Cover page

Title: Consideration of Transient Creep in the Eurocode Constitutive Model for Concrete in the Fire situation

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ABSTRACT

This paper presents a new formulation of the generic Eurocode 2 concrete model that contains an explicit term for consideration of the transient creep. The simplicity and generic characteristics of the Eurocode model are preserved and the new explicit formulation is calibrated to give the same results as the implicit formulation that is proposed in the Eurocode when the material is heated under constant load. However, the improvements allow taking into account with more accuracy the phenomenon of transient creep in concrete under more complex situations such as, for example, the cooling phase of a fire. The differences between the two formulations are highlighted for a simple structure. A comparison is given between experimental and calculated results on a centrally loaded concrete column submitted to heating-cooling sequence.

DEFINITIONS

The total strain can be divided into its components as follows:

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{m} \tag{1a}$$

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{tr} \tag{1b}$$

where ε_{tot} is the total strain, ε_{th} the thermal strain, ε_{m} the mechanical strain, ε_{σ} the instantaneous stress-related strain and ε_{tr} the transient creep strain. The instantaneous stress-related strain can in turn be divided in elastic and plastic

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strains. Basic creep, defined as the additional strain that develops when only time is changing with all other conditions such as stress and temperature being constant, could also be added as another component of the total strain, but this term is generally omitted for the structural calculation of building structures in the fire situation. Eq (1a) is used in implicit models where the transient creep is implicitly included in the mechanical strain whereas, in Eq. (1b), the transient creep is considered explicitly.

Physically, the transient creep strain is the additional strain that develops irrecoverably during first-time heating of concrete under load [1]. Even though several models have been proposed in the literature [1 and 2], the transient creep has been incorporated into the Eurocode model [3] in an implicit manner, leading to some approximations in the representation of this effect. The aim of this paper is to present a new formulation of the Eurocode 2 (EC2) model which contains an explicit term for the transient creep strain.

LIMITATIONS OF THE IMPLICIT MODEL OF THE EUROCODE

The EC2 model is commonly used for structural calculations. The advantages of this model are its simplicity and its relative reliability established by a widespread use for many years, at least under ISO fire conditions. Nevertheless, some limitations remain due to the implicit consideration of transient creep. For instance, no distinction is made in the model between heating under stress and loading at elevated temperature. Moreover, the transient creep that is implicitly considered is treated as reversible because, at a given temperature, the elastic modulus used for unloading is taken as the initial tangent to the constitutive curve in terms of $(\varepsilon_m ; \sigma)$ instead of $(\varepsilon_\sigma ; \sigma)$ [4].

The necessity to use an explicit transient creep model has been questioned [5], based on the fact that sufficiently accurate results have been obtained in numerous occasions when modeling reinforced concrete or composite steel-concrete elements with the implicit model of EC2. This opinion was yet based on simulations considering only the heating phase of the fire. However, the structural behavior during the cooling phase may not be so accurately represented by an implicit model because of its inherent limitations.

EXPLICIT TRANSIENT CREEP FORMULATION OF THE MODEL

Assumptions

1) For developing the new formulation, it was assumed that the stress-strain relationship of concrete at high temperature from EC2 implicitly includes transient creep. Accordingly, for first-time heating under constant stress, the new formulation was calibrated to yield the same mechanical strain as the EC2 model. From Eq. (1a) and (1b), this leads to:

$$\varepsilon_m^{\text{implicit}} = \varepsilon_\sigma^{\text{explicit}} + \varepsilon_{tr}^{\text{explicit}} \tag{2}$$

2) The actual elastic modulus of the material is the initial tangent of the instantaneous stress-strain relationship curve ($\varepsilon_\sigma ; \sigma$). In the ENV version of Eurocode 2 [6], the ($\varepsilon_m ; \sigma$) relationship based on the minimum value of the peak stress strain $\varepsilon_{c1,\min}$ does not include transient creep strain, as shown for example by Schneider [7], see Figure 1. Therefore the elastic modulus from ($\varepsilon_m ; \sigma$) of ENV can be seen as a good estimation of the actual elastic modulus of ($\varepsilon_\sigma ; \sigma$) for an explicit formulation. It can in fact be noted that relationships for the evolution of the elastic modulus with temperature presented by Schneider et al. [2] as well as Nechnech [8] are in line with the values given by ENV.

3) Transient creep models have been developed by several authors in literature and, generally, transient creep is proportional to the applied stress [1 and 2]. Adopting the same assumption, the formulation was developed as follows:

$$\varepsilon_{tr} = \phi(T) \times \sigma \tag{3}$$

Development of the Model

Let $E_{\text{EC2}}^{\text{implicit}}(T)$ be the Young modulus of concrete considered in the EC2 implicit model, i.e. the initial tangent to the EC2 ($\varepsilon_m ; \sigma$) curve:

$$\frac{E_{\text{EC2}}^{\text{implicit}}(T)}{f_c(T)} = \frac{3}{2\,\varepsilon_{c1,EC2}(T)} \tag{4}$$

with $\varepsilon_{c1,EC2}$ the peak stress strain and f_c the compressive strength [3]. Similarly, $E_{ENV}(T)$ is the modulus of concrete considered in the ENV constitutive relationship with the minimum value of the peak stress strain $\varepsilon_{c1,\min}$.

The transient creep is assumed to be, on one hand, a linear function of the applied stress and, on the other hand, the difference between the mechanical strain and the instantaneous stress-related strain. In the elastic part of the constitutive law,

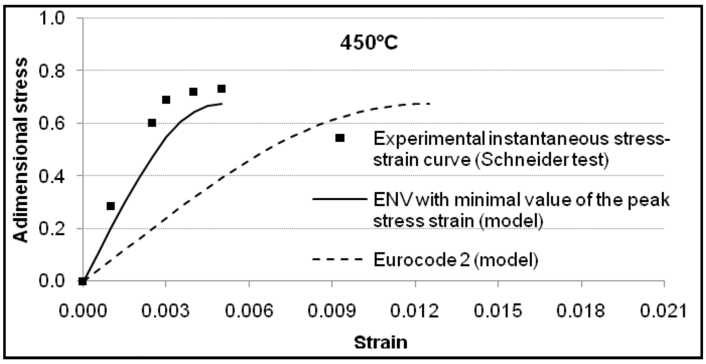

Figure 1. Comparison of EC2 and ENV models with experimental data of the instantaneous stress-strain relationship at 450°C [7].

i.e. for a stress level $\sigma^* / f_{c,T} \ll 1$, the instantaneous stress-related strain ε_σ and the elastic strain ε_{el} coincide. Therefore, considering the modulus from ENV as the actual elastic modulus of concrete, relationship (5) can be written.

$$\varepsilon_\sigma = \sigma^* \big/ E_{ENV} \tag{5}$$

For the same stress level, the mechanical strain according to the EC2 relationship is related to the stress by the apparent modulus as expressed by Eq. (6).

$$\varepsilon_m = \sigma^* \big/ E_{\mathrm{EC2}}^{\mathrm{implicit}} \tag{6}$$

Transient creep strain has been defined as the difference between mechanical and instantaneous stress-related strains. Since it has been assumed proportional to the applied stress, Eq. (7) is valid whatever the stress level.

$$\varepsilon_{tr}(T) = \left[\left(\frac{1}{E_{\mathrm{EC2}}^{\mathrm{implicit}} / f_c} \right) - \left(\frac{1}{E_{ENV} / f_c} \right) \right] \frac{\sigma}{f_c} = \frac{2}{3} \left(\varepsilon_{c1,EC2} - \varepsilon_{c1,\min} \right) \frac{\sigma}{f_c} = \phi'(T) \frac{\sigma}{f_c} \tag{7}$$

The Young modulus is calculated taking into account the fact that transient creep is not recovered during the cooling phase:

$$\frac{E(T)}{f_c(T)} = \frac{1}{\left(\dfrac{2.\varepsilon_{c1,EC2}(T)}{3} - \phi'(T_{\max}) \right)} \tag{8}$$

where $\phi'(T_{\max})$ is given by Eq. (7) with the maximum value of temperature reached in the material during its history.

Figure 2 compares the transient creep of the model presented here with experimental data and models given in the literature [7]. In this example, the test specimen was subjected to a constant uniaxial compressive load equal to 0.33 f_c and immediately afterwards heated at a constant rate to a pre-specified temperature.

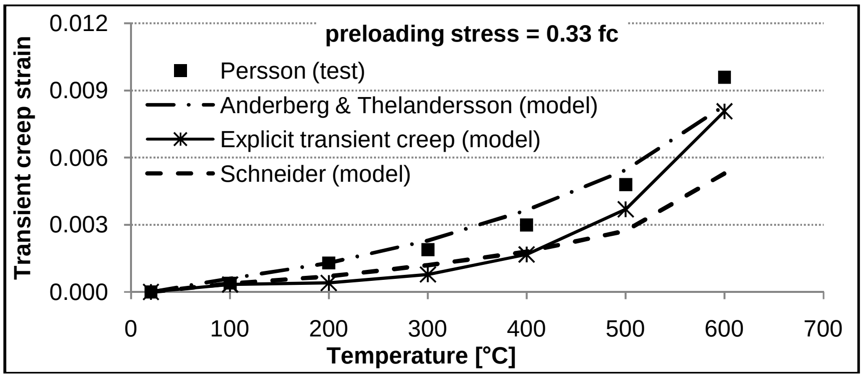

Figure 2. Comparison between different models of transient creep and experimental data.

Introduction of Transient Creep into an Existing Code

The transient creep term is calculated during the step-by-step analysis of the structure using the incremental form of equation (7). At each step, the path followed by the material in the stress-temperature space is considered in order to determine whether the transient creep term has to be incremented or not. Knowledge of the transient creep term allows deriving the instantaneous stress-related strain from the mechanical strain as follows:

$$\varepsilon_{\sigma}^{\text{explicit}} = \varepsilon_{m} - \varepsilon_{tr}^{\text{explicit}} = \varepsilon_{tot} - \varepsilon_{th}^{\text{explicit}} - \varepsilon_{tr}^{\text{explicit}} \tag{9}$$

In the explicit transient creep formulation (ETC) of the model, the aim is to express the constitutive relationship in terms of the instantaneous stress-related strain, in order to treat the transient creep effects separately from the elastic and plastic effects.

The constitutive relationship of the implicit model of EC2 is given by Eq. (10) (for the ascending branch).

$$\frac{\sigma}{f_c(T)} = \frac{3\,\varepsilon_{m}^{\text{implicit}}}{\varepsilon_{c1,EC2}(T)\left(2+\left(\varepsilon_{m}^{\text{implicit}} \big/ \varepsilon_{c1,EC2}(T)\right)^{3}\right)} \tag{10}$$

According to the first assumption, Eq. (2) has to be satisfied for first-time heating under constant stress. In this case, the transient creep that develops is directly given by Eq. (7) (no incremental calculation) because the stress is constant. After replacing Eq. (7) into Eq. (2), the first assumption gives Eq. (11). In this equation, $\phi^{'}(T_{\max})$ is calculated with the maximum temperature reached in the material during its history to generalize the theory when it is not a first heating.

$$\varepsilon_{m}^{\text{implicit}} = \varepsilon_{\sigma}^{\text{explicit}} + \phi^{'}(T_{\max})\left(\sigma / f_c\right) \tag{11}$$

When replacing Eq. (11) into Eq. (10), the relationship between the stress and the instantaneous stress-related strain is obtained:

$$\frac{\sigma}{f_c(T)} = \frac{3\left(\varepsilon_{\sigma}^{\text{explicit}} + \phi'(T_{\max})\left(\sigma / f_c\right)\right)}{\varepsilon_{c1,EC2}(T)\left(2+\left(\dfrac{\varepsilon_{\sigma}^{\text{explicit}} + \phi'(T_{\max})\left(\sigma / f_c\right)}{\varepsilon_{c1,EC2}(T)}\right)^{3}\right)} \tag{12}$$

At a given step, knowledge of the instantaneous stress-related strain can theoretically give the stress from Eq. (12). However, it is not easy to extract σ from Eq. (12). Two methods can be applied: a direct relationship $\sigma = f\left(\varepsilon_{\sigma}^{\text{explicit}}\right)$ can be derived that approximates Eq. (12) or an algorithmic strategy can be implemented to solve Eq. (12). The first method should probably be preferred in order to allow an easier generalization of the ETC model in three dimensions.

It is noteworthy that the instantaneous stress-related strain, as calculated by Eq. (9), is stress-dependent because of the transient creep term. However, a possible method is to increment the transient creep term at the beginning of the time step, considering the stress at the previous converged step. This allows decoupling the calculation of the transient creep strain from the integration of the constitutive law of the material.

The Young modulus is calculated according to equation (8). The distinction between the Young modulus and the initial tangent modulus to the constitutive curve in terms of (ε_m, σ) allows including the transient creep as permanent strain.

RESTRAINED ELEMENT SUBMITTED TO HEATING-COOLING SEQUENCE

Law and Gillie have demonstrated the significant difference between the apparent and the actual elastic modulus of a model [4] and its implication for structural behavior. The explicit calculation of transient creep strain developed in this paper allows distinguishing between both moduli. The influence is demonstrated on the simple case presented by Law and Gillie [4] and analyzed here with the finite element software SAFIR [9]. The specimen is an axially restrained concrete cylinder (Figure 3). The temperature was raised uniformly to 500°C and then cooled down to 20°C. The implicit formulation of the Eurocode model was compared with the explicit transient creep formulation (ETC). The resulting stress during the heating and cooling regimes was plotted against the temperature (Figure **3**).

During heating, thermal expansion caused compressive stresses to build up in the column due to its fixed ends. During this heating phase, the response of both models was the same, which confirms that the new model gives the same results as the EC2 model in the cases where transient creep fully develops.

Though both models followed the same path through heating, the transient creep explicitly calculated in the new model was accounted as irreversible, while the

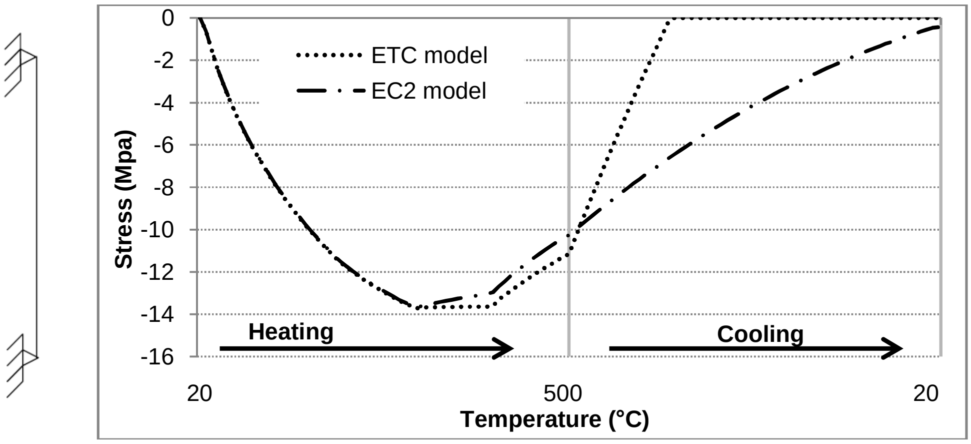

Figure 3. Stress response to heating and cooling regime.

implicit model considered transient creep as elastic. The difference is notable during the cooling phase, where the implicit formulation released the stresses slowly while, in the new model, the strains developed were unable to recover and the stress rapidly decreased. This highlights the importance of considering the irreversibility of transient creep when studying the cooling phase of a fire.

COMPARISON WITH EXPERIMENTAL DATA

In order to validate the model on a structural member, an experimental fire test made in Japan on centrally loaded concrete columns was simulated [10]. A comparison between the numerical results considering different concrete models and the experimental data was performed. The column is 300 by 300 mm² in cross section with a centre hole of 100 mm diameter. The concrete compressive strength is 55 MPa. Four 16 mm longitudinal rebars are present with a cover of 40 mm. The column, submitted to a load of 677 kN, was exposed to Japanese standard fire temperature-time curve during 180 minutes. Then, the element was allowed to cool down. The deformation behavior can be observed on Figure 4.

- The ENV model with recommended value of the peak stress strain [6] leads to too large elongations, because of a highly underestimated transient creep strain. This model had been found to be by far too stiff and has been removed when transforming the Eurocode from an ENV to an EN.
- The ETC model leads to results comparable with the EC2 model during approximately the first 140 minutes of heating. Beyond 140 minutes, the behavior predicted by the ETC model tends to differ from the behavior predicted by the EC2 model, i.e. the effect of the explicit consideration of transient creep on the structural behavior becomes notable. The ETC model matches better than the EC2 model the actual behavior of the structure.
- The difference between the behaviors predicted by the ETC and the EC2 models is particularly significant during the cooling phase. Measured data showed a very important decrease of the elongation, due to a progressive decrease of

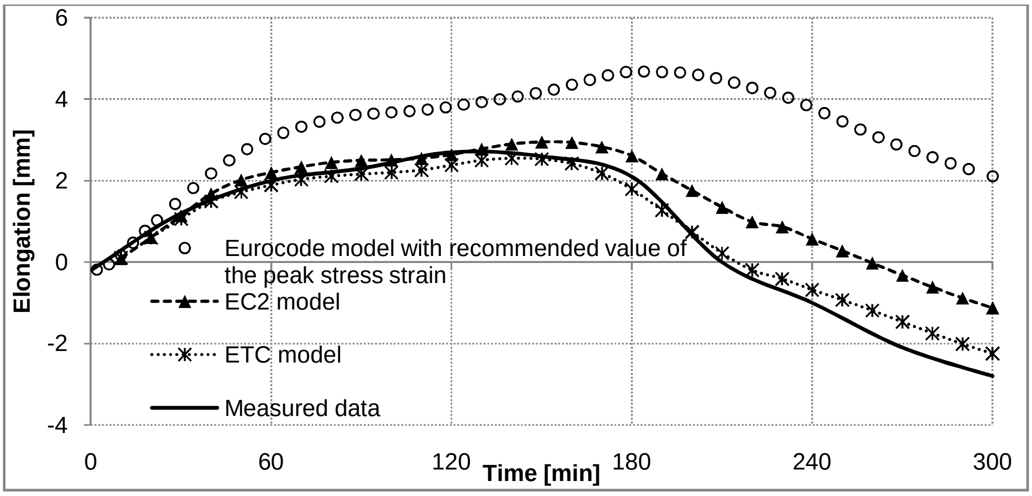

Figure 4. Comparison between numerical simulations and experimental test.

thermal strain coupled with a very limited recovery of mechanical strain. Indeed, mechanical strain is mostly composed of permanent strain. This behavior is well represented with the ETC model owing to the explicit consideration of transient creep. However, the EC2 model implicitly recovered the transient creep leading to an underestimated final shortening of the column.

CONCLUSION

The implicit consideration of transient creep in the current model of the Eurocode leads to some approximations in the representation of the transient creep strain, especially when modeling the behavior of concrete structures during the cooling phase of a fire. The new formulation of the generic Eurocode 2 concrete model that contains an explicit term for consideration of the transient creep (ETC) brings a supplementary accuracy without removing the generic characteristic of the EC2 model. The model implementation in finite-element software can be performed by an adaptation of the current EC2 model. The improvement is significant as it has been showed by modeling an experimental test. The ETC model is particularly useful when modeling the cooling phase of the fire because the irreversibility of transient creep is considered.

REFERENCES

1. Anderberg, Y. 1976. “Fire-exposed hyperstatic concrete structures – an experimental and theoretical study”, University of Lund, Sweden.
2. Schneider, U.; Schneider, M.; Franssen, J.-M. 2008. “Consideration of nonlinear creep strain of siliceous concrete on calculation of mechanical strain under transient temperatures as a function of load history”. Proceedings of the Fifth International Conference – Structures in Fire SIF 08 Singapore, pp. 463-476.
3. Eurocode 2. 2004. “Design of concrete structures – Part 1-2: General rules – Structural fire design”.
4. Law, A. and M. Gillie. 2008. “Load induced thermal strain: implications for structural behavior”. Proceedings of the Fifth International Conference – Structures in Fire SIF 2008 Singapore, pp. 488-496.
5. Franssen, J.-M. 2005. “Plastic analysis of concrete structures subjected to fire”. Proceedings of the Workshop "Fire Design of Concrete Structures: What now? What next?", pp. 133-145.
6. Eurocode 2. 1995. “Design of concrete structures – Part 1-2: General rules – Structural fire design”, European Prestandard.
7. Youssef, M.A., M. Moftah. 2007. “General stress-strain relationship for concrete at elevated temperatures”, *Engineering structures*, 29, pp. 2618-2634.
8. Nechnech, W. 2000. “Contribution à l’étude numérique du comportement du béton et des structures en béton armé soumises à des sollicitations thermiques et mécaniques couplées : Une approche thermo-élasto-plastique endommageable”, Thèse, INSA Lyon.
9. Franssen, J.-M. 2005. “SAFIR. A thermal/Structural Program for Modeling Structures under Fire”, *Engineering Journal*, A.I.S.C., Vol 42, No. 3, pp. 143-158.
10. Schneider, U.; Morita, T.; Franssen, J.-M. 1994. “A concrete model considering the load history applied to centrally loaded columns under fire attack”. Fourth International Symposium on Fire Safety Science, Ottawa, pp. 1101-1112.