A NEW CONCRETE CREEP MODEL WITH MINIMUM EMPIRICAL COEFFICIENTS

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Creep is a well-known property of concrete elements, which cannot be avoided. It is defined as an increase in deformations over time due to constant stresses at uniaxial compression. In general, linear and non-linear creep of concrete elements are considered. However, there are no strong dependences that govern these two types of creep. It is still not clear when linear creep becomes non-linear, how creep changes the concrete modulus of elasticity, which energy is dissipated by the concrete section at linear and non-linear creep, etc. Predicted creep values are important for accurate design of concrete elements at service and ultimate limit states. The present study analyzes linear and non-linear creep and proposes a creep effect algorithm. The methodology is based on Structural Phenomenon and new theoretical concepts, using just one empirical coefficient related to non-linear creep. It can be used by engineers in order to perform more accurate and rather simple design of concrete elements considering creep.

Keywords: *concrete creep; linear and non-linear creep; elastic and elastic-plastic potential of an RC system at creep; Structural Phenomenon*

1. Introduction

Approximately one-hundred years since concrete theory was developed, empirical coefficients still dominate in many properties of concrete as a material and structural element. Such an approach limits development of concrete theory in many aspects, including concrete creep. Let us analyze the present state of concrete creep theory from the viewpoint of modern design codes and recent scientific publications. The concrete creep problem is given special attention in existing design codes [1 – 5]. Although wide research on concrete creep has been carried out during the last century, design provisions still have a rather fussy character. The codes include experimentally-based solutions of such structural problems as:

- Linear creep coefficient value (φ_{cr}), which practically decreases linearly from 2.8 to 1.6 with increasing concrete class from C20 to C50, accordingly [1] (Figure 1) and the average value of linear creep coefficient, $\varphi_{cr\,m}$ is 2.2 (this value is close to 2.0 that is obtained theoretically according to Structural Phenomenon, which will be explained in a more detailed form below in section 3);
- Similarly, the value of concrete modulus of elasticity decreases proportionally to surrounding environment relative humidity (RH) from 1 for RH = 100% to 0.75 for RH = 40% [4]. The ratio of concrete modulus of elasticity for different RH values, E_c (RH), and initial concrete modulus of elasticity, E_c, are given in Figure 2;

Concrete creep deformation rate decays in time, asymptotically approaching zero value at 3 - 4 years [6] (Figure 3). Following EC 2 [1], linear creep coefficient depends on concrete element thickness.

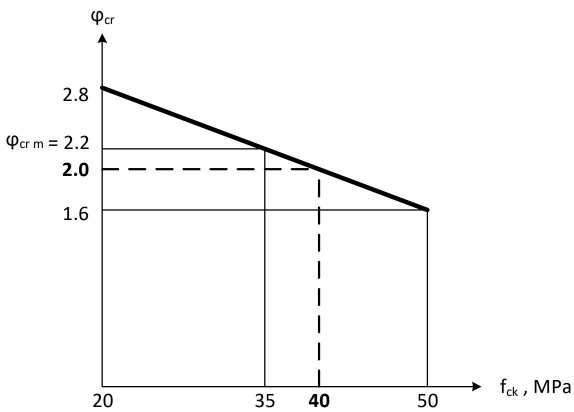

Fig. 1 - Linear creep coefficient, φ_{cr}, vs. concrete class following [1]: $\varphi_{cr\,m}$ = 2.2, based on Structural Phenomenon φ_{cr} = 2.

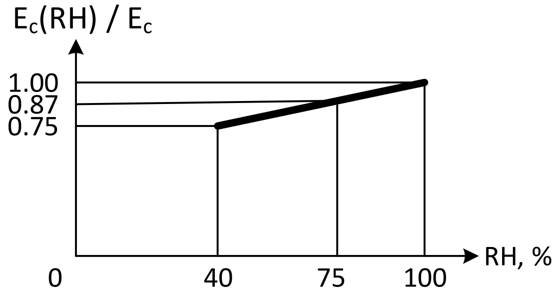

Fig. 2 - Concrete modulus of elasticity vs. surrounding environment humidity, RH, following [4].

The value of this coefficient, $\varepsilon_{cr} = \varphi_{cr}\ \varepsilon_c$, decreases asymptotically, from 3.0 to 1.8 (for element thickness of 50 mm), from 2.5 to 1.6 (for 150 mm) and from 2 to 1.2 (for 600 mm), as shown in Figure 4.

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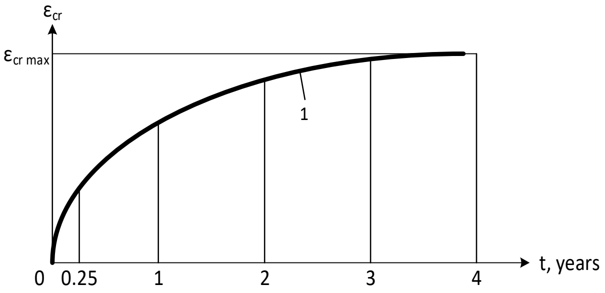

Fig. 3 - Asymptotic decay of concrete creep in time, following [6].

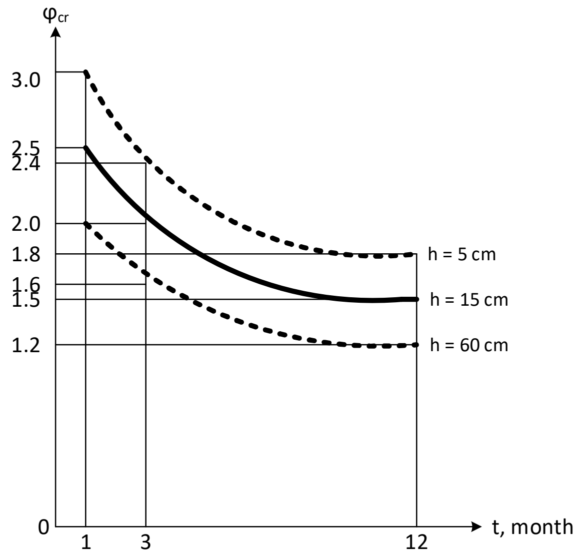

Fig. 4 -Asymptotic decay of concrete creep during the first 12 months, following [1]: for a typical thickness of 15 cm the average value of φ_{cr} = 2.

For most typical reinforced concrete (RC) element thickness of 150 mm (solid line in the figure), the average value of φ_{cr} is 2;

- Non-linear creep is considered by using the appropriate coefficient, φ_{nl} [1];
- Creep deformations increase linearly and become twice as high relative to the initial deformation [2], however this statement will be verified below;
- Linear creep takes place if compressed concrete stress is up to 0.315 f_{ck} [1, 2], however it will also be verified below.

The above mentioned models are based on experimental data. Our research presents a certain theoretical interpretation and explanation of those and other problems, using Structural Phenomenon and just one empirical coefficient, related to non-linear creep.

Basic research on concrete creep was carried out by Bažant, resulting in important creep theory concepts such as non-linear effect, influence of temperature and humidity, etc. [7]. These findings have generated corresponding practical solutions that became part of modern codes and have been used in structural design for many years.

Dependence of elastic modulus on loading duration at creep leads to asymptotic modulus for instant loading [8]. It was mentioned that common misconceptions in creep data, like initial strains, are incompatible with the elastic modulus. The importance of updating long-term predictions on the basis of short-time measurements on structures was emphasized.

Long-term deflections of cracked thin-walled RC flexural structures may cause delayed damage in non-structural elements [9]. The time-dependent response of cracked sections in creep leads to change of curvature, which yields corresponding redistribution of internal forces. A simplified method for the calculation of long-term curvatures and deflections in flexural members was proposed. Constant stress in the tensile reinforcement was assumed, according to experimental and numerical results on cracked section time-dependent behavior. Good agreement was obtained with the available literature results of 217 previously tested beams. It was concluded that creep coefficient empirical formulae can be simplified using the proposed method.

Creep deformations monitoring of a 32 m precast pre-stressed concrete simply supported box girder was performed [10]. The creep development was obtained and the factors influencing concrete creep were further analyzed using ANSYS finite element software. The obtained results provided a basis for long-term deformation control of creep by comparing the numerical results with the experimental data. However, a pure theoretical model of concrete creep deformations was not proposed.

Most of the existing prediction models cannot accurately reflect structural concrete creep. An innovative creep analysis method was recently developed [11]. Parameters in the fib MC 2010 creep model have been used with respect to the long-term loading test results of the pre-stressed concrete beam. The measured strains of concrete and the mid-span deflections of the test beam were compared with the predicted results using the fib MC 2010 creep model. The predicted results were in good agreement with the experimentally obtained ones.

The existing creep models in concrete are empirical in nature and are based on available experimental data [12]. A coupled hydro-thermo-mechanical formulation was proposed to model creep of concrete structures. Uncertainty methods based on a probabilistic framework were used. A distance measure-based response sensitivity analysis was adopted to identify the maximum impact on the output responses. The predicted concrete creep values were compared with available experimental data. This technique was used for predicting the long-time pre-stress losses in post-tensioned concrete beams and slabs.

It is important to accurately estimate creep empirical coefficients in concrete structures. Based on the experiments on creep of the plain concrete, applicability of different creep models for high-strength concrete was evaluated [13]. It was reported in the literature that the accuracy of creep prediction can be enhanced by carrying out short-term creep measurements on the given concrete and modifying the prediction model parameters for long-term creep.

Thus, in our opinion, the known creep models are based on empirical coefficients and have little strong theoretical basis. The present study is focused on developing a proper theoretical model of concrete creep. It is based on an idea, called the "Structural Phenomenon", that was proposed by the authors in 2016 [14]. Based on this idea, some theoretical problems were solved that had an empirical basis (for example, transverse deformations, stress–strain model for compressed composite cement materials, etc.) [15 - 17].

2. Main Hypotheses, Aims, Scope and Novelty

The following main hypotheses are used in this research

- according to modern codes, concrete creep increases up to 4 - 5 years [4, 5] and after that it asymptotically approaches to a constant value;
- uniaxial concrete compression at constant stress is assumed;
- concrete creep increases as an exponential curve that becomes practically parallel to the time axis [6].

At the moment, different empirical coefficients are used in various design codes and in research. This situation does not allow for development of a common creep theory. The main aim of this research is to develop a creep model with minimum empirical coefficients (in fact, only one coefficient of non-linear creep will be used). The present study deals with ordinary concrete classes up to C 50. The proposed model does not deal with the surrounding environment humidity and concrete mixture proportioning aspects.

The present research novelty includes the following aspects:

- as a basis for concrete creep values, a relationship between concrete stresses and strains is used that was previously obtained by the authors [16];
- a relationship between σ_c and ε_c was developed separately for two pieces of the stress-strain graph.
- for the linear piece, $0 \le \sigma_c \le 0.5\, f_c$, $0 \le \varepsilon_c \le \varepsilon_{c\,el}$ and the parabolic part is given as $0.5\, f_c \le \sigma_c \le f_c$, $\varepsilon_{c\,el} \le \varepsilon_c \le \varepsilon_{c1}$;
- the stress-strain relationship has a border between the linear and non-linear parts that corresponds to the ultimate concrete stress of $0.5\, f_c$;
- the maximal elastic deformation of concrete is 0.5 ‰, the ultimate elastic deformation *is* 1 ‰;
- consequently, concrete creep is defined as a linear or non-linear process: if concrete creep is within deformations of $\varepsilon_c \le 0.5$ ‰, then there are no non-linear deformations of concrete.

This definition allows considering separately linear and non-linear creep deformations;

- presence of elastic potential of a system at linear creep and elastic-plastic potential at non-linear creep are revealed;
- it is shown that concrete creep deformations can be used as one of the indicators for reinforced concrete structures repairing efficiency and/or necessity.

3. Essence of Structural Phenomenon

The Structural Phenomenon [14] is based on analysis of available experimental and theoretical data, obtained for different structures (beams, frames, spatial structures and structural joints) under static or/and dynamic loadings. The phenomenon was analyzed for the following groups of experiments:

- investigation of structural concrete at material level;
- behavior of reinforced concrete structures and elements under static loads;
- response of reinforced concrete structures and elements to dynamic loads.

The phenomenon is valid for various design parameters at the ultimate limit state of a structure or its elements.

The phenomenon enables:

- to predict the ultimate limit states by strength and deformation parameters of the structure from the viewpoint of load bearing capacity and serviceability;
- to assess the limit changes of strength and deformation parameters in buildings before beginning their real design;
- to find the theoretical limit values of a compressed reinforcement section in the bending element at the ultimate limit state;
- to find the level of structural load bearing capacity under a strong earthquake;
- to reveal the stage when the structural static scheme is changed (for example, due to formation of plastic hinges), etc.

The advantage of using the phenomenon from the mathematical viewpoint is the possibility to obtain additional equation(s), enabling the calculation of parameters, which are usually obtained using some empirical coefficients that are different in various design codes. At the same time, as previously demonstrated by the authors [14], the above - mentioned changes of structural parameters are limited twofold (increasing or decreasing). These limits can be demonstrated by the data, shown, for example, in Tables 1 and 2. The tables demonstrate the essence of the

Table 1

Values of $\varepsilon_{c\ el}$ vs. f_c according to [1] and [2].

f_c, MPa		20	30	40	50
	[1]	0.9	1.21	1.37	1.57
$10^3\ \varepsilon_{c\ el}$	dolomite aggregate	0.754	1.035	1.275	1.496
	chalky aggregate [2]	0.84	1.15	1.42	1.666

Table 2

Deflections [cm] in a full scale RC shell vs. damping ratios (following [14]).

Earthquake type	Damping ratio, %						
	0	2	4	6	8	10	12
Low frequency	2.50	2.25	2.21	2.15	2.09	2.05	2.00
Medium frequency	3.63	2.38	2.23	2.17	2.10	2.06	2.00
High frequency	4.40	3.32	2.81	2.63	2.41	2.30	2.19

phenomenon, for parameters of the structure that were measured experimentally under static or/and dynamic loadings increase or decrease by about a factor of two.

Thus, the phenomenon provides valuable indicators for experiment planning, estimation of structural state (elastic, elastic-plastic, plastic or failure), evaluating possibilities of retrofitting, etc. Therefore, using this phenomenon can lead to developing proper design concepts in which the number of empirical design coefficients will be minimal.

4. Linear Creep of Compressed Concrete and its Elastic Potential

Following modern design codes that were reviewed in section 1.1, linear concrete creep is a function of various variables [1 – 5]:

$$\varepsilon_{cr} = f(\text{C}, \varepsilon_c, t, \text{RH}, h, etc.) \quad (1)$$

where C is concrete class from 20 to 50;

ε_c is deformations of compressed concrete;

t is time (years or months);

RH is the surrounding environment humidity;

h is the element thickness.

This study is focused on the main parameter - concrete compression deformations at creep (without considering humidity and structural elements dimensions).

According to Structural Phenomenon [14], maximum linear creep corresponds to an up to twofold increase in compressed concrete deformation:

$$\varepsilon_{cr\ max} = 2\ \varepsilon_c \quad (2)$$

which explains theoretically and verifies the empirical approach used in most design codes.

The linear concrete creep limits, at which the creep initiates and ends within elastic deformations only, are as follows:

$$0 \leq \varepsilon_c \leq 0.5\ ‰ \quad (3)$$

Here, following [16] the value of

$$\varepsilon_{c\ el\ max} / 2 = 0.5\ ‰ \quad (4)$$

And $\varepsilon_{c\ el\ max}$ = 1 ‰ is the potential ultimate elastic deformation of concrete in compression.

At the same time, considering Eqs. (2 and 3), when creep deformations appear, linear creep zone increases up to twice:

$$\varepsilon_{cr\ p} = 2\ \varepsilon_{c\ el} = 1‰ \quad (5)$$

and $\varepsilon_{cr\ p}$ denotes the twofold increase up to achieving the concrete elastic potential at linear creep.

This fact is defined as elastic linear creep potential and it is one of the novelties of this research.

The above-mentioned equations can be illustrated by Figure 5: line segment Ob characterizes elastic behavior of concrete at compression; part ab characterizes the elastic linear creep potential, related to Eq. (5); point b corresponds to the ultimate elastic behavior of concrete at compression [16]. Figure 5 is obtained, based on the known equation from EC2 [1]:

$$\varepsilon_{cr} = \varphi_{cr} \varepsilon_c \quad (6)$$

where φ_{cr} is creep coefficient.

In our study, according to Structural Phenomenon [14],

$$\varphi_{cr} = 2 \quad (7)$$

At the same time, point b in Figure 5 is located on the border between linear and non-linear creep. This point corresponds to $\varepsilon_{c\ el\ max} = 1‰$ in the usual stress-strain relationship of concrete (point c in Figure 6) and it is an existing theoretical value that is presently not used in concrete theory. It is also a novelty of the present study. This fact enables the increase

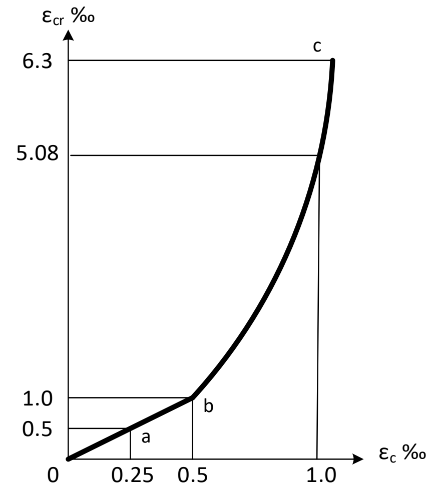

Fig. 5 - Concrete creep deformations, ε_{cr}, vs. compressed concrete deformations, ε_c: oa – linear creep; ab – additional linear creep based on elastic potential of compressed concrete; bc – non-linear creep.

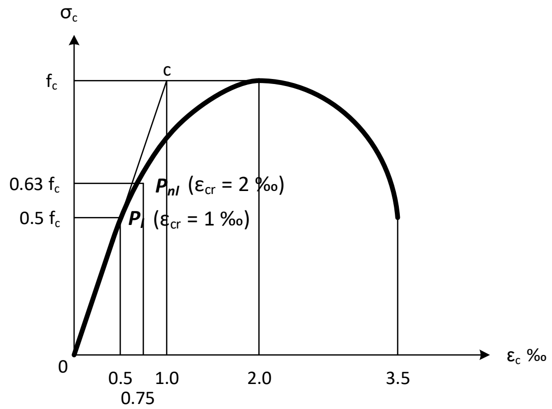

Fig. 6 - Concrete stress – strain diagram, following [16]: P_l and P_{nl} are elastic and plastic potentials of concrete that are evident for linear and non-linear creep, respectively.

of the linear creep zone for design purposes and provides additional possibilities for analysis of concrete behavior at long term loading. P_l in Figure 6 corresponds to the beginning of concrete elastic potential at linear creep and line P_l - c on the graph demonstrates this potential. Further non-linear deformations will begin. This will be discussed in the following section.

5. Non-Linear Creep and its Plastic Potential

When deformations of compressed concrete

$$\varepsilon_c \geq 0.5‰ \tag{8}$$

non-linear creep appears at long term loading. Following [1], non-linear creep appears if

$$\sigma_c \geq 0.45 f_{ck} \tag{9}$$

The value of 0.45 is empirical. According to [2] this value is equal to 0.315 and following our previous investigations [16], it should be equal to 0.5.

According to Eq. (8) and Figure 6, non-linear creep appears when

$$\sigma_c > 0.5 f_{ck} \tag{10}$$

The difference between Eqs. (9) and (10) is explained by the fact that according to Structural Phenomenon [14] and similar to the case that was studied by the authors for the stress-strain model of compressed concrete [16], elastic-plastic deformations of concrete begin at

$$\sigma_c = 0.5 f_{ck} \tag{11}$$

At the same time, for developing the non-linear creep model in the frame of this research, only one empirical equation is used, based on [2]:

$$\varphi_{nl} = \varphi_{cr}\, e^{[1.5(k_\sigma - 0.45)]} \tag{12}$$

Here $k_\sigma = \sigma_c / (0.7 f_{ck}) = 1.43\, \sigma_c / f_{ck}$. Substituting Eq. (11) leads to $k_\sigma = 0.715$ and $1.5(k_\sigma - 0.45) \approx 0.4$. Therefore, Eq. (12) takes the following form:

$$\varphi_{nl} = \varphi_{cr}\, e^{0.4} \approx 1.5\, \varphi_{cr} \tag{13}$$

Based on this equation, a curve for non-linear creep was obtained (part bc in Figure 5). At ultimate elastic deformation of concrete ε_c = 1 ‰ the ratio $\sigma_c / f_{ck} = 0.75$ [16], $k_\sigma = 1.07$, $\varepsilon_{cr} = 5.08$ (point c in Figure 5), $\varphi_{nl} = 2.04\, \varphi_{cr}$. Increasing the value of ε_c leads to non-linear creep deformations according to the theoretical model approach to infinity. We have stopped the analysis at ε_{cr} = 6.3 ‰ (see Figure 5). It should be mentioned that this figure presents linear creep deformations (line oab) and non-linear ones (line bc).

In a common case, compressed concrete non-linear creep deformations, ε_{nl}, can be calculated using Structural Phenomenon [14] as follows:

$$\varepsilon_{nl} = 2\, \varphi_{nl}\, \varepsilon_c \tag{14}$$

As the difference between linear and non-linear creep is rather big and the ultimate elastic-plastic deformation of concrete $\varepsilon_{c\,max}$ = 2 ‰ (see Figure 6), it is desired to avoid non-linear creep in reinforced concrete structures at long term loading. It is especially important for pre-stressed concrete structures, in which the pre-stress losses rapidly increase at $\sigma_c / f_{ck} > 0.5$, i.e. at non-linear creep. Therefore, an additional novelty of this study is that the value of $\sigma_c / f_{ck} = 0.5$ can be used as one of the limit states for deformations of pre-stressed concrete structures. This is explained by the fact that when $\sigma_c / f_{ck} > 0.5$, it leads to non-linear deformations of compressed concrete, which in turn yields sharp increase in losses of pre-stress.

Similar to linear potential in case of linear creep, for non-linear creep there is a non-linear potential, when deformations in compressed concrete $\varepsilon_c \geq$ 1 ‰. In this case creep deformations

$$\varepsilon_{cr} \geq 2 ‰ \tag{15}$$

Though the compressed concrete section is in a non-elastic stage, the element continues to serve under external loads.

The non-linear creep problem is directly related to reliability of structures and their strengthening. Presently, this issue is discussed just from the viewpoint of strength, crack resistance, etc. Our approach allows considering also non-linear creep deformations as a calculated factor that enables us to decide if the building should be repaired or demolished. As it will be shown below, in case of non-linear creep, the initial modulus of elasticity can decrease up to 3 … 5 times, which can be higher than the allowable deformations of the structure.

6. Concrete Modulus of Elasticity and Creep Deformations

As concrete stresses at long term loading are constant and deformations increase with time, concrete creep significantly decreases its initial modulus of elasticity. Figure 7 shows the dependences of the relative modulus of elasticity (E_{cr} / E_c) vs. deformations at ordinary compression (right part of the graph) and creep deformations (left part of the graph).

Considering the relationship between concrete stresses and strains (see Figure 6), it is evident that if at ordinary compression in the elastic stage concrete modulus of elasticity remains constant (see dashed line between $\varepsilon_c = 0$ and $\varepsilon_c = 0.5$ ‰ in Figure 7), for linear creep at the same deformations the value of modulus of elasticity decreases twice, which corresponds to the Structural Phenomenon [14]:

$$E'_{cr} = E_c\, \varepsilon_c / \varepsilon_{cr} = 0.5\, E_c \quad (16)$$

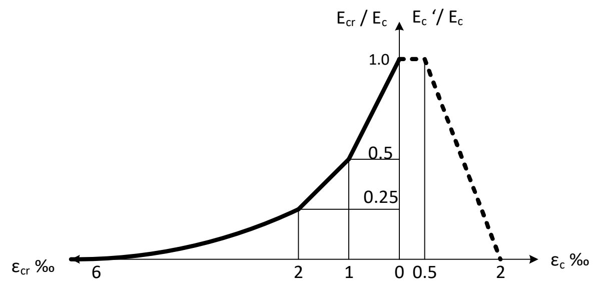

Fig. 7 - Concrete modulus of elasticity vs. concrete deformations, ε_c, and concrete creep deformations, ε_{cr}: E_{cr} / E_c = 0.5 is the border between linear and non-linear creep.

In Figure 7 and Eq. (16) E_{cr} is the modulus of elasticity of concrete in the beginning of the creep process; E'_c is the modulus of deformations of concrete when σ_c / f_{ck} > 0.5 [16]; E'_{cr} is the modulus of deformations of concrete during the creep process.

At further increase in compressed concrete deformations (ε_c > 0.5 ‰) non-linear creep takes place (see Figure 7). Correspondingly, a sharp increase in concrete modulus of elasticity is evident:

- When concrete creep deformations ε_{cr} = 2 ‰ (ε_c = 1‰), the relative modulus of elasticity decreases 4 times;
- At ε_c = 0.75 ‰ the value of ε_{cr} = 0.75 ϕ_{nl} = 0.75 · 6.3‰ = 4.875 (see Figure 5), i.e. the modulus of elasticity decreases up to 1 / 4.875 = 0.205 E_c;
- Further development of creep deformations over ε_{cr} = 2 ‰ yields an exponential decrease in the initial concrete modulus of elasticity;
- Theoretically at $\varepsilon_{cr} \approx$ 6 ‰ the relative modulus of deformations approaches to zero.

Following the design codes [4], at normal humidity E_c' = 0.319 E_c and at low humidity E'_c = 0.212 E_c. Thus, the calculated values that were presented above correspond to these data.

7. Energy Dissipation Capacity and Ductility

Concrete creep requires higher energy dissipation capacity, compared to ordinary compression (Figure 8). For example, at elastic deformation in case of ordinary compression, the elastic energy (see the right part of the figure) is

$$En_{el} = 0.5 \cdot 0.5 \cdot 0.5 \text{ ‰} = 0.125 \text{ ‰} \quad (17)$$

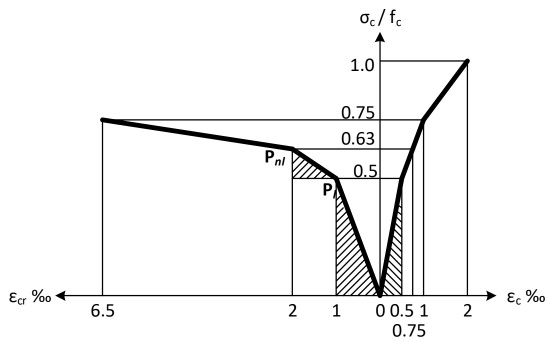

Fig. 8 - Compressed concrete stress vs. concrete deformations, ε_c, and concrete creep deformations, ε_{cr}: P_l and P_{nl} are elastic and plastic potentials of concrete; σ_c / f_c = 0.5 is the border between linear and non-linear creep (the hatched areas correspond to creep energy (left part of the figure) and compressed concrete energy (right part).

At the same time, under linear creep (see the left part of the figure)

$$En_l = 0.5 \cdot 0.5 \cdot 1 \text{ ‰} = 0.25 \text{ ‰} \quad (18)$$

i.e. the energy dissipation capacity increases twice. This is the “price” paid by the compression element at long term loading, which corresponds to the Structural Phenomenon [14]. A similar situation occurs when concrete deformations are between

0.5 to 0.75‰. Further increase of compression deformations corresponds to non-linear creep, and the energy dissipation capacity increases exponentially.

The above-mentioned calculations enable us to obtain the section ductility coefficient, μ. At linear creep μ = 1. At non-linear creep

$$\mu = 1 + En_{nl} / En_{l} \qquad (19)$$

where En_{l} is calculated according to Eq. (18).

En_{nl} is energy dissipation capacity in a non-linear stage, which is taken according to Figure 8, i.e. the non-hatched area in the left part of the figure under the graph of σ_c / f_c vs. ε_{cr}.

8. Creep Effect Algorithm

Considering the above-proposed methodology, the following algorithm was developed in order to allow the designers to use the proposed concepts for practical implementation (Figure 9). At the initial stage data available in modern design codes, Structural Phenomenon and static analysis should be prepared. These data should include E_c, σ_c, ε_c, etc. Further design depends on the section behavior stage: elastic stage (left part of the algorithm) and elastic-plastic stage (right part). At each of these stages the following factors should be estimated:

- section modulus of elasticity and its dependence on the surrounding environment humidity;
- coefficient of linear or non-linear creep;
- linear or non-linear creep potential;
- energy dissipation capacity for the corresponding case;
- section ductility;
- maximum values of deformations at linear or non-linear creep.

On this basis, the designer can predict the creep effect in the section.

The proposed creep model is a theoretical one and further experimental research should be carried out to verify it for different cases.

9. Conclusions

The present study is focused on developing a theoretical model of concrete creep. It is based on Structural Phenomenon that enables the solving of some theoretical problems that had an empirical basis. The research results include a new creep model with minimum empirical coefficients related to non-linear creep.

For the first time in concrete creep theory, definitions of elastic and plastic potentials of a system were given for linear and non-linear creep

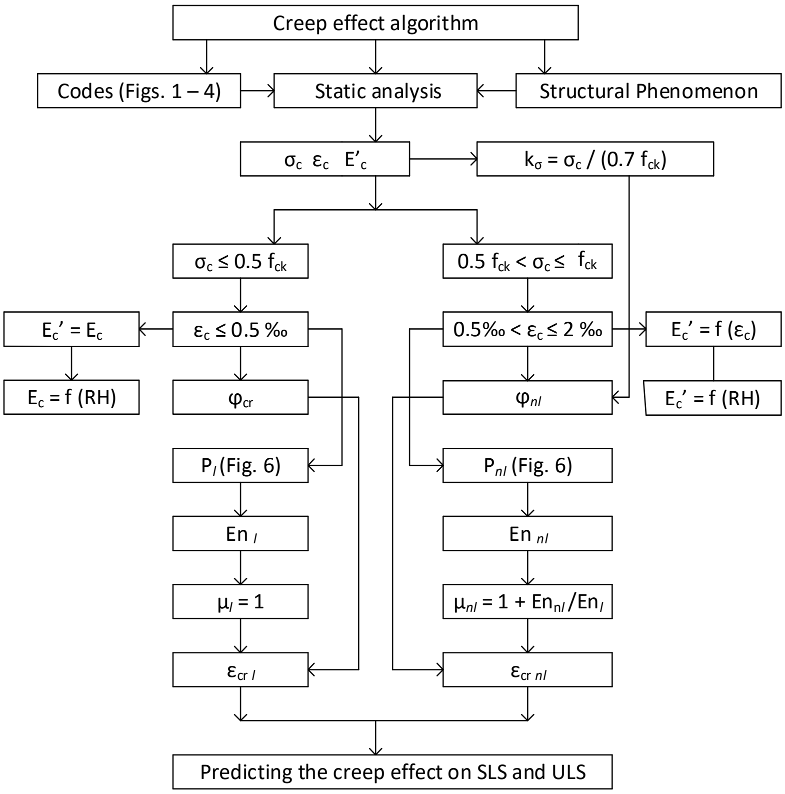

Fig. 9 - Creep effect algorithm.

correspondingly. It was shown that concrete creep deformations can be used as one of the indicators for reinforced concrete structure repair efficiency and/or necessity.

A strict separation was made between linear and non-linear creep, and the point on the border between them was proposed to be used as an additional theoretical value for design of concrete elements. It was also proposed to use the value of σ_c / f_{ck} = 0.5 as one of the limit states for deformations of RC structures.

Considering the relationship between concrete stresses and strains, it is evident that if at ordinary compression in the elastic stage, the concrete modulus of elasticity remains constant, for linear creep at the same deformations the value of the modulus of elasticity decreases twice, which corresponds to the Structural Phenomenon.

The initial modulus of elasticity can decrease up to 3 … 5 times, which can be higher than the allowable deformations of the structure. This fact should be considered in structural design.

It can be assumed that the non-linear creep problem is also related to structure reliability, but it still requires further investigation.

Based on the proposed methodology, an algorithm was developed to allow designers to use these concepts for practical implementation.

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