

Modeling of concrete thermal power resistance during the high-temperature heating

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Abstract. A model of concrete deformation under the high temperature heating in a loaded state is proposed. It reflects the physical nature of deformation has a rather compact form and requires a minimum number of normalized parameters. In order to describe the curve of concrete deformation and temperature parameters change exponential relationships were assumed and calibration of their coefficients was performed.

1. Introduction

In case of fire, reinforced concrete structures are subjected to non-stationary high-temperature fire impact in the loaded condition. However, the diagrams of concrete deformation that are necessary for calculations can be obtained in direct form from the test results before the destruction of preheated samples as well as at the normal temperature, (heat-then-load regime, HTL, Figure 1). Tests of preloaded samples under the nonstationary heating are closer to the real working conditions of concrete in structure (load-then-heat regime, LTH, Figure 2).

A comparison of the large amount of test results revealed that the concrete deformation under heating in a loaded state is approximately twice as high as the loaded one after heating [1]. It is usually associated with the Load Induced Thermal Strain (LITS), which is also called Transient Thermal Creep (TTC), Transient Thermal Strain (TTS), Drying Creep, etc.

In the scientific and regulatory literature there is a large amount of options for representing the correlation between strain and stress of concrete under the short-term high-temperature heating. These options differ by the normalizing temperature parameters, recording the stress-strain relationship, the inclination angle of the descending branch, etc. But when modeling the thermal strength of concrete, it is important not only to offer an adequate mathematical model, but also to consider the conditions in which its initial characteristics were obtained.

2. Deformation of concrete under transient heating in a loaded state

The first experimental evidence of LITS appeared in 1960s. A detailed review of the studies that took place before the mid-1980s was prepared by Khoury et al. [2], the results of later experimental and analytical work on LITS in uniaxial and multiaxial conditions are contained in a review by Torelli et al. [3]. The experimental data indicates that LITS occurs only on the first heating and does not depend on the heating rate when it varies within 1-15 °C / min.

The reason for the LITS occurrence is generally associated with the movement of moisture in uninsulated concrete samples, as well as with chemical reactions and microstructural changes occurring in cement stone, such as dehydration, drying and rearrangement of water molecules.



Typically, the same factors are pointed out as the reasons for the concrete Young modulus reduction under heating.

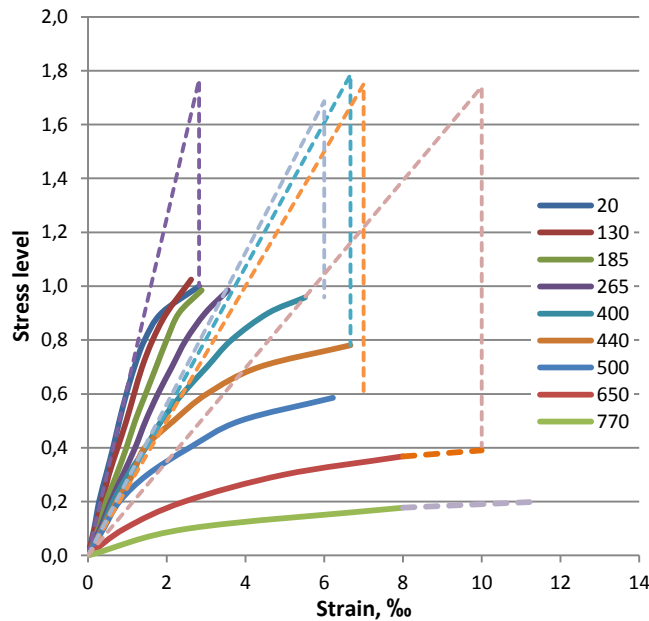


Figure 1. Diagrams of deformation at different temperatures (loading after heating). Experimental data [1].

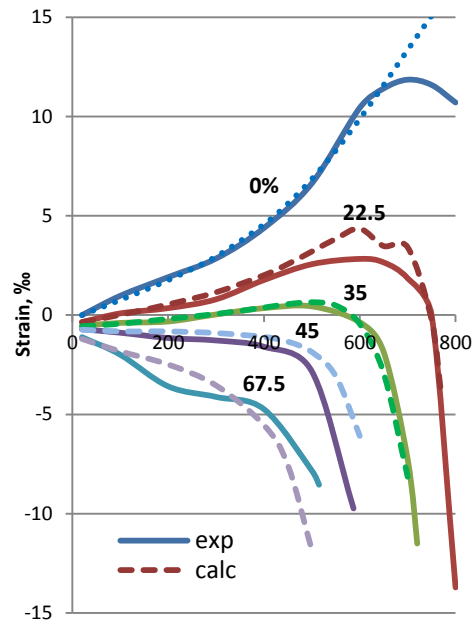


Figure 2. Curves of total deformations during heating (5°C/min) under load. Experimental data [1].

The existing LITS models are divided into explicit and implicit ones. The term "explicit" is used to refer to models, where the LITS component is explicitly stated in the governing relations in addition to the instantaneous stress-related strain [4]. For explicit models the deformation decomposition proposed in [1] is usually applied:

$$\varepsilon_{c,tot}(\sigma, T, t) = \varepsilon_{th}(T) + \varepsilon_{\sigma}(\sigma, T) + \varepsilon_{cr}(\sigma, T, t) + \varepsilon_{tr}(\sigma, T), \quad (1)$$

where σ is stress, T is temperature, t is time, ε_{th} is the temperature strain, ε_{σ} is the instantaneous stress-related strain (arising upon loading after heating), ε_{cr} is the isothermal creep strain, ε_{tr} is the transient strain (LITS).

Under the short-term heating conditions typical for a fire, the component ε_{cr} can be omitted, since the contribution of isothermal creep to the total deformation is negligible. This is due to the fact that the time necessary for the development of creep strains is usually much greater than the duration of the transition phase, even for the low heating rates [5].

The researchers proposed various ways the component ε_{tr} could be recorded depending on the rate of stress [1, 6, 7, 8]. However to use them in calculations, it is necessary to know the stress rate.

In contrast to explicit models, implicit models consider instantaneous stress-related strain ε_{σ} and transient strain ε_{tr} as a single mechanical elastoplastic strain component ε_c :

$$\varepsilon_{c,tot}(\sigma, T) = \varepsilon_{th}(T) + \varepsilon_c(\sigma, T). \quad (2)$$

The main disadvantage of implicit models is that they cannot catch the difference between the HTL and LTH modes, since they are only suitable for LTH conditions. In addition, they do not allow modeling of the cases related to mechanical unloading of the material [4]. However, if the stress-strain relation is recorded in the function of deformations, the use of implicit models becomes more convenient [9].

3. Initial assumptions

Before the modeling of concrete behavior under the heating in a load state, we introduced the following initial assumptions, which are confirmed by the results of numerous experimental studies.

- Linear and nonlinear deformation components are considered. Linear deformations are associated with the viscous and elastic behavior of the material and are partially reversible. Nonlinear deformations are caused by the development of micro cracks in the structure of concrete (brittle component). They are irreversible and lead to a reduction of strength.
- Nonlinear deformations under short-term heating conditions are determined only by the stress rate and temperature. They are assumed independent of the temperature and force effects application order and on the regime of changes in the force action during the non-stationary heating. This fact is confirmed by the results of tests with a constant, increasing and decreasing loading regime, shown in Figure 3. The destruction temperature of the samples was determined only by the last value of the stress, and the deformation growth occurred along the same curves shifted by the amount of irreversible deformations obtained in the previous heating steps (for example, shown by the dashed line for the loading level of 22.5%).
- The diagram of concrete deformation when heated in the loaded state has the same form as when loaded after heating, and differs only in the magnitude of the initial modulus. The deformations of LITS are explicitly included in the magnitude of the linear component. This confirms the conclusions of [1; 2; 10] that LITS deformations are proportional to the stress level when they do not exceed 30-40% of the compressive strength.
- The limiting structural stresses in the concrete $E_c \varepsilon_{cu}$ are assumed independent of the heating temperature (see Figure 1), which makes it possible to identify a relationship between the decrease of concrete strength during the heating and the level of its nonlinear deformations growth. The decrease in the concrete modulus of deformation during heating in this case may be determined from the magnitude of the ultimate power deformation of concrete:

$$E_c \varepsilon_{cu} = E_{c,T} \varepsilon_{cu,T} \quad (3)$$

where E_c is the initial modulus of deformation of concrete, ε_{cu} is the deformation at the peak of the diagram.

The diagrams of concrete deformation under loading after heating and under heating in a loaded state, obtained in accordance with the introduced assumptions, are shown in Figure 4. If we assume that the concrete strength, in the process of heating, in order to a given temperature, does not depend on the temperature and load impacts, then the magnitude of structural damage to the concrete will be the same. Despite the fact that the nonlinear part of the LTH diagram visually seems on the graph more developed, the ratio of nonlinear strains to linear deformations at a given loading level remains the same. Replacing the sum of deformations by a product let us avoid the sophisticated nonlinear assumptions in LITS modeling undertaken by many authors [1; 6; 7; 8].

4. Model of concrete thermomechanical resistance

The thermal power deformations of the loaded concrete under the high-temperature heating will be represented in implicit form (2) as the sum of two particular components: temperature and force. The equation that describes the relation between stresses σ_c and force deformations of concrete ε_c under heating in a loaded state is formed using the secant modulus of concrete deformation $E_{c,T} \nu_c$ in a form similar to loading after heating

$$\sigma_c = E_{c,T} \cdot \nu_c \cdot \varepsilon_c. \quad (4)$$

The index T hereinafter is for parameters that depend only on the temperature of the concrete heating, which do not depend on its loading rate.

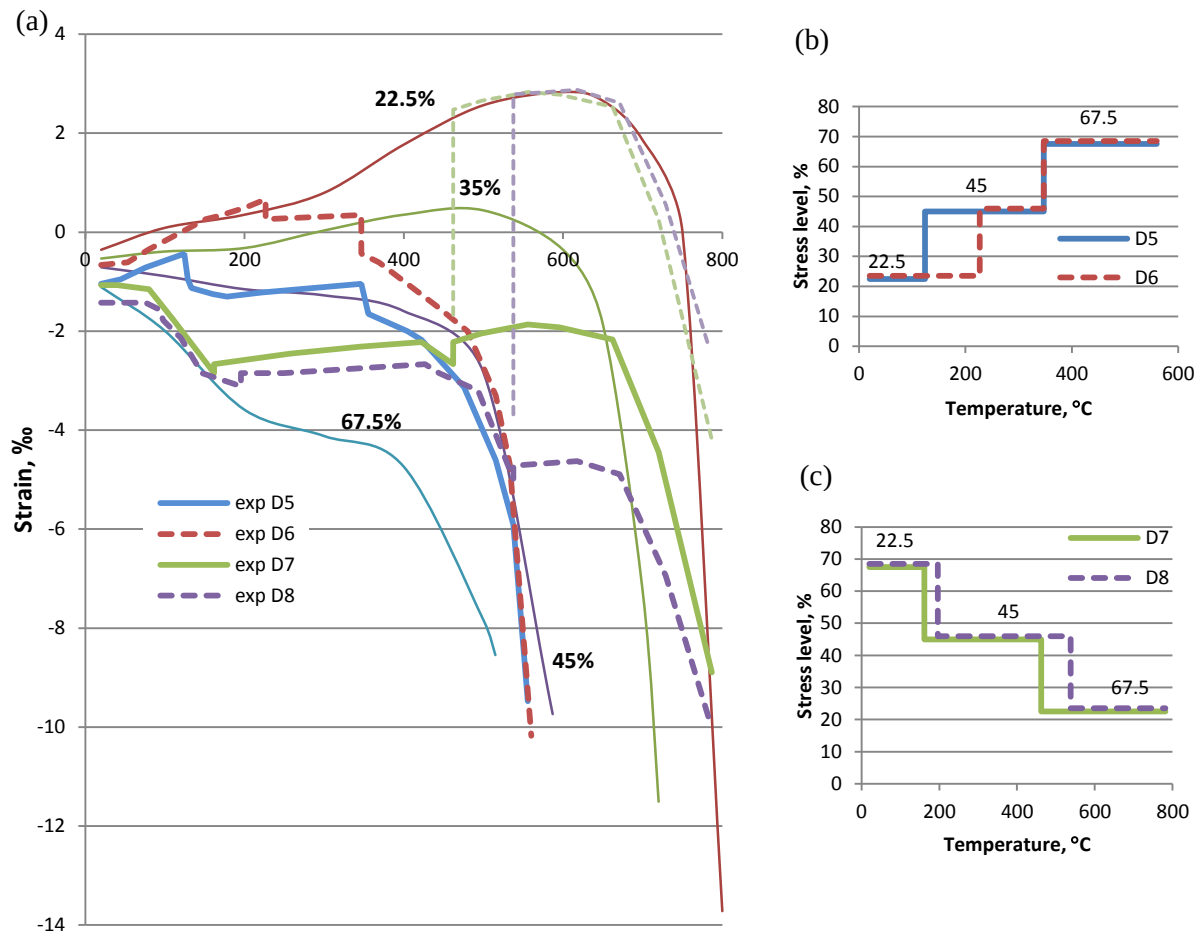


Figure 3. Deformation of concrete during non-stationary heating in the conditions of constant, increasing and decreasing loading; (a) - growth of complete deformations; (b) - increasing regime; (c) - decreasing regime. Experimental data [1].

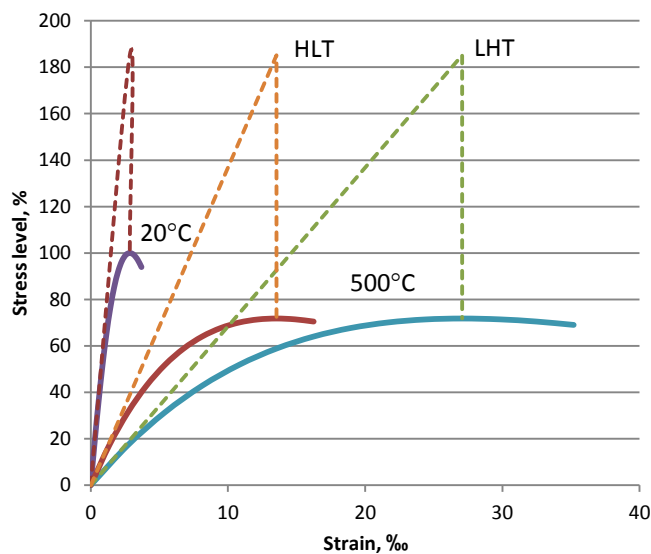


Figure 4. Diagrams of concrete deformation at loading after heating (HLT) and under heating under load (LHT). The dashed lines show the independence of the limiting structural stresses on the heating temperature.

The coefficient of the secant modulus v_c is expressed by an exponential dependence:

$$v_c = \exp \left[-k_{c,T} \cdot \left(\frac{\varepsilon_c}{\varepsilon_{cu,T}} \right)^{1/k_{c,T}} \right], \quad (5)$$

where $\eta_\varepsilon = \varepsilon_c / \varepsilon_{cu,T}$ is the current level of concrete deformation, $k_{c,T}$ deformation nonlinearity parameter, determined by the coefficient of the secant modulus at the peak of the diagram $v_{cu,T}$:

$$k_{c,T} = -\ln v_{cu,T}. \quad (6)$$

At normal temperature, the coefficient of the secant modulus at the peak v_{cu} is determined using the corresponding limiting strain ε_{cu} , strength f_{ck} and initial modulus of concrete strain E_c :

$$v_{cu} = \frac{f_{ck}}{E_c \varepsilon_{cu}}. \quad (7)$$

When heated, the reduction of strength and initial modulus of concrete strain is taken into account by the coefficients $\gamma_{c,T}$ and $\beta_{c,T}$:

$$f_{c,T} = f_{ck} \cdot \gamma_{c,T}, \quad (8)$$

$$E_{c,T} = E_c \cdot \beta_{c,T}. \quad (9)$$

The assumption of the concrete ultimate structural stresses independence of the heating temperature makes it possible to use the parameter $\gamma_{c,T}$ to determine the coefficient of the secant modulus at the peak $v_{cu,T}$:

$$v_{cu,T} = v_c \cdot \gamma_{c,T}, \quad (10)$$

and the parameter $\beta_{c,T}$ for determining the corresponding limiting strain $\varepsilon_{cu,T}$:

$$\varepsilon_{cu,T} = \varepsilon_{cu} / \beta_{c,T}. \quad (11)$$

The relations between temperature and coefficients $\gamma_{c,T}$ and $\beta_{c,T}$, as well as the temperature strain ε_{th} are written in the form of exponential functions similar to the expression (5):

$$\gamma_{c,T} = \exp \left[-\gamma \cdot \left(\frac{T_c - 20}{1000} \right)^m \right], \quad \beta_{c,T} = \exp \left[-\beta \cdot \left(\frac{T_c - 20}{1000} \right)^n \right]; \quad (12)$$

$$\varepsilon_{th} = \alpha_1 \cdot (T_c - 20) + \varepsilon_\alpha \cdot \left(1 - \exp \left[-\alpha_2 \cdot \left(\frac{T_c - 20}{1000} \right)^p \right] \right), \quad (13)$$

where T_c is the temperature of concrete heating, 20°C is the initial temperature, γ , β , m , n , α_1 , α_2 , p , ε_α are experimental parameters obtained from the results of tests of preloaded samples under nonstationary heating.

5. Results

For the composition of concrete assumed in [1], the coefficients of the proposed model were calibrated: $\gamma = 3$, $\beta = 3.5$, $m = 3$, $n = 0.6$, $\alpha_1 = 0.0095$, $\alpha_2 = 4$, $p = 4$, $\varepsilon_\alpha = 12$. The characteristic diagrams of concrete deformation at various heating temperatures in the loaded state are shown in Figure 5. The calculated curves of total concrete deformations (see Figure 2), as well as the diagrams of the reactive force variation in a sample heated with a complete limitation of temperature deformations (Figure 6) showed satisfactory convergence with experimental data [1].

6. Conclusion

In order to simulate the thermal strength of compressed concrete under high-temperature heating in the loaded state, it is necessary to specify 8 temperature parameters, as well as three operating characteristics under normal conditions (f_{ck} , E_c , ε_{cu}). These relationships are expressed as a function of deformations and are convenient for computational realization.

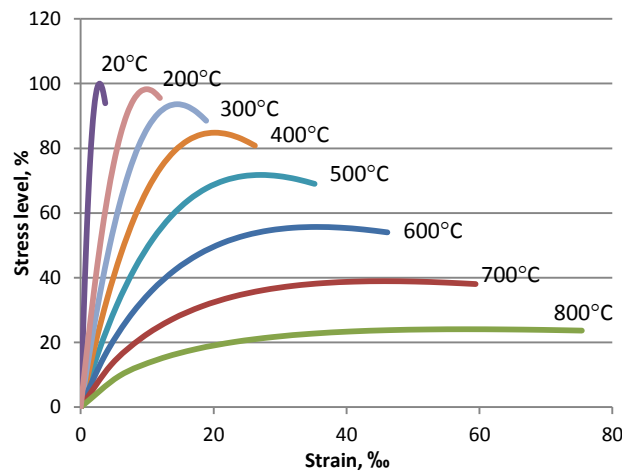


Figure 5. Diagrams of concrete deformation at various temperatures (heating under load).

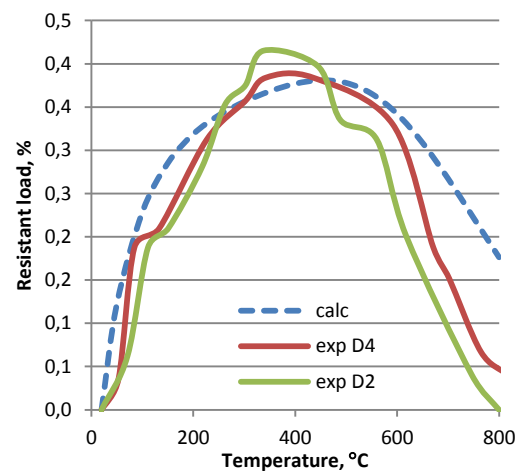


Figure 6. Reaction in a sample heated with a complete limitation of temperature deformations at a rate of 5°C/min (D2) and 1°C/min (D4). Experimental data [1].

References

- [1] Anderberg Y and Thelandersson S 1976 Stress and Deformation Characteristics of Concrete at High Temperatures. 2. Experimental Investigation and Material Behaviour Model *Bulletin of Division of Structural Mechanics and Concrete Construction*, Lund Institute of Technology Bulletin 54 86 pp
- [2] Khoury G A, Grainger B N and Sullivan P J E 1985 *Mag Concr Res* **37** 131–44
- [3] Torelli G et al 2016 *Engineering Structures* **127** 172–88
- [4] Gernay T and Franssen J M 2011 A comparison between explicit and implicit modelling of transient creep strain in concrete uniaxial constitutive relationships. *Proc. 12th Fire and Mater. Conf.* San Francisco, CA 405–16
- [5] Schneider U 1988 *Fire Saf. J.* **13** 55–68
- [6] Nielsen C V, Pearce C J and Bicanic N 2002 *Mag. Concr. Res.* **54** 239–49
- [7] Li L and Purkiss J 2005 *Fire Saf J* **40** 669–86
- [8] Terro M J 1998 *ACI Struct J* **95** 183–93
- [9] Fedorov V S and Levitskiy V E 2015 *Applied Mechanics and Materials* **725-726** 124–9
- [10] Mindeguia J-C, Hager I, Pimienta P, Carré H and La Borderie C 2013 *Cem Concr Res* **48** 40–52