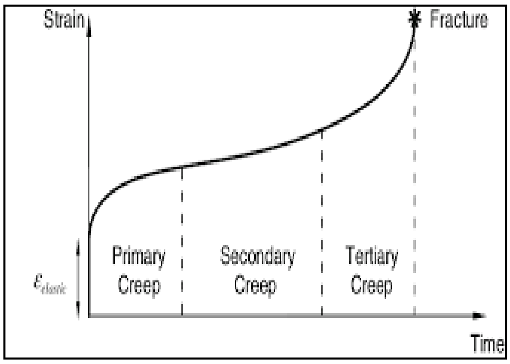


Figure (5): Creep strain due to a constant applied stress (Ceroni et al., 2015)

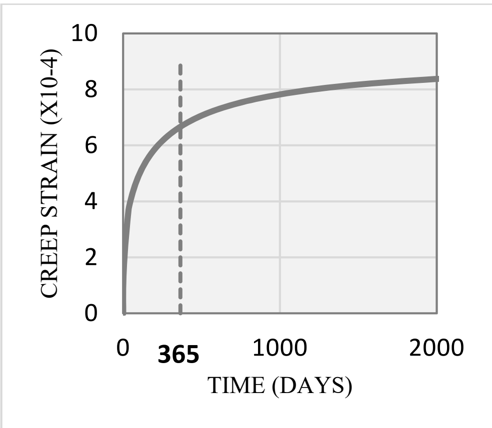


Figure (6): Creep strain *versus* time according to EC2

DETERMINING COEFFICIENTS OF ANSYS CREEP LAW

The ANSYS equation (see Eq.18) needs C_1, C_2, C_3 and C_4 to be provided as input for equation constants. For this study, the temperature term is ignored and C_4 is zero, making exp(-0) equal to 1.

Taking the natural logarithm of Eq.18 while holding stress constant yields the following:

$$\ln(\varepsilon) = (C_3 + 1)\ln(t) + c \quad (19)$$

where c is a constant.

For several applied stresses, the creep strain is calculated according to EC2 model. Fig.7 shows the natural log creep strain, ln(ε), plotted *versus* natural log time, ln(t), for the several applied stresses. Eq.19 is fitted through each applied stress and the slope (C_3+1) is determined. The average (C_3+1) is 0.2778, then C_3 is equal to -0.7222.

Similarly, the natural logarithm of Eq.18 while holding time constant yields the following:

$$ln(\varepsilon) = C_2\, ln(\sigma) + c \quad (20)$$

The creep strain is calculated for several stresses at one time according to EC2 model. Fig.8 shows the natural log creep strain, ln(ε), plotted *versus* natural log stress, ln(σ). Slope C_2 is determined and it is equal to 1.

The coefficient C_1 is determined by putting the value of C_2 and C_3 into Eq.18 along with creep strain calculated according to EC2 model. The average C_1 is 2.385E-12.

The creep strain model MTHM based on the calculated coefficients can be written as:

$$\varepsilon = 8.585 \times 10^{-12} \sigma t^{0.2778} \quad (21)$$

with time, t, in days and stress, σ, in Pa.

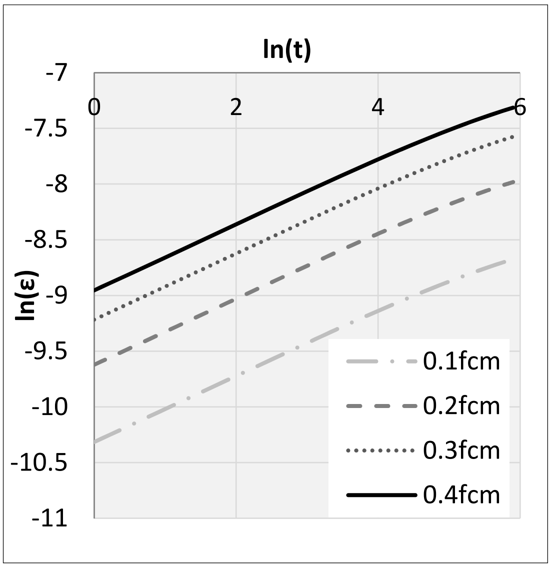


Figure (7): EC2 creep model results: ln(ε) *versus* ln(t)

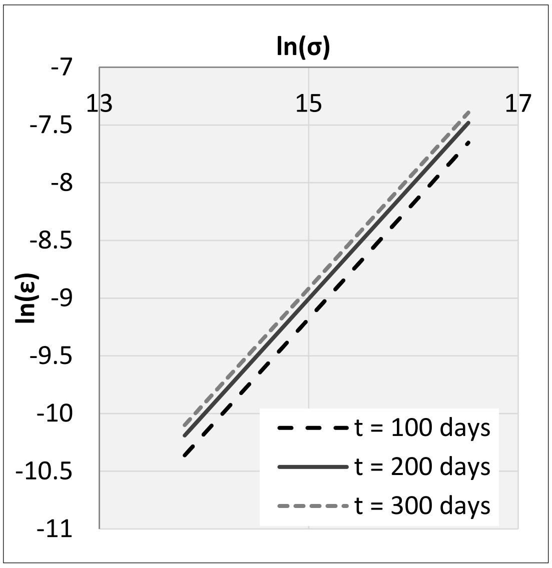


Figure (8): EC2 creep model results: ln(ε) *versus* ln(σ)

Fig. 9 shows the creep strain predicted according to EC2 model and the ANSYS model. Therefore, the modified time hardening represents EC2 creep model accurately over 365 days for a relative humidity of 60%, mean concrete compressive strength of 40 MPa and time at loading of 28 days of the terminal.

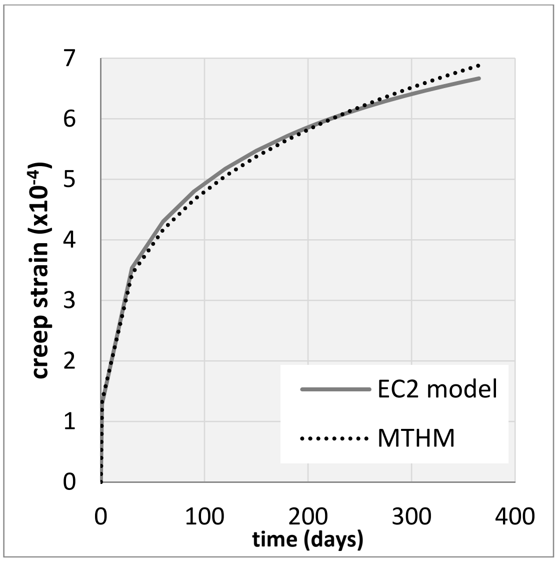


Figure (9): EC2 results compared to MTHM results

RESULTS AND DISCUSSION

A nonlinear analysis of Terminal 2E is carried out using ANSYS. Various methods are used in this study to investigate the effect of creep.

Viscoelastic Material Model

Effective Modulus Method

The first calculation of Terminal 2E was performed using the step-by-step method. In each investigated time step, the particular linear calculation was performed by assigning the appropriate effective modulus of elasticity method, EMM. The time at loading, t_0, was set at 28 days; therefore, $E_c(t_0)$ corresponds to the concrete modulus, E_{c28}. The time interval in which the strain was monitored was set to 365 days. The results of the creep coefficient according to EC2 are listed in Table 2. The time 0 in Table 2 refers to the moment of the introduction of load. The material properties are defined with the effective modulus of elasticity, $E_{c,eff}$ (see Table 2). The response of Terminal 2E was determined from the moment of the introduction of load, at the age of concrete 28 days; i.e., time of the introduction of load is $t_1 = 0$.

The results show that the maximum strain increases from 0.0005 at $t_1 = 0$ to 0.0021 after 365 days, while the maximum stress decreases from 19.6 MPa to 17.8 MPa. The maximum instantaneous deflection is approximately 5.8 cm and about 8.4 cm after 365 days. Therefore, an increase of 45% in the deflection has occurred after 365 days.

Age-adjusted Effective Modulus of Elasticity Method

The second analysis of Terminal 2E is also performed using the step-by-step method, but this time with the age-adjusted effective modulus of elasticity method, AEMM. The values of $E_{c,adj}$ are calculated for every step and listed in Table 2. Similarly to the first method, for every investigated time step, the linear calculation is performed by assigning the appropriate $E_{c,adj}$.

The results show that the maximum strain increases to 0.0019 after 365 days, while the maximum stress decreases to 17.9 MPa. Moreover, the maximum deflection after 365 days is 7.9 cm. This method results in an increase of 36% in the deflection after 365 days.

Prony Series

The Prony series calculated in Eq.14 for the shear modulus and in Eq.17 for the bulk modulus are defined for the viscoelastic properties of concrete. A relative modulus of 0.42 and 0.18 was assumed to have a relaxation time of 10.27 and 136.18 days, respectively. At the infinite time, 40% is the remaining percentage of the instantaneous modulus.

Based on the results, the maximum strain increases to 0.0013 after 365 days, while the maximum stress decreases to 17.7 MPa. Moreover, the maximum deflection after 365 days is 8.1 cm. Therefore, an increase of 40% in the deflection occurred after 365 days.

Table 2. Creep coefficient, elasticity modulus and shear modulus over time

Time (days)	$\phi(t,t_0)$	$E_{c.eff}$ (GPa)	$E_{c,adj}$ (GPa)
0	0.000	33.35	33.35
30	0.757	18.98	20.77
60	0.920	17.37	19.21
100	1.055	16.22	18.08
140	1.150	15.51	17.37
181	1.224	14.99	16.85
220	1.281	14.62	16.47
260	1.329	14.32	16.16
300	1.370	14.07	15.91
340	1.406	13.86	15.70
365	1.425	13.75	15.58

Modified Time Hardening Model

The fourth analysis is performed using the ANSYS creep law, MTHM, calculated in the previous section and shown in Eq.21. The equation coefficients are calculated according to EC2 creep model and are only specified for Terminal 2E, because these coefficients are calculated for a specified mean concrete compressive strength, f_{cm}, relative humidity, time at loading, t_0 and volume-surface ratio.

The evolution of the total and creep strain with time is shown in Fig.10. The creep strain increases significantly in the first days. After one year, the change in creep strain is not so significant. Therefore, the study of the creep for one year is sufficient to investigate its effect on the terminal response. The advantage of this method is that the creep strain can be displayed. The distribution of the creep strain of the terminal is shown in Fig. 11.

Based on the MTHM, the maximum strain increases to 0.0012 after 365 days, while the maximum stress decreases to 17.7 MPa. Moreover, the maximum deflection reaches 7.9 cm; thus, an increase of 36% occurred in the deflection after 365 days.

Fig.12 shows the results of the maximum deflection of Terminal 2E over time using these various methods. In the early days, the increase of deflection was considerable in all methods. According to EMM, the time analysis is similar to the elastic analysis in which $E_{c,eff}$ is used instead of E_c. Therefore, the creep strain at time t depends only on the stress at this time t, so it is independent of the previous stress history. This means that the aging of the concrete is ignored. For that, the EEM can give excellent results when the concrete stress is constant in time. Good results may also be obtained if the concrete is old when first loaded and the effect of aging is not significant. AEMM is similar to EMM, but it requires the calculation of $E_{c,adj}$ instead of $E_{c,eff}$. As shown in Fig. 12, AEMM is more conservative than EMM, since the aging coefficient χ is estimated. Therefore, this method could be used in case that more detailed knowledge on concrete is found. EMM gives results greater than the Prony series and MTHM, because the analysis is linear and does not take into account the nonlinearity of the stress-strain relationship. Based on the viscoelastic model, the increase in deflection is rapid in the beginning because of the exponential function in the Prony series. The response becomes asymptotic, showing that the maximum deflection at a time equal to 365 days' increases by 40% of the maximum instantaneous deflection. MTHM produces results differently from the viscoelastic material model in the early days, but after 365 days, it almost leads to the same results. Therefore, in this study, MTHM and Prony series gave approximately similar results in the long term. As the Prony series and MTHM take into account the nonlinearity of materials, they provide an effective tool in solutions from ANSYS for calculating the deformation of materials where stiffness changes as a function of loading, time and temperature. Noting that the Prony series is effective and limited to the elastic range, the creep law can also be used within the plastic zone.

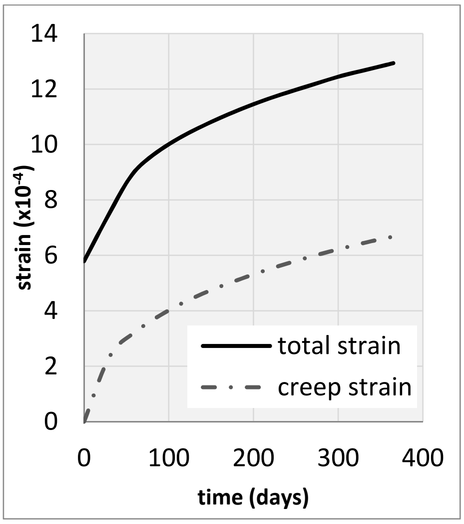


Figure (10): The evolution of the total strain and creep strain with time

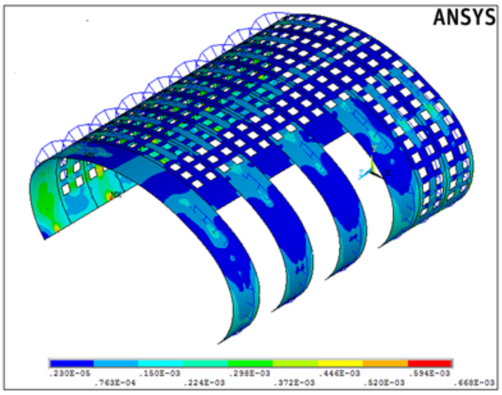


Figure (11): ANSYS creep strain of the terminal after 365 days

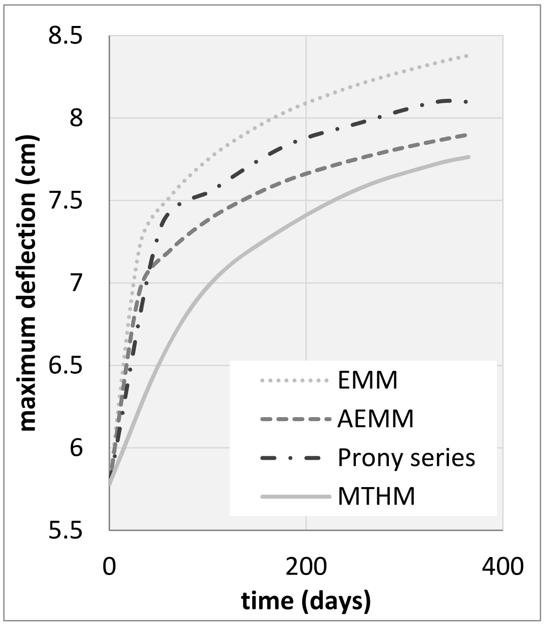
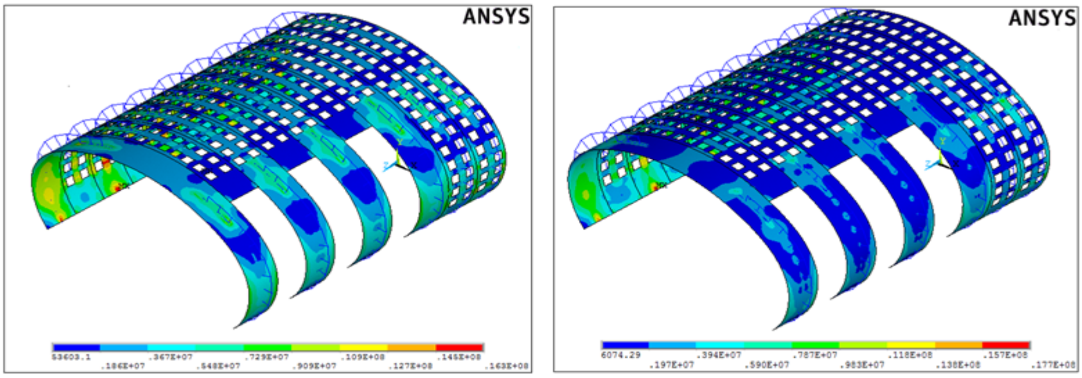


Figure (12): Maximum deflection of the terminal as a function of time using different creep analysis methods

Creep has an important effect on the deflection of Terminal 2E. According to MTHM, the maximum deflection after 365 days is 34% larger than short-time or elastic deflection. Therefore, the designers must make sure that the long-term deflections are tolerable. These excessive deformations resulted in excessive forces in the struts and therefore punching shear in the terminal shear. Fig.13 shows the instantaneous stress and the stress after 365 days. Creep also causes a redistribution of internal forces. These redistributions are sometimes favorable, because they tend to relax the maximum stresses, but are sometimes harmful. As shown in Fig.13, the maximum stress after 365 days is located at the fractured zone of Terminal 2E. The stresses produced by differences in creep among various parts of the terminal caused deleterious cracking, accompanied by degradation of terminal structural stiffness. Consequently, corrosion of reinforced may be promoted due to the ingress of water, which may cause spalling of concrete and ultimately a loss of serviceability of the terminal. Moreover, by altering the long-time stress state, creep indirectly causes a change in stress maxima for superimposed live loads. Therefore, and due to the limited ductility of concrete, creep exerted in this manner a significant influence on the brittle failure of the terminal. Hence, the importance of predicting accurately creep during the design phase is manifested to avoid structural failure.



(a) (b)

Figure (13): Terminal's stress (a) at time 0 (instantaneous) and (b) after 365 days

SUMMARY AND CONCLUSIONS

The time-dependent analysis of a concrete structure involves the determination of strains, stresses, curvatures and deflections at critical points and at critical times during the life of the structure. The objective of this paper was to compare various creep calculation methods used to perform time-dependent analysis of Terminal 2E at Roissy at Charles De Gaulle Airport, Paris. ANSYS software has several options for modeling the time-dependent behavior of materials. Time analyses were performed using the EMM, AEMM, Prony series and MTHM. A nonlinear finite element model of the terminal was implemented using the element finite software ANSYS and nonlinear analyses were performed to study the behavior of Terminal 2E.

The effective modulus of elasticity, EMM, is the simplest and oldest technique for including creep in structural analysis. It is based on the modulus of elasticity at 28 days from concreting. The age-adjusted effective modulus of elasticity, AEMM, is similar to the EMM, but it requires an aging coefficient. The degradation of the viscoelastic behavior of concrete with time was converted to the Prony series. The modified time hardening model, MTHM, was chosen from creep laws found in ANSYS. Procedures to calculate the coefficients of the Prony series and MTHM were described. The EEM is a simple method for the time analysis of concrete structures, but its use is limited to the case when the concrete stress is constant in time or if the concrete is old when first loaded and the effect of aging is not significant. The EMM linear viscoelastic material model overestimated the creep strain and therefore the maximum deflection was greater than the one obtained by the Prony series nonlinear viscoelastic material model. The AAEM is more conservative than the EEM, since the aging coefficient χ is estimated. Therefore, the AEMM may be used instead of the EEM in case that more detailed knowledge on concrete is found. The nonlinear viscoelastic material model (Prony series) gave approximately similar results to the ANSYS creep law used, MTHM. Prony series is effective and limited to the elastic range, while ANSYS creep law can also be used within the plastic zone.

Creep caused an increase in terminal strain after 365 days causing an excessive deflection. These excessive deformations resulted in excessive forces in the struts and therefore punching shear in the terminal shear. Creep also caused a redistribution of internal forces. These redistributions are sometimes favorable, because they tend to relax the maximum stresses, but are sometimes harmful. The stresses produced by differences in creep among various parts of the terminal caused deleterious cracking, accompanied by degradation of terminal structural stiffness. Moreover, by altering the long-time stress state, creep indirectly caused a change in stress maxima for superimposed live loads. Therefore, and due to the limited ductility of concrete, creep exerted in this manner a significant influence on the brittle failure of the terminal. Therefore, it is required to predict accurately creep during the design phase to avoid structural failure.

REFERENCES

Alnaki, A. A., Wegian, F. M., Abdalghafar, M. A., Alotaibi, F. A., Ali, I. A., Almurshed, M. M., and Alwan, A. B. (2014). "Assessment of the strength of remixed concrete structures." Jordan Journal of Civil Engineering, 8 (2), 227-238.

Altenbach, H., Naumenko, K., and Gorash, Y. (2007). "Numerical benchmarks for creep-damage modeling." Proc. Appl. Math. Mech., 7.

Asraff, A. K., Sheela, S., Paul, A., Mathew, A., and Savithri, S. (2016). "Cyclic stress analysis of a rocket engine thrust chamber using chaboche, voce and creep constitutive models." Transactions of the Indian Institute of Metals, Springer India, 69 (2), 495-500.

Asraff, A.K., Sunil, S., Muthukumar, R., and Ramanathan, T.J. (2010). "Stress analysis and life prediction of a cryogenic rocket engine thrust chamber considering low cycle fatigue, creep and thermal ratchetting." Transactions of the Indian Institute of Metals, 63 (2-3), 601-606.

Avci, O., and Bhargava, A. (2019). "Finite-element analysis of cantilever slab deflections with ANSYS SOLID65 3D reinforced-concrete element with cracking and crushing capabilities." Practice Periodical on Structural Design and Construction, 24 (1), 1-14.

Barthélémy, J.-F., Sellin, J.-P., and Torrent, J.-M. (2015). "The effects of long-term behavior of both concrete and prestressing tendons on the delayed deflection of a prestressed structure." CONCREEP 10, Vienna, Austria, 621-630.

Bažant, Z.P., and Buyukozturk, O. (1988). "Creep analysis of structures." Mathematical Modeling of Creep and Shrinkage of Concrete, 217-273.

Bhashyam, G. R. (2002). "ANSYS mechanical: A powerful nonlinear simulation tool." ANSYS, Inc.

CEN. (2004). "EN 1992-1-1, Eurocode 2: Design of concrete structures - Part 1-1: General rules and rules for buildings."

Ceroni, F., Pecce, M., Carloni, C., Leusmann, T., Budelmann, H., and Nigro, E. (2015). "Special problem." Design Procedures for the Use of Composites in Strengthening of Reinforced Concrete Structures.

Choi, S., Cha, S. W., and Oh, B. H. (2010). "Identification of viscoelastic behavior for early-age concrete based on measured strain and stress histories." Materials and Structures/Materiaux et Constructions, 43, 1161-1175.

Creus, G.J. (1986). "Representation of concrete's behavior." Viscoelasticity- Basic Theory and Applications to Concrete Structures, Springer-Verlag Berlin, Heidelberg, 64-82.

Daou, H., Abou Salha, W., Raphael, W., and Chateauneuf, A. (2019a). "Explanation of the collapse of Terminal 2E at Roissy–CDG Airport by nonlinear deterministic and reliability analyses." Case Studies in Construction Materials, 10.

Daou, H., Raphael, W., Chateauneuf, A., and Geara, F. (2019b). "Probabilistic assessment of structural safety of complex structures: Application to Terminal 2E at Roissy, CDG Airport." Procedia-Structural Integrity, Elsevier B.V., 22, 17–24.

El Kamari, Y., Raphael, W., and Chateauneuf, A. (2015). "Reliability study and simulation of the progressive collapse of Roissy Charles de Gaulle Airport." Case Studies in Engineering Failure Analysis, Elsevier, Ltd., 3, 88-95.

Faddoul, R., Raphael, W., Soubra, A.-H., and Chateauneuf, A. (2013). "Incorporating Bayesian networks in markov decision processes". Journal of Infrastructure Systems, 19 (4), 415-424.

Fan, L.F., Wong, L.N.Y., and Ma, G.W. (2013). "Experimental investigation and modeling of viscoelastic behavior of concrete." Construction and Building Materials, 48, 814-821.

Ge, J., and Zhang, H. (2011). "Practical method for concrete creep calculation based on ANSYS." Advanced Materials Research, 255-260, 1915-1919.

Huanyun, Z., and Yang, L. (2012). "Thermal stress analysis on steel bridge deck with epoxy asphalt concrete under low temperature based on viscous-elastic method." Advanced Materials Research, 598, 504-510.

Kaljas, T. (2017). "Reasons for Charles de Gaulle Airport collapse." Journal of Civil Engineering and Architecture, 11, 411-419.

Kodur, V.K.R., and Dwaikat, M.M.S. (2010). "Effect of high-temperature creep on the fire response of restrained steel beams." Materials and Structures, 43, 1327-1341.

Li, G. Q., and Zhang, C. (2012). "Creep effect on buckling of axially restrained steel columns in real fires." Journal of Constructional Steel Research, Elsevier, Ltd., 71, 182-188.

Liu, G. J. (2014). "Research on mechanism of concrete creep." Applied Mechanics and Materials, 670-671, 441-444.

Luzio, G. Di, Felicetti, R., and Cedolin, L. (2015). "Numerical and experimental study of creep and shrinkage in high-performance concrete." CONCREEP 10, Vienna, Austria, 128-137.

Minhas, Z.E.H., and Qin, S. (2013). "Evolution of the coefficient of dynamic viscosity with growing damage in metals." Applied Mechanics and Materials, 72-76, 313-314.

Naganathan, S., and Mustapha, K.N. (2015). "Effect of water temperature on concrete properties." Jordan Journal of Civil Engineering, 9 (3), 292-302.

Raphael, W., Faddoul, R., Feghaly, R., and Chateauneuf, A. (2012a). "Analysis of Roissy Airport Terminal 2E collapse using deterministic and reliability assessments." Engineering Failure Analysis, Elsevier, Ltd., 20, 1-8.

Raphael, W., Faddoul, R., Geara, F., and Chateauneuf, A. (2012b). "Improvements to the Eurocode 2 shrinkage model for concrete using a large experimental database." Structural Concrete, 13 (3), 174-181.

Raphael, W., Zgheib, E., and Chateauneuf, A. (2018). "Experimental investigations and sensitivity analysis to explain the large creep of concrete deformations in the bridge of Cheviré." Case Studies in Construction Materials, 9, e00176.

Shakir, Q.M. (2016). "Non-linear analysis of high-strength reinforced concrete beams with large openings." Jordan Journal of Civil Engineering, 10 (4), 451-461.

Slanik, M.L., Nemes, J.A., Potvin, M.J., and Piedboeuf, J.C. (2000). "Time domain finite element simulations of damped multilayered beams using Prony series representation." Mechanics Time-dependent Materials, 4, 211-230.

Toumi, B., Resheidat, M., Guemmadi, Z., and Chabil, H. (2009). "Coupled effect of high temperature and heating time on the residual strength of normal and high-strength concretes." Jordan Journal of Civil Engineering, 3(4), 322–330.

Tvrdá, K., and Drienovská, J. (2017). "Analysis of creep effects on a concrete beam using various software." Key Engineering Materials, 738, 79-88.

Veglianti, D., and Sgambi, L. (2003). "Approximate methods for analysis of viscoelastic behavior of concrete structures." Second International Structural Engineering Construction Conference, 6.

Wang, Q., Ren, Z., and Zhang, Z. (2011). "Research on the creep material nonlinearity of UEA expansive concrete." Advanced Materials Research, 89-92, 261-263.

Wu, X., Li, J., Yi, X.S., and Zhang, Z.C. (2014). "Numerical analysis of creep and longitudinal crack effects on PC bridge deflection." Applied Mechanics and Materials, 638-640, 969-972.

Zhu, L., Wang, J. J., Li, X., Zhao, G. Y., and Huo, X. J. (2020). "Experimental and numerical study on creep and shrinkage effects of ultra-high-performance concrete beam." Composites-Part B: Engineering, Elsevier, Ltd., 184.