EFFECT OF TRANSIENT CREEP STRAIN MODEL ON THE BEHAVIOR OF CONCRETE COLUMNS SUBJECTED TO HEATING AND COOLING

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Abstract

In the numerical analysis of structures in fire, the material models that are used have important implications on the global behavior of the structure. In concrete, a particular phenomenon appears when subjected to high temperatures: the transient creep strain. Models integrating explicitly a term for transient creep strain have been proposed in the literature but, in the current Eurocode 2 model, there is no explicit term for transient creep strain. This phenomenon is included in the Eurocode 2 model, but it is implicitly considered in the mechanical strain term. A series of experimental fire tests on axially restrained concrete columns subjected to heating and cooling has been recently performed at South China University of Technology and described by Wu [1]. In the original paper, it was shown that using the implicit model of Eurocode 2, the behavior of the columns cannot be simulated properly, especially during the cooling phase. The objective of the present paper is to perform again the fire tests simulations using a new formulation of the Eurocode 2 model that contains an explicit term for transient creep. In the first part of the paper, the explicit formulation of the Eurocode 2 model is presented. In the second part, the fire tests are modeled with the software SAFIR using, on the one hand, the implicit Eurocode model and, on the other hand, the new explicit model. It is shown that the transient creep model has significant implications on the global behavior of structural concrete members, as the residual axial load sustained by the columns at the end of the fire can differ by up to 25% of the initial applied load depending on the transient creep strain model that is used for the calculation. The experimental behavior is better matched with the new explicit model than with the current Eurocode model. Particularly, the results given by the Eurocode model during the cooling phase are unconservative as the residual axial load is overestimated. Finally, it is explained why, on the basis of an example, in a performance-based approach, these results can have important implications on the global fire resistance of a structure.

KEYWORDS: Concrete, Constitutive Model, Fire, Transient Creep

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1. Introduction

1.1 Transient creep strain

Structural fire engineers frequently use numerical analysis to assess the performance of building structures in accidental fire situations. For these numerical simulations, temperature dependent constitutive relationships are required for the load bearing materials used in the structure such as, for instance, concrete. Since the pioneering works of Anderberg & al. [2] and Schneider [3], concrete uniaxial constitutive models have been available for linear structural members such as beams and columns.

In concrete, a particular phenomenon appears when subjected to high temperatures: the transient creep strain. Physically, the transient creep strain is the additional strain that develops irrecoverably during first-time heating of concrete under load, compared to concrete loaded at elevated temperature [2]. A number of analytical models capable of predicting transient creep strain have been developed in the literature. In Anderberg's model [2], the transient creep strain was assumed to be proportional to the applied stress and to free thermal strain, and to depend on the type of aggregate (siliceous or carbonate). Yet, Khoury & al. [4] showed that transient creep strain was physically independent from free thermal strain. In Terro's model [5], based on the experimental results by Khoury & al., the transient creep strain was nonlinearly proportional to the temperature and the model also accounted for the effect of the volume fraction of aggregates on the transient creep strain. In Schneider's model [3], the transient creep strain is a function of the initial stress before heating, in addition to the applied stress, the temperature and the temperature dependent concrete modulus of elasticity and strength. Interesting state of the art reviews can be found in the recent literature, e.g. Li & al. [6], Law & al. [7] and Youssef & al. [8].

The uniaxial concrete models proposed by these authors integrate explicitly a term for transient creep strain. In most of these explicit models, the transient creep strain is linearly proportional to the applied stress and increases with temperature but not linearly, e.g. Anderberg & al. [2], Schneider [3], Diederichs (reported in Li & al. [6]) and Terro [5]. Another approach consists in including implicitly the transient creep strain in the stress-mechanical strain relationship, e.g. in the current Eurocode 2 (EC2) model [9]. In the latter approach, there is no explicit term for transient creep strain. This phenomenon is included but it is implicitly considered in the mechanical strain term.

It is well-admitted in the literature that transient creep has to be considered in any fire analysis involving concrete in compression [4, 6]. The effect of not including transient creep strain in a full stress-strain model can be shown to produce erroneous unsafe results for the behavior of columns heated in three sides, thus inducing a thermal moment, in fire [10], although the effect may be exacerbated due to the coexistence of thermal and moment gradient. However, the necessity of taking transient creep into account by an explicit term in the strain decomposition has been questioned [11] because the current Eurocode 2 model, which is an implicit model, has proved for many years to yield quite satisfactory results when modelling experimental tests made on concrete structural elements in fire. But it should be noted that these tests mostly consist in simple structural elements subjected to standard fire, thus considering only the heating phase. The capability of implicit transient creep model, such as the EC2 model, to accurately represent the response of concrete elements subjected to natural fire, including the cooling phase, has not been demonstrated yet to the author knowledge. Law & al. [7] have recently shown that considering the transient creep term implicitly can have important implications on the Young modulus calculation of concrete during cooling. For a simplified pure concrete column consisting of a single member pinned at both end, which was uniformly heated and then cooled back down to ambient temperature, Law & al. have shown that the response during cooling was significantly different using an explicit or an implicit model of transient creep strain. Indeed implicit models slowly released the stresses during cooling and were only pulled into tension when the temperature was close to returning to ambient, whereas explicit models were unable to recover the strains and rapidly progressed into tension. However, the implications on the behavior of a complete structure are still a pending question.

1.2 Objectives of the study

The current EC2 model, which treats the transient creep strain implicitly, is widely used and accepted by regulators for practical applications in structural fire engineering. It has been used for many years for structural fire calculations, usually based on prescriptive approach based on the standard ISO fire. As long as concrete columns are checked for fire resistance during the heating phase only, the EC2 has proved to yield quite satisfactory results, which to the author could partially explain why the explicit concrete models have not imposed themselves instead of the EC2.

However, performance-based design is now more and more used for assessing the fire resistance of structures. In a performance-based approach, the aim is to model the response of a real structure subjected to a real scenario of fire. A more realistic representation of the fire will be used that comprises non only a heating phase but also a cooling phase during which the temperature of the fire is decreasing back to ambient temperature. The influence of such realistic fire scenarios in the evaluation of the fire resistance is a key issue in the performance-based approach, as presented for example by Fike & al. for concrete-filled hollow structural section columns [12]. Modeling the cooling phase of the fire is important to analyze the risk of collapse of the structure during cooling. For instance, collapse during the cooling phase of a fire occurred in a full scale fire test conducted in 2008 by Wald [13] in the Czech Republic. Modeling the cooling phase of the fire is also important to assess the residual load bearing capacity of a structure that survived to a fire. A tragic incident occurred in Switzerland in 2004 when seven members of a fire brigade were killed by the sudden collapse of the concrete structure in an underground car park in which they were present after having successfully fought the fire [14].

In line with the performance-based design requirements, the study reported here is interested in the behavior of axially restrained concrete columns subjected to heating and cooling. The objective was to show that the type of model that is used for transient creep strain, i.e. an implicit or an explicit model, can have a significant influence on the behavior of structural elements subjected to natural fire. Implicit models such as the EC2 model have limitations that, even though they were not considered as significant when following a prescriptive design, could lead to inappropriate results when a performance-based design including the cooling phase is performed. To highlight the difference in the structural response obtained using implicit or explicit models, a series of experimental fire tests performed at South China University of Technology [1] has been numerically modeled using the nonlinear software SAFIR [15]. Two different concrete models were used for comparison: on the one hand, the current EC2 model, and on the other hand, a new formulation of the EC2 model that contains an explicit term for transient creep strain. At the end of the paper, the practical implications of the results on real building structures subjected to natural fire are explained based on an example.

2. Implicit and Explicit Models

2.1 Definitions

In implicit models such as the current EC2 model, the total strain ε_{tot} is considered as the sum of free thermal strain (FTS) ε_{th}, mechanical strain ε_{m}, and possibly basic creep strain ε_{cr} as expressed by Eq. (1).

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{m} \left(+ \varepsilon_{cr} \right) \tag{1}$$

Basic creep, defined as the strain that develops when only time is changing with all other conditions such as stress and temperature being constant, is generally omitted for the structural calculation of building structures in the fire situation [6].

In explicit models, the total strain is split into FTS ε_{th}, instantaneous stress-related strain ε_{σ} and transient creep strain ε_{tr} (and possibly basic creep strain ε_{cr}):

$$\varepsilon_{tot} = \varepsilon_{th} + \varepsilon_{\sigma} + \varepsilon_{tr} \left(+ \varepsilon_{cr} \right) \tag{2}$$

The instantaneous stress-related strain can in turn be divided in elastic and plastic strains: $\varepsilon_{\sigma} = \varepsilon_{el} + \varepsilon_{p}$. From Eq. (1) and (2) it is clear that the mechanical strain is the sum of the instantaneous stress-related strain and the transient creep strain.

These strain components can be highlighted by comparing two experiments (see Fig. 1). In the first one, called steady-state test, the concrete specimen is first heated uniformly to a pre-defined temperature and then loaded while the temperature is kept constant. The strain that appears at the end of the heating process is only composed of free thermal strain, whereas the strain at the end of the experiment is the sum of FTS and instantaneous stress-related strain. In the second experiment, called transient test, the specimen is first loaded up to a given load and then heated while the load is kept constant. The strains at the end of the latter and the former experiment are different even though the final stress and temperature states are the same. The difference in final strain is denoted as the transient creep strain. Note that for more readability, the strain components have been added in absolute values in

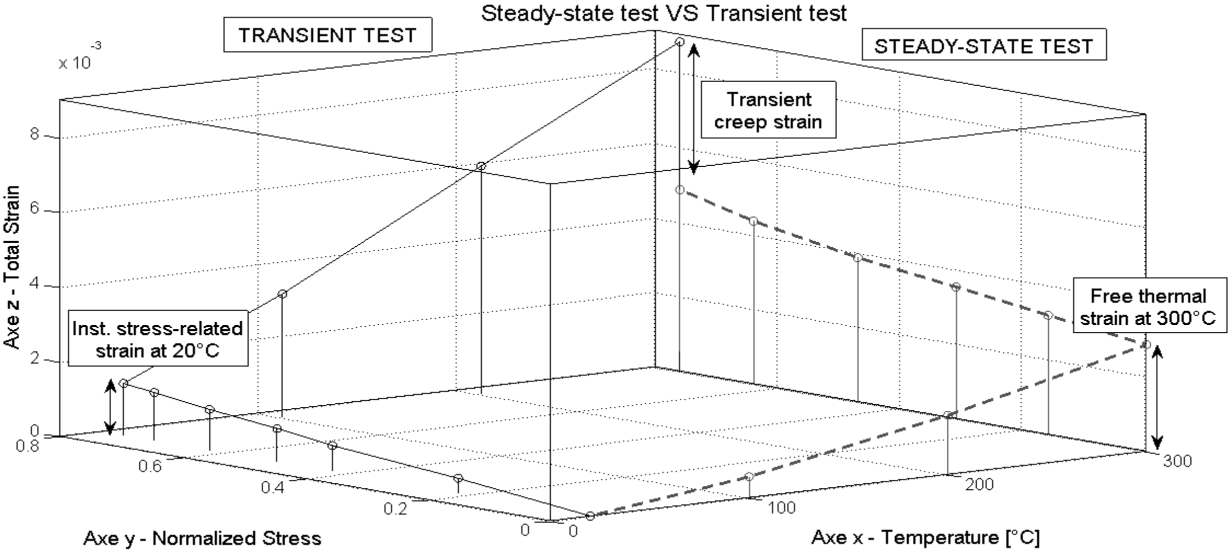


Fig. 1 Transient creep strain

Fig. 1 even though FTS is opposed to the other strains in compression. Experimental data from steady-state and transient tests can be found in the literature [3, 16].

2.2 Concrete models used for the numerical modeling of the test

The constitutive model of EC2 has imposed itself as one of the most widely used generic models in the last decade, in Europe and beyond. It has been proposed by a draft committee comprising several European experts, has proved to yield quite satisfactory results when applied to structural calculations (although most application where under ISO fire, which means under constantly increasing temperature) and it is well accepted by authorities and regulators. It has thus been chosen as the reference implicit model for the present analysis.

The choice of the explicit concrete model to use for the numerical simulation of the test was not as obvious as the choice of the implicit model, because none of the explicit models presented in the literature has been widely used for practical applications or recognised as by far superior to the others. As this study is oriented towards structural applications, an important aspect to the author regarding the explicit model was to use a generic model, i.e. not depending on the properties of a particular type of concrete to be used in particular conditions. To have a chance to see a breakthrough in the utilization of explicit models, it was also estimated that the explicit model should not require particular tests. Considering the fact that the EC2 model had imposed itself as one of the reference implicit concrete model for practical applications, it was estimated that it would be particularly interesting to propose an explicit model based on experimental data but which formulation is derived from the EC2 model and which parameters can be deduced from the Eurocode parameters. The explicit calculation of transient creep strain should allow for an accurate representation of the mechanical strain for any stress-temperature path, based on experimental tests. In the particular situation of transient test, the explicit model would yield the same results as the present EC2 implicit model, because the EC2 model implicitly includes the transient creep strain that develops in transient test situation. This explicit model could then be seen as a new formulation of the Eurocode model and be called Explicit Transient Creep Eurocode model (ETC Eurocode model). It should of course encompass the most widely accepted characteristics of transient creep.

3. Explicit Transient Creep Formulation of the Eurocode Model

3.1 Description of the model

A new formulation of the current EC2 concrete model is proposed in this paper. The new formulation was calibrated to yield the same mechanical strain as the EC2 model for a material first-time heated under constant stress (i.e. transient test). From Eq. (1) and (2), this leads to Eq. (3).

$$\varepsilon_m^{\mathrm{EC2}} = \varepsilon_\sigma^{\mathrm{ETC}} + \varepsilon_{tr}^{\mathrm{ETC}} \tag{3}$$

Transient creep models have been developed by several authors in the literature and, generally, transient creep is proportional to the applied stress (Anderberg & al.[2], Schneider [3], Terro [5]). Adopting the same assumption, the formulation was developed according to Eq. (4):

$$\varepsilon_{tr}^{\mathrm{ETC}} = \phi(T) \times \frac{\sigma}{f_{ck}} \tag{4}$$

where $\phi(T)$ is a nonlinear function of temperature and f_{ck} is the compressive strength at 20°C.

From Eq. (2), Eq. (3) and Eq. (4), neglecting the basic creep, it holds:

$$\varepsilon_{tot} - \varepsilon_{th} - \varepsilon_{tr}^{\mathrm{ETC}} = \varepsilon_m^{\mathrm{EC2}} - \phi(T) \times \frac{\sigma}{f_{ck}} = \varepsilon_\sigma^{\mathrm{ETC}} \tag{5}$$

where the term $\varepsilon_\sigma^{\mathrm{ETC}}$ is the strain obtained by steady-state tests. The function $\phi(T)$, which appears in the expression of $\varepsilon_\sigma^{\mathrm{ETC}}$ given by Eq. (5), was derived to calibrate the instantaneous stress-strain curve $\sigma - \varepsilon_\sigma^{\mathrm{ETC}}$ on the experimental response of the concrete material subjected to steady-state test. In particular, the tangent to the instantaneous stress-strain curve at zero stress is calibrated on the initial stiffness of the material subjected to steady-state test. A good indication of values of this initial stiffness is given by the initial tangent to the ENV curves [17] with the minimum values of the peak stress strain (PSS), $\varepsilon_{c1,\min}$, since the ENV relationship with $\varepsilon_{c1,\min}$ is based [18] on steady-state tests made by Schneider [19], see Fig. 2.

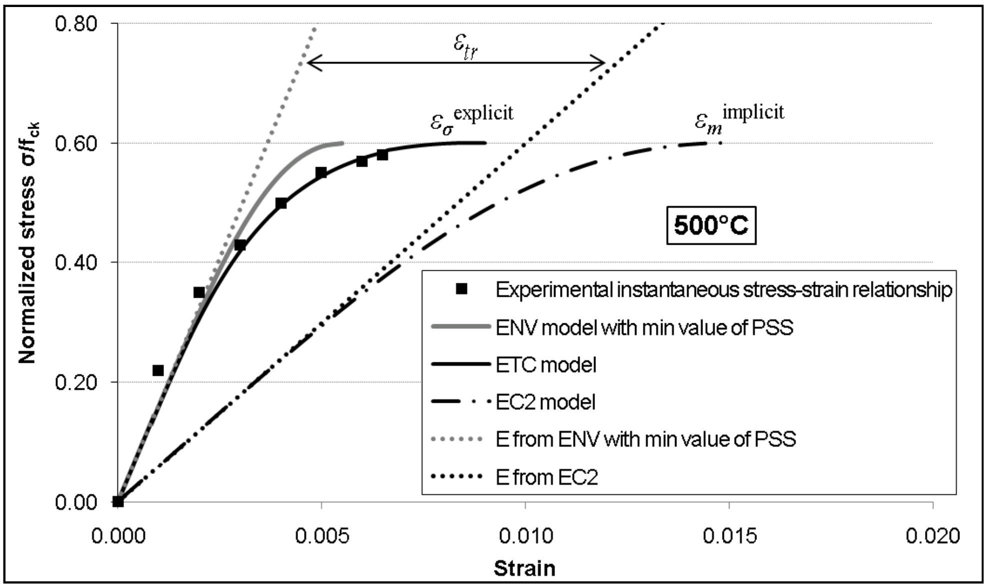


Fig. 2 Comparison at 500°C of ENV [17], ETC and EC2 [8] models with experimental data from Schneider [19]

The tangent to the curve relating the instantaneous stress-related strain $\varepsilon_{\sigma}^{\mathrm{ETC}}$ and the stress σ at zero stress is thus taken equal to the ENV modulus, written here as $E_{\mathrm{ENV}}(T)$. The tangent to the curve relating the mechanical strain $\varepsilon_{m}^{\mathrm{EC2}}$ and the stress σ at zero stress is the EC2 modulus, denoted as $E_{\mathrm{EC2}}(T)$. Finally, the function $\phi(T)$ is given by Eq. (6):

$$\phi(T) = \frac{1}{(\sigma/f_{ck})}\left(\frac{\sigma}{E_{\mathrm{EC2}}} - \frac{\sigma}{E_{\mathrm{ENV}}}\right) = \frac{2}{3}\,\frac{\left(\varepsilon_{c1,EC2} - \varepsilon_{c1,\min}\right)}{\left(f_c/f_{ck}\right)} \tag{6}$$

where $\varepsilon_{c1,\mathrm{EC2}}$ and $\varepsilon_{c1,\min}$ are the EC2 value and the ENV minimum value of the PSS respectively, and f_c is the temperature dependent compressive strength. The function $\phi(T)$ is a growing function of temperature that is not reversible during cooling, as each of its components $\varepsilon_{c1,EC2}$; $\varepsilon_{c1,\min}$; f_c/f_{ck} is irrecoverable. This is in line with the definition of transient creep that is not recovered during the cooling phase. The components of the function $\phi(T)$ are given in the EC2 and ENV.

The instantaneous stress-strain relationship of the model (i.e. the curve $\sigma = f(\varepsilon_{\sigma}^{\mathrm{ETC}})$), given by Eq. (5), is not exactly equal to the ENV relationship because the transient creep has been considered as linearly stress dependent. However, the initial stiffness of the new relationship is exactly equal to the ENV elastic modulus, see Fig. 2.

The mathematical expression to model the instantaneous stress-strain relationship is approximated by a direct relationship $\sigma = f(\varepsilon_{\sigma}^{\mathrm{ETC}})$ with the same generic form as the current EC2 model, see Eq. (7):

$$\frac{\sigma}{f_c(T)}=\frac{n\ \varepsilon_\sigma^{\mathrm{ETC}}}{\varepsilon_{c1,\mathrm{ETC}}(T)\left[(n-1)+\left(\dfrac{\varepsilon_\sigma^{\mathrm{ETC}}}{\varepsilon_{c1,\mathrm{ETC}}(T)}\right)^n\right]} \tag{7}$$

where n is a parameter to be determined and $\varepsilon_{c1,\mathrm{ETC}}(T)$ is the PSS for the ETC relationship, given by Eq. (8):

$$\varepsilon_{c1,\mathrm{ETC}}=\varepsilon_{c1,\mathrm{EC2}}-\phi\frac{f_c}{f_{ck}}=\frac{2\,\varepsilon_{c1,\min}+\varepsilon_{c1,\mathrm{EC2}}}{3} \tag{8}$$

The ETC tangent modulus and the ETC initial stiffness (elastic modulus) are obtained directly by derivation of Eq. (7). The parameter n is chosen to obtain the best possible correlation between Eq. (7) and the curve obtained as the difference between the EC2 relationship and the transient creep strain. It was chosen to use a single value of n for all temperatures. Good correlation in the range of temperatures from 100°C and 1100°C is obtained using $n=2$.

The presented ETC model is based on the current EC2 model but it contains an explicit term for transient creep. The comparison between the experimental behavior of a reinforced concrete column subjected to natural fire and the numerical simulation performed with the software SAFIR using the ETC model is given in [20].

3.2 Implementation in the software SAFIR

The procedure of the finite elements calculation method implemented in the non linear software SAFIR is schematized in Fig. 3, particularized for the ETC concrete material law. The following notation has been used: $\underline{f}_{\mathrm{ext}}$ is the vector of the external nodal forces at a particular moment, $\Delta\underline{f}$ is a given increment of force between step (s-1) and step (s), T is the temperature (which has been calculated for every time step before the beginning of the mechanical calculation), $\underline{r}^{(i)}$ is the residual force after (i) rounds of iteration, $\underline{f}_{\mathrm{int}}$ is the vector of the internal forces, $\Delta\underline{u}$ is the increment of displacement corresponding to $\Delta\underline{f}$, $\underline{\underline{K}}^{(i)}$ is the stiffness matrix, $\underline{\underline{B}}$ is the matrix linking deformations and nodal displacements and $\underline{\underline{D}}_t$ is the tangent stiffness matrix of the non linear material law.

It is of current practice to calculate the thermal strain at the beginning of each time step, as a function of the temperature. This thermal strain does not vary during a time step. When entering into the material law during the iterative resolution of the equilibrium, the thermal strain is subtracted to the total strain, which allows for writing the material law in terms of the mechanical strain. This approach has been used in the current EC2 model.

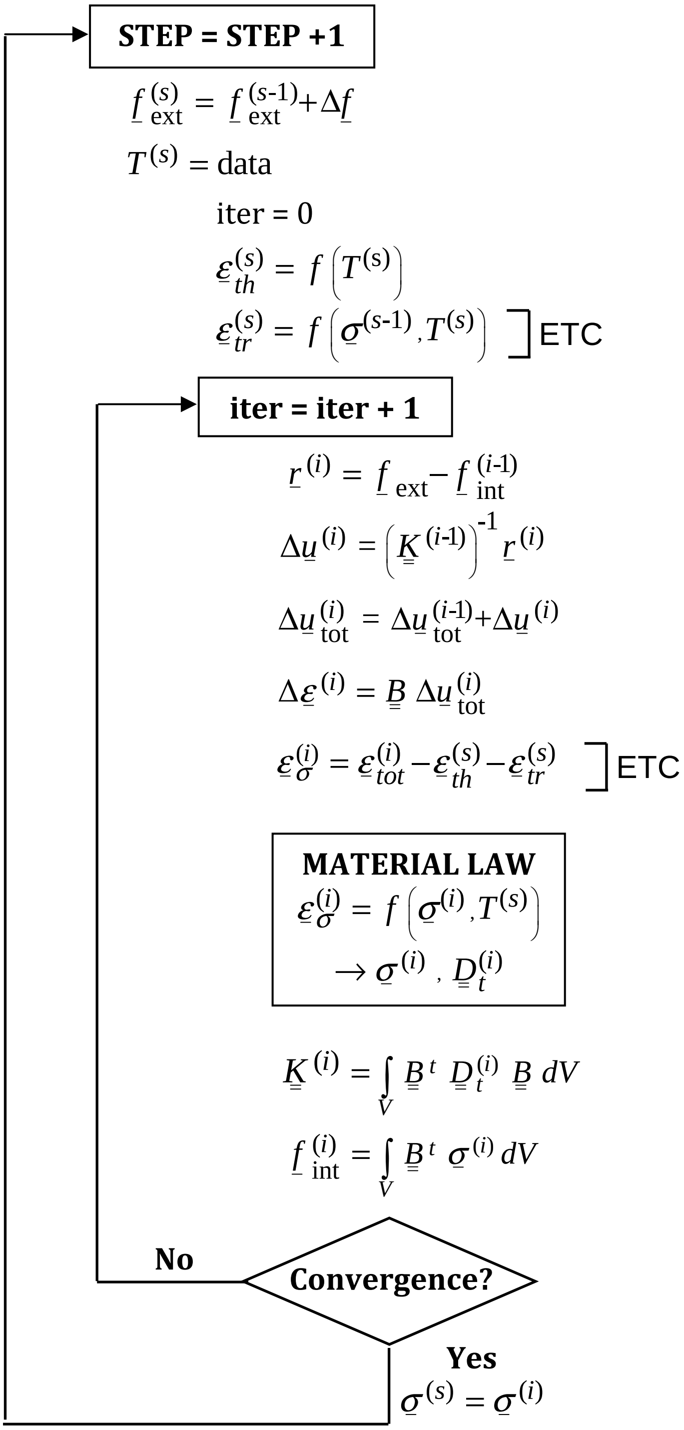


Fig. 3 Implementation of the ETC concrete model in SAFIR

In the ETC model, it was decided to calculate the transient creep strain at the beginning of each time step, at the same time as the thermal strain. This assumption allows for treating the transient creep effects separately from the elastic and plastic effects, i.e. the transient creep calculation is decoupled from the integration of the constitutive law of the material. The aim in the ETC model was to obtain a direct constitutive relationship in terms of the instantaneous stress-related strain.

At the beginning of the time step, the stress at the equilibrium is not known. Consequently, it was decided to calculate the transient creep strain as a function of the stress at the previous time step. This assumption is required to avoid an additional iterative process for the calculation of the transient creep strain. It was considered by the author that this assumption was valid for the structural applications for which the model is developed, and that the additional complexity and CPU time required to include the transient creep calculation into the integration of the material law were not justified for these applications.

The transient creep strain calculation takes into account the stress-temperature history. Between step (*s*) and step (*s*-1), if the temperature has increased, the increment in transient creep strain is calculated by the following expression:

$$\Delta\varepsilon_{tr} = \left[\phi\left(T^{(s)}\right) - \phi\left(T^{(s-1)}\right)\right] \frac{\sigma^{(s-1)}}{f_{ck}} \quad \rightarrow \quad \varepsilon_{tr}^{(s)} = \varepsilon_{tr}^{(s-1)} + \Delta\varepsilon_{tr} \tag{9}$$

where $\sigma^{(s-1)}$ is the compressive stress at the previous time step. If the temperature has decreased or remained constant between step (*s*) and step (*s*-1), there is no variation of transient creep strain. As the function $\phi(T)$ is growing with temperature, the transient creep term can only increase. Note that it is assumed that the transient creep strain is the same for loading and unloading as long as the stress is in compression [6]. In tension, it has been assumed that there is no transient creep strain.

As the thermal strain and the transient creep strain have been calculated at the beginning of the step, the material law is written in terms of the instantaneous stress-related strain in the ETC model. The ETC constitutive relationship (written in instantaneous stress-related strain) has a generic form that is similar to the EC2 constitutive relationship (written in mechanical strain), but using different values for the parameters, see Eq. (7). However, the main difference between the ETC and the EC2 model is the explicit calculation of the transient creep strain in the ETC model.

4. Axially Restrained Reinforced Concrete Columns Subjected to Heating and Cooling

A series of experimental fire tests made at South China University of Technology on axially restrained concrete columns, described by Wu [1], was simulated using the nonlinear finite element software SAFIR [15]. The experimental data were compared with the computed results obtained respectively with the EC2 concrete model and the ETC concrete model. The columns are all 2340 mm height (Fig. 4) but only their central portion of 1650 mm is exposed to fire. Two different cross sections were considered, t-shape and l-shape cross sections (Fig. 5). The C30 concrete cross sections are reinforced with 12 longitudinal steel bars of HRB400 (hot rolled ribbed bar of 400 MPa grade) with a diameter of 10 mm. The columns are axially restrained using a restraining beam. The columns were initially concentrically loaded and then subjected to the standard ISO-834 fire on all sides. Two

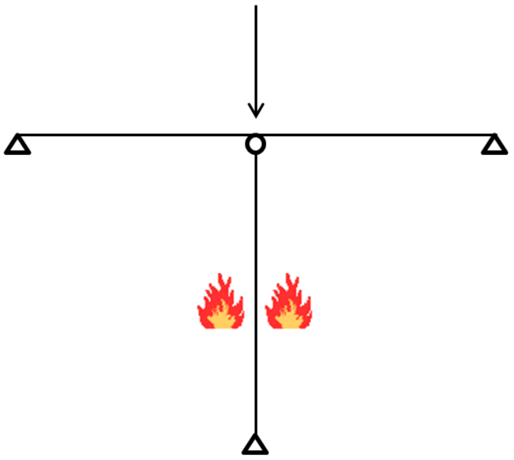


Fig. 4 Elevation view of the column

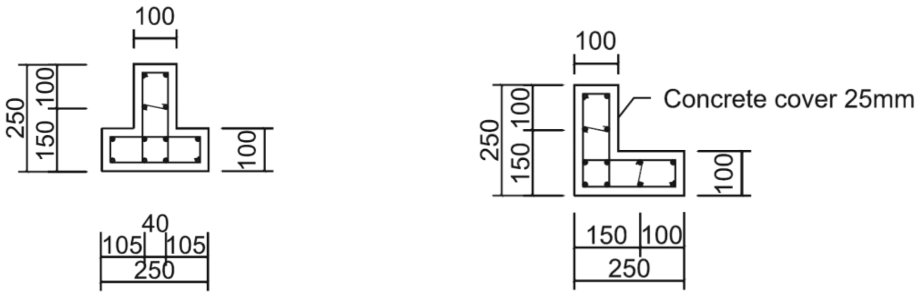


Fig. 5 T-shape and L-shape cross sections

Table 1
Applied load and axial restraint for the fire tests

Column no.	Load [kN]	Axial restraint [MN/m]
RCT11	271	34.5
RCT12	272	51.9
RCT21	375	34.5
RCT22	377	51.9
RCL11	292	34.5
RCL12	285	51.9
RCL21	382	34.5
RCL22	380	51.9

different levels of axial restraint and two different levels of load were considered for each shape of cross section, which leads to eight different cases, see Table 1. The fire was stopped when approximately 50% of the working load was transferred from the column to the restraining beam, i.e. after a time varying between 90 and 105 min depending on the case, followed by a cooling phase.

Thermal parameters for concrete and steel recommended by EC2 were used in the heat transfer analysis by SAFIR. Note that, in the original paper presenting the test, the thermal analysis of the tests has been performed using the thermal parameters from the EC2 and the software SAFIR and the simulations showed good agreement with the measured temperatures in the section [1]. For the structural analysis, initial eccentricity of 3 mm was introduced as it is the same value used by Wu to perform the numerical simulation of its tests. No buckling phenomenon was observed during the test. After the fire tests, minor spalling of concrete was observed for several columns. But in the numerical simulations, accidental spalling because of close fire exposure was hard to predict and thus not considered. The mechanical law for the steel reinforcement was taken from Eurocode. It should be noted that no creep is explicitly considered in these relationships for steel reinforcement, which is an important assumption as the creep of the steel reinforcement is known to have an effect on stress and strain state in reinforced concrete frames when temperature in reinforcement bars exceeds 400°C [21, 22], as is the case here. The axial restraint stiffness remains unchanged during the simulations, which can be justified by the fact that the maximum displacement at the center of the restraining beam is only about 13 mm [1]. The deformation behavior and the evolution of the axial load for the eight experiments can be observed in Fig. 6.

The ETC model and the EC2 model lead to comparable results during the expanding phase of the column. Then during the contracting phase, the behavior predicted by the ETC model tends to differ from the behavior predicted by the EC2 model; the effect of the explicit consideration of transient creep on the structural behavior becomes notable. The difference between the behaviors predicted by the ETC and the EC2 models is particularly significant during the cooling phase. The ETC model matches better than the EC2 model the actual behavior of the structure for all eight experiments.

In these experiments, the contracting phase is associated with the unloading of the column because of the axial restraint. It appears that the unloading stiffness predicted by the EC2 model is underestimated. This is due to the fact that the transient creep strain that is implicitly considered in the EC2 model is recovered during unloading. On the contrary, owing to the explicit term for transient creep strain, the ETC model allows for a better modeling of the column behavior in unloading and cooling situations.

5. Practical Significance of the Results

It has been shown that the new concrete constitutive model performs better than the existing Eurocode 2 model at predicting the evolution of the axial force in the column and the overall axial deformation during the cooling phase of the fire. The effect of the transient creep strain model on the global behavior of the columns is significant as the residual axial load sustained by the columns at the end of the fire can differ by up to 25% of the initial applied load depending on the transient creep strain model that is used for the calculation. The new model is more accurate than the EC2 model owing to the explicit calculation of transient creep strain during the step-by-step analysis. Particularly, the results given by the Eurocode model during the cooling phase are unconservative as the residual axial load is overestimated.

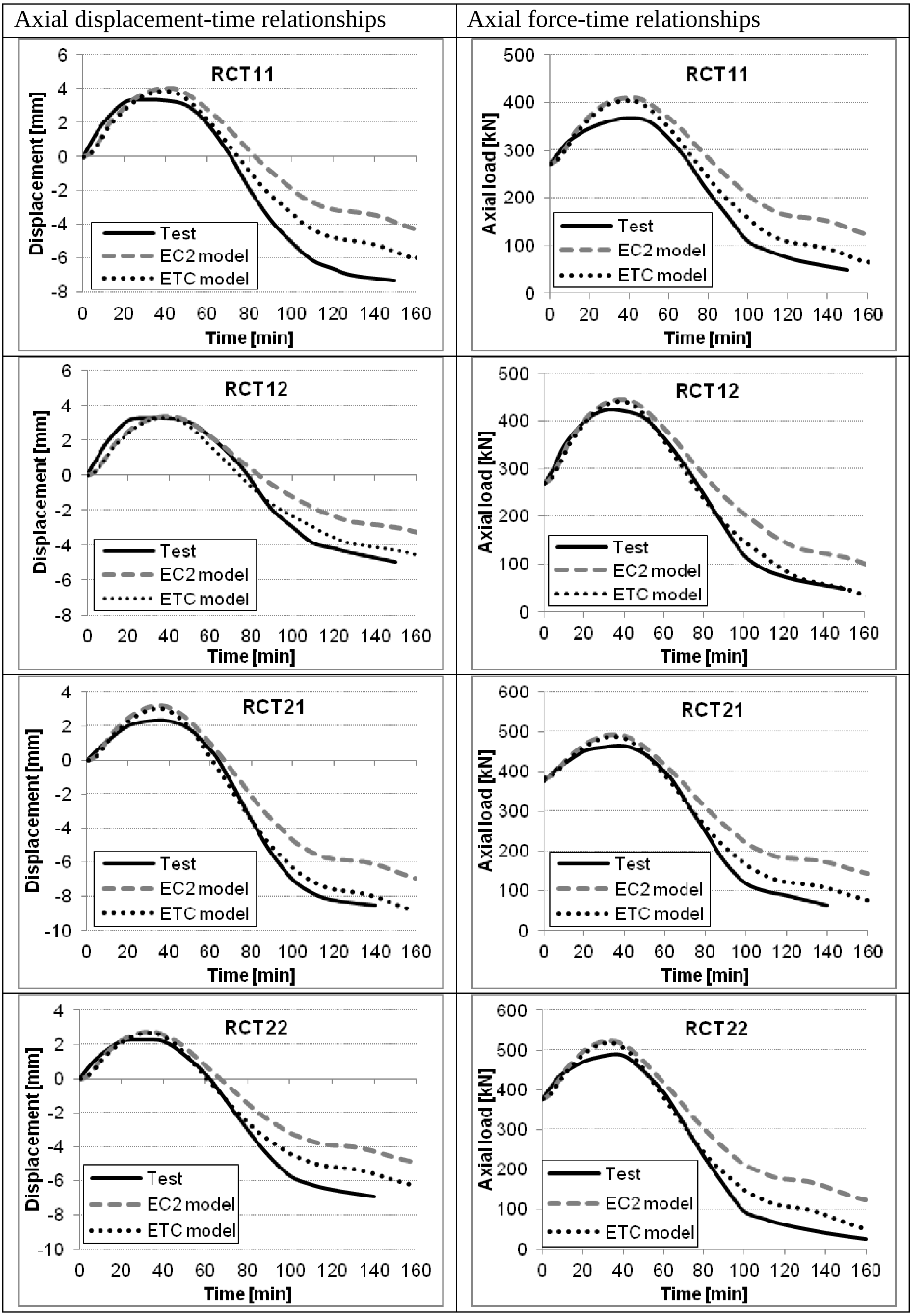


Fig. 6 Comparison between measured and computed results

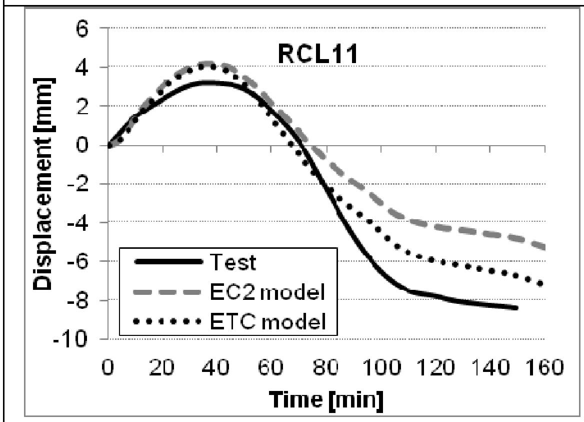
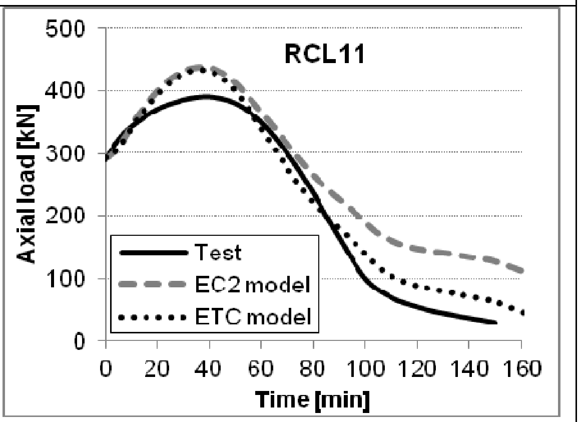
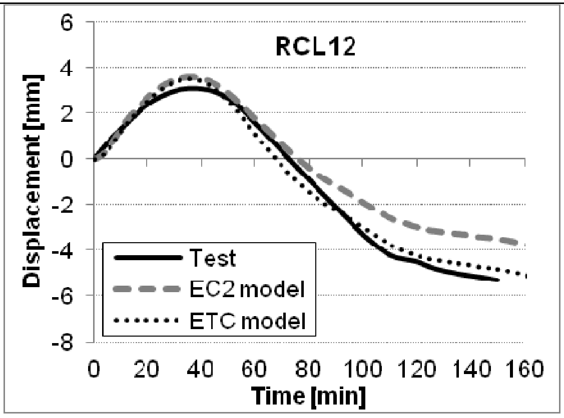
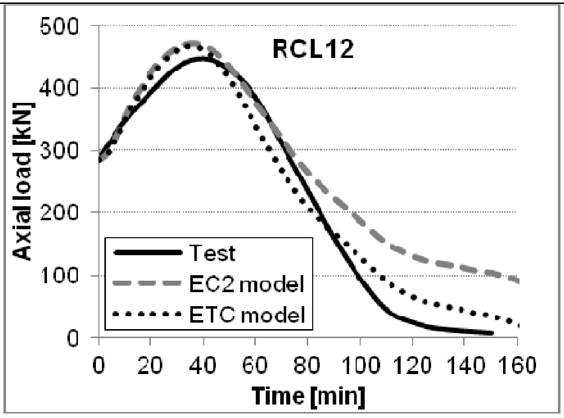
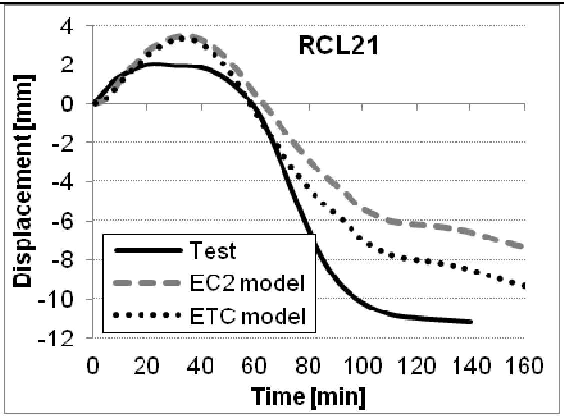
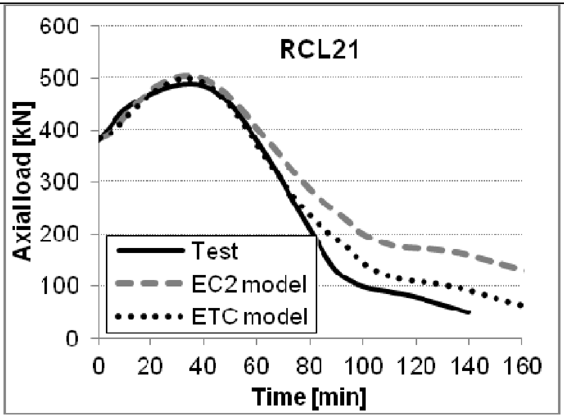
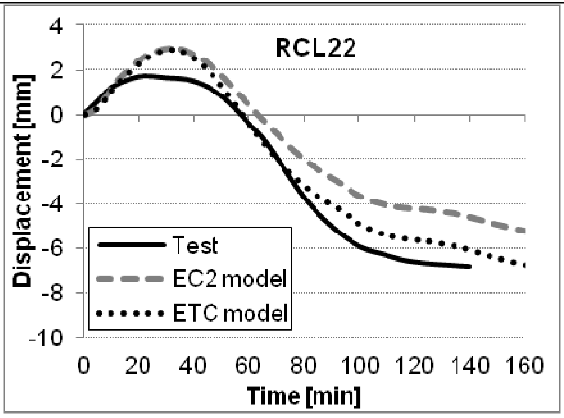
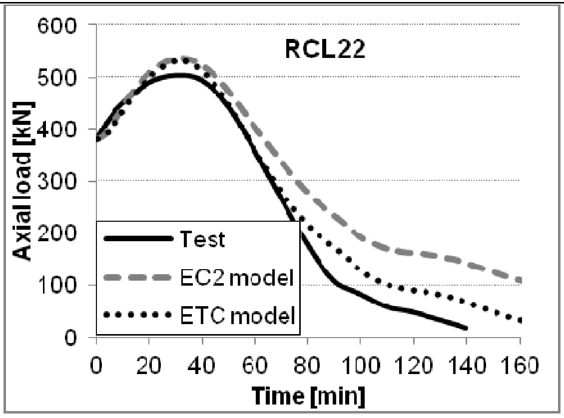
Axial displacement-time relationships	Axial force-time relationships
	
	
	
	

Fig. 6 continued

In a prescriptive approach, the columns are checked for fire resistance when subjected to standard fire (such as the ISO fire), in which only the heating phase is considered. However in a performance-based approach, it can be very important to model the cooling phase of the fire too as explained in Section 1.2.

Similarly in a prescriptive approach, the structural member should be given a failure criterion beyond which it is considered that the collapse has been reached. In such approach, the load decrease in a column could never reaches the levels obtained in the simulations of Section 4, where load decrease of up to 90% were observed, because the failure criterion would have been reached much before. Yet in a performance-based approach, the structural fire engineers do not consider the structural members as isolated of the rest of the structure but aim to model the actual behavior of the entire structure. Indeed, if the structure is properly design, it may have a certain robustness that allows for a redistribution of the forces during the fire. In a robust structure, the fact that one of the structural elements is not able to sustain the applied load any more does not automatically imply the collapse of the entire structure.

In the experiment presented in Section 4, the column is axially restrained and it is considered that the applied vertical load can shift to the axial restraint beyond the time when the column displacement goes back to the initial equilibrium state. In a real building, this would correspond to a situation where the structure, that has certain robustness, is able to redistribute the load initially supported by the column to the other columns thanks to horizontal elements. For instance, let’s consider the structure of Fig. 7 and let’s assume that a localized fire is attacking only the central column. If the structure is sufficiently robust, the load that was supported by the central column can be redistributed to the other columns through the beam. In this case, the collapse of the central column, that can be considered as the time when the column is not able to support the initial applied load any more, does not automatically imply the collapse of the entire structure. The discussion would be the same for instance if the fire had developed in the entire compartment but that the central column, that had less strength in reserve, had reached collapse before the other columns.

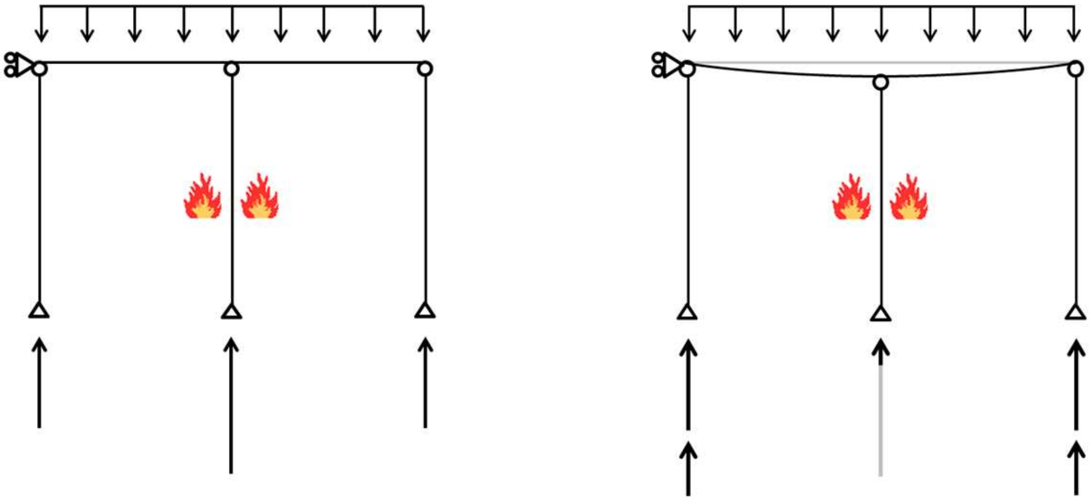


Fig. 7 Redistribution of forces in a robust structure subjected to localized fire. Left: at the beginning of the fire; Right: at the end of the fire.

In the practical application described here, it is clear that if the evolution of the axial load in the central column is not properly evaluated, the additional load redistributed to the rest of the structure could be underestimated. Finally, this could lead to a wrong estimation of the global fire resistance of the structure. The constitutive model that is used for the concrete material, and especially the type of transient creep strain model, could thus have an implication on the estimation of the global fire resistance of a structure. Simplified models such as Eurocode 2 are well adapted for prescriptive approaches, i.e. to model the behavior of concrete elements subjected to the heating phase of a fire; but the fire engineer should be careful when using such simplified models during the cooling phase as they were not validated for these applications. When it comes to performance-based design, more accurate models should probably be used, and notably the transient creep strain should be properly modeled with an explicit term.

6. Conclusion

Modeling the transient creep strain either implicitly or by an explicit term in the constitutive model can have an influence on the global behavior of structural concrete members in fire situation. This influence becomes significant when the cooling phase is taken into account. For instance, it has been shown that the residual axial load sustained by a column at the end of a natural fire can be overestimated by up to 25% of the initial applied load, compared to the experimental results, if an implicit transient creep strain model is used. The residual axial load computed with the explicit transient creep strain model is much closer to the experimental results. The transient creep strain model that is used can thus have important implications if, for instance, the residual load bearing capacity of a building after a fire has to be evaluated.

The current Eurocode 2 concrete model, that includes implicitly the transient creep strain, has shown limitations for representing accurately the behavior of axially restrained concrete columns subjected to heating and cooling. It has been shown that an explicit model could be more appropriate, especially when modeling the cooling phase of a fire. A new, explicit formulation of the EC2 concrete model has been proposed in this paper, in order to benefit from the capabilities of explicit models while keeping the generic formulation of the Eurocode.

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