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RESPONSE OF RC COLUMNS WITH TRANSIENT CREEP IN A NATURAL FIRE ENVIRONMENT

A. SADAOUI*, K. LATTARI* AND A. KHENNANE†

* Department of civil Engineering, Faculté de Génie de la Construction
University of Mouloud Mammeri, Tizi-ouzou, Hanaoua II, Algeria
e-mail: a_sadaoui@yahoo.com

* Department of civil Engineering, Faculté de Génie de la Construction
University of Mouloud Mammeri, Tizi-ouzou, Hanaoua II, Algeria
e-mail: lattari_kamel@hotmail.fr

† University of New South Wales (UNSW), Australian Defence Force Academy
PQ Box 7916, Canberra, Australia
email: a.khennane@adfa.edu.au

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Abstract. The aim of this study is to investigate the effect of transient creep on the structural response of RC columns subjected to natural or parametric fires using a finite element model developed by the authors. The model, capable of analysing the response of RC columns from pre-fire stages to collapse in fire environment, is specially developed for the analysis of RC structures under severe thermo-mechanical loads, which accounts for transient creep explicitly as an additional component of the total strain of the concrete or implicitly through the use of the materials' properties recommended by EC2. Through the obtained results, it is shown that the transient creep phenomenon significantly influences the fire response of RC columns. It was also found that the conventional method based on standard fire exposure may not be conservative if the resulting fire has a decay phase similar to the severe fire scenario used in this work.

1 INTRODUCTION

The performance of a reinforced concrete (RC) structure in a fire environment depends particularly on the behaviour of the columns subjected to fire. These structural elements form the main mean of load transfer to the foundations because a failure of column is more detrimental to a building than that of a beam or a slab, and more likely to result in a progressive collapse [1,2,3]. Columns are subject to a combination of thermo-mechanical actions that arise from restrained thermal elongations, degradation of the mechanical properties of the constituents, and transient creep in the concrete. The transient creep, also usually referred to as transitional thermal creep or load induced creep, is unique to concrete and develops only during first time heating of the concrete under compressive stresses [4,5,6].

Temperature increase in fire conditions is well known to decrease the load bearing capacity of concrete and to increase its deformability. The structural and chemical changes taking place in the material, the internal stresses caused by the temperature gradients, as well as the high pore pressures caused by the evaporation of pore water, combine to develop internal microcracks or damage within the concrete [7]. For instance, as the temperature increases, the cement paste begins to decompose as a consequence of dehydration. Physical-chemical changes also take place in the aggregates. For this reason the decrease of compressive strength of concrete at elevated temperatures depends also on the type of aggregates used. Hence the mechanical properties, such as the elastic modulus and compressive strength, decrease with increasing temperatures. The concrete becomes more compliant. Its thermal dilatation coefficient increases non-linearly with temperature [8]. Concrete spalling may also appear as a result of thermal gradients and increasing pore pressure [9].

The majority of studies carried out on the behaviour of RC columns are based on the standard heating conditions, which do not take into account post-flashover fire temperature-time curve. There is no reliable experimental data, mathematical models, or design specifications for predicting the behavior of these elements under realistic fire scenarios. Thus, the current approach of determining fire resistance of RC columns by testing under standard fire conditions may not be realistic, since a number of factors such as compartmentation characteristics (opening size, fire load density, thermal properties) are not accounted for. Furthermore, the mechanical response depends on both load and temperature histories. Such dependence manifests itself in the absence of transient creep if a concrete specimen has already been subject to a high temperature cycle prior to testing. It is believed that any structural analysis of heated concrete that ignores this phenomenon will yield erroneous results, particularly for columns exposed to fire. Consequently, the design of columns is of paramount importance to the structural integrity of the whole structure, and should be based on more direct analytical approach that determines the structural fire response, which takes into account the fire compartmentation characteristics, the ventilation conditions, and, among all, the thermo-mechanical properties of the structural materials as well as transient creep phenomenon effects.

The aim of this study is to investigate the effect of transient creep on the structural response of RC columns subjected to natural or parametric fires using a finite element model developed by the authors [3,4]. The model, capable of analysing the response of RC columns from pre-fire stages to collapse in fire environment, is specially developed for the analysis of RC structures under severe thermo-mechanical loads, which accounts for transient creep explicitly as an additional component of the total strain of the concrete or implicitly through the use of the materials' properties recommended by EC2 [10].

2 BASIS OF THE NUMERICAL MODEL

The thermo-mechanical response of RC columns is obtained in an uncoupled way with incrementing time in steps. Because of the dependence of the material properties on temperature, thermal and mechanical responses are obtained incrementally. But initially, the element is analyzed at ambient temperature under service loads only, just prior to the beginning of a fire.

2.1 Main steps of fire analysis

Within a time step, the fire resistance analysis of a restrained RC column subject to natural fire scenarios is performed through four main steps as briefly illustrated on figure 1.

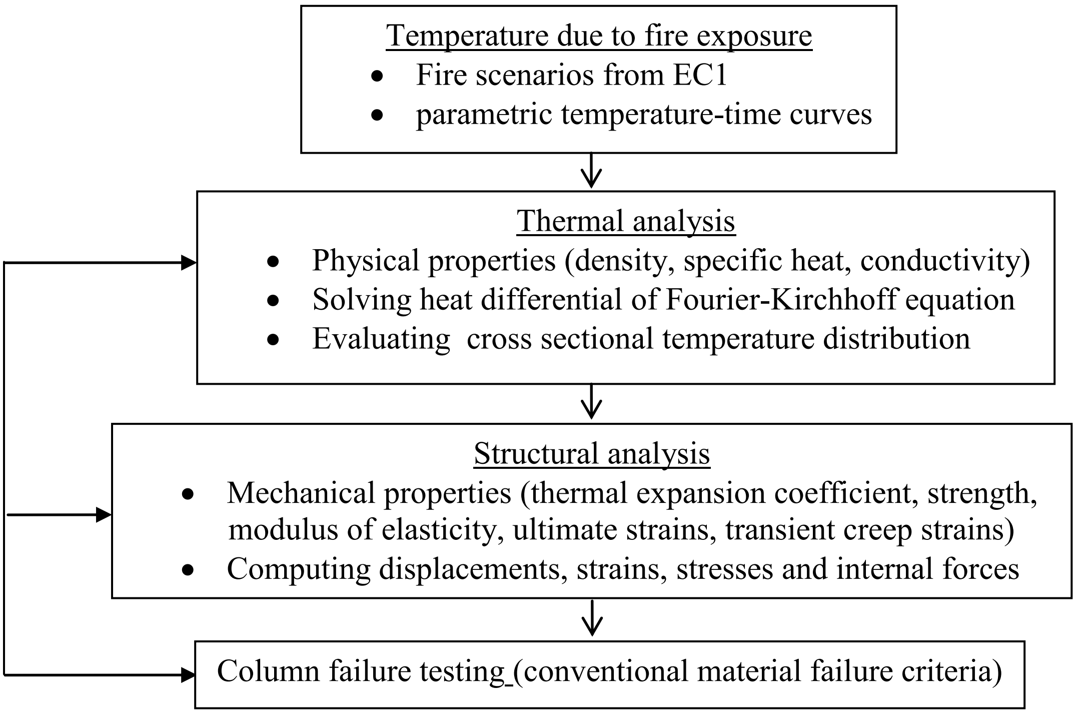

Figure 1: Main steps of fire analysis of RC columns

The first step consists in determining the temperature distribution due to fire exposure with help of the natural fire scenario defined in EC1 [11] as parametric temperature time curves. The second step is the thermal analysis to determine the temperature distribution along the cross-section of the column in order to evaluate the changes occurring in the material mechanical properties. This is followed by a static structural analysis to obtain the equilibrium configuration of the structural element at any time of the fire exposure. The computer model generates various critical output parameters, such as temperatures, stresses, strains, displacements and fire induced transient creep forces at various given fire exposure times. These parameters are then used to check against pre-determined failure criteria, in which the failure of a RC column is said to occur when the column element is unable to resist the specified applied service load (conventional material failure criterion). The failure occurs either by loss of the stability of the column or by exceeding the load-bearing capacity of the cross-section, which may be expressed by the failure criterion material (crushing of concrete and/or yielding of the steel).

2.2 Thermal analysis

The computed temperature-time curves describing the fire scenario are used to calculate the temperatures within the column cross-section using a finite element formulation. Cross sectional area of each column finite element is subdivided into a number of layers or sub-layers forming a two dimensional mesh. The temperature rise is obtained by establishing a heat balance of the cross section and detailed equations for the calculations are derived [12]. The temperature is assumed to be uniform along the length of the column and thus the calculations are performed for a unit length of the cross section. Steel reinforcement is not specifically considered in the thermal analysis because it does not significantly influence the temperature distribution. The initial moisture content is taken equal to 6%, which, according to EC2, corresponds to a peak value of the specific heat equal to 3700 J / kg. ° K.

2.3 Structural analysis

The cross-sectional temperatures generated from thermal analysis are used as input to the structural analysis step. A two-dimensional Euler-Bernoulli beam-column element based on the finite element displacement method approach and a Lagrangian co-rotational formulation are used in order to describe the deformation behavior of the column at any time of the fire exposure. Gaussian and Simpson rules are also employed to integrate stiffness matrices and internal forces along the longitudinal and transverse directions. Furthermore, the equilibrium equations which are derived from the incremental formulation of the principle of virtual displacements, make use of a tangential operator derived by integrating the stress-strain rates of concrete and steel at elevated temperatures. The formulation includes geometrical nonlinear effects resulting from large displacements, and material nonlinearities due the degradation of the elastic and inelastic properties with temperature. Detailed equations for formulations have been already described to some extent in [13]. Also, the concrete model accounts for cracking and crushing, as well as transitional thermal creep, which is considered in the present work explicitly as an additional component of the total strain, or implicitly through the use of the materials' properties of the concrete as recommended by the EC2.

2.4 Displacement and strain decompositions

Given, the equilibrium configurations of the element at the instants t_0 , t and t + Δt such as represented schematically on figure 2. Taking into account the geometrical configuration of a beam element for which the longitudinal dimension is very important compared to the two other dimensions, and the Navier Bernoulli hypothesis of straight sections, it follows that the axial strain of any point at time t is given by:

$$ {}^{t}\varepsilon_x = {}^{t}u_0' - y\,{}^{t}v_0'' + \frac{1}{2}\left({}^{t}v_0'\right)^2 \tag{1} $$

The prime denotes derivative with respect to ${}^{0}x$. In an expression analogous to (1), the strain at t+Δt is obtained as :

$$ {}^{t+\Delta t}\varepsilon_x = {}^{t+\Delta t}u_0' - y\,{}^{t+\Delta t}v_0'' + \frac{1}{2}\left({}^{t+\Delta t}v_0'\right)^2 \tag{2} $$

The preceding expressions give the strains at times t and t+Δt of any point of the section in the case of important displacements and small strains. In order to introduce the incremental formulation of the principle of virtual displacements, let's write the following incremental decompositions in stress and displacements:

$$^{t+\Delta t}\sigma_x = {}^{\mathrm{t}}\sigma_x + \Delta\sigma_{\mathrm{x}} \tag{3}$$

$$^{t+\Delta t}u_0 = {}^{\mathrm{t}}u_0 + \Delta u_0 \tag{4}$$

$$^{t+\Delta t}v_0 = {}^{\mathrm{t}}v_0 + \Delta v_0 \tag{5}$$

Substituting (4) and (5) in (2) leads:

$$^{t+\Delta t}\varepsilon_x = {}^{\mathrm{t}}\varepsilon_x + \Delta\varepsilon_{\mathrm{x}} \tag{6}$$

$$\Delta\varepsilon_x = \Delta \mathrm{u}_0' - \mathrm{y}\Delta \mathrm{v}_0'' + {}^{\mathrm{t}}v_0'\Delta v_0' + \frac{1}{2}\left(\Delta v_0'\right)^2 \tag{7}$$

which in turn can be decomposed into a linear and non linear parts :

$$\Delta\varepsilon_x = \Delta \mathrm{e}_{\mathrm{x}} + \Delta\eta_{\mathrm{x}} \tag{8}$$

$$\Delta \mathrm{e}_{\mathrm{x}} = \Delta \mathrm{u}_0' - \mathrm{y}\Delta \mathrm{v}_0'' + {}^{\mathrm{t}}v_0'\Delta v_0' \tag{9}$$

$$\Delta\eta_x = \frac{1}{2}\left(\Delta v_0'\right)^2 \tag{10}$$

2.5 Materials thermo-mechanical law

In a time increment, Δt, the total strain increment, $\Delta\varepsilon_x$, of a generic material fibre of a beam-column finite element is assumed to be the sum of increments of elastic, $\Delta\varepsilon_e$, plastic, $\Delta\varepsilon_p$, thermal, $\Delta\varepsilon_{th}$, transient creep, $\Delta\varepsilon_{tr}$; the latter being non-zero in concrete and assumed that develops under first time of heating and under a state of compression only [6]. The sum elastic and plastic parts of strain increment is termed the mechanical strain increment $\Delta\varepsilon_\sigma = \Delta\varepsilon_e + \Delta\varepsilon_p$ which can be written as:

$$\Delta\varepsilon_\sigma = \Delta\varepsilon_x - \Delta\varepsilon_{\mathrm{th}} - \Delta\varepsilon_{\mathrm{tr}} \tag{11}$$

We assume that the relationship between the mechanical strain and the longitudinal normal stress, σ, is given by the constitutive law $\sigma=f(\varepsilon_\sigma,\Theta)$, where f is a functional pertinent to the chosen material. In the present work, we use the temperature dependant constitutive laws of concrete and reinforcing steel as suggested in EC2. An isotropic strain-hardening model is assumed in loading-unloading cycles. The adopted incremental thermo-mechanical law can be written in the form:

$$\Delta\sigma_x = \mathrm{E}_T\left(\Delta\varepsilon_x - \Delta\varepsilon_{\mathrm{TH}} - \Delta\varepsilon_{\mathrm{TR}}\right) \tag{12}$$

where $E_T = E_T({}^t\varepsilon_x)$ is the tangent modulus corresponding to a strain ${}^t\varepsilon_x$ of the material σ-ε curve at time fire exposure t. $\Delta\varepsilon_{th}$, and $\Delta\varepsilon_{tr}$ are respectively the incremental strains of free thermal elongation and transient creep computed during the time step Δt at any given iteration Newton-Raphson process as described in the following section.

2.6 Free thermal elongation and transient creep strains

The free thermal elongation strain in concrete and steel, $\Delta\varepsilon_{th,c}$ and $\Delta\varepsilon_{th,s}$, is assumed to be a function of the current temperature, Θ, and is given by the generic relation $\Delta\varepsilon_{th}=\Delta\varepsilon_{th}(\Theta)$. The approximation of the function for concrete and steel as defined in EC2 is adopted here. The concrete transient creep strain, $\Delta\varepsilon_{tr,c}$, is assumed to be a function of the current stress σ_c, time and temperature. We adopt the model proposed by Anderberg and Thelanderson [14], accounted for with a simple formula as:

$$\Delta\varepsilon_{tr,c} = \frac{k\sigma_c}{f_{c20}}\Delta\varepsilon_{th,c} \tag{13}$$

where f_{c20} is the compressive strength at ambient temperature (=20°C), $\Delta\varepsilon_{th,c}$ is the free thermal elongation strain increment of the concrete and, k a coefficient varying between 1.8 and 2.35.Noting that the transient creep strain is proportional to σ_c and thus a sign that is opposite to the sign of $\Delta\varepsilon_{th,c}$ where concrete is stressed in compression.

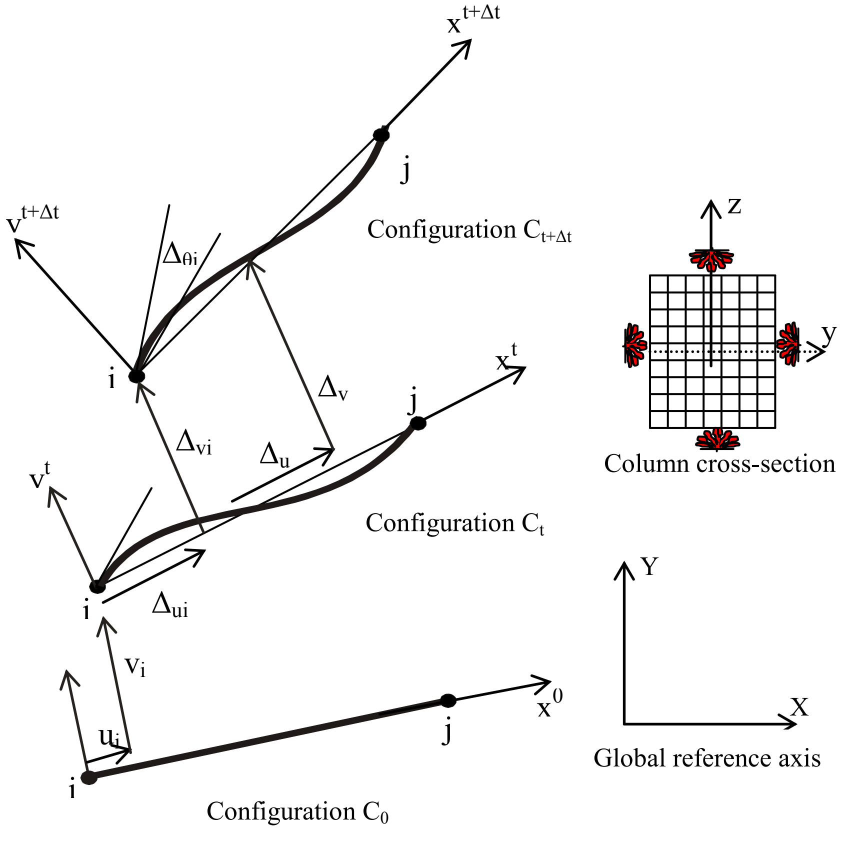

Figure 2: Equilibrium configurations of a structural finite element ij in a Lagrangian co-rotational formulation at any time fire exposure (t)

3 FIRE SCENARIOS

Three fire scenarios are investigated; namely ISO834 and two design fire scenarios: Fire I and Fire II. There is no decay phase in the time-temperature curves for the standard fire scenario. However, in realistic fires represented by the two design fires, there is always a decay phase, since the amount of fuel or ventilation runs out leading to the burn out phase of the fire. The parametric fire time-temperature curve proposed in EC1 are selected to represent the design fire scenarios used in the analysis, which are influenced by compartment properties such as the fuel load, ventilation opening and wall linings. To develop the two design fire scenarios, a fire is assumed to occur in a room with dimensions of 6mx4mx3m as illustrated in figure 3 [13]. Two values of the fuel load and the opening dimensions are also assumed. More details about the properties of the room for the two fires are represented in Table 1. The values were assumed in such a way that Fire I represents a severe design fire whose temperatures exceeds 1200°C, such as in a library or storage room where large amount of combustible materials and sufficient ventilation are available. Fire II represents a moderate design fire whose temperatures reach 600°C. The obtained time-temperature curves are shown in Figure 4. The results from the analysis indicate that the fire scenario has a significant influence on the temperature distribution across the column section. As expected, the temperature at various depths of concrete increases with the fire exposure time for the standard fire scenario. The results also show that the increase in concrete is slightly larger for the ISO 834.

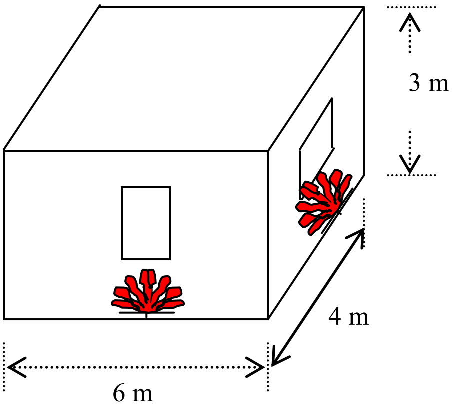

Figure 3: Compartment in fire

Table 1: Compartment characteristics

Design Fire	Lining material	$Ws^{0.5}/m^2°K$ (Thermal capacity lining material)	Opening (m)	MJ/m^2 floor area (Fire load)
Fire I	Gypsum	488	2.25x1.5	1200
Fire II	Concrete	1500	2.85x1	400

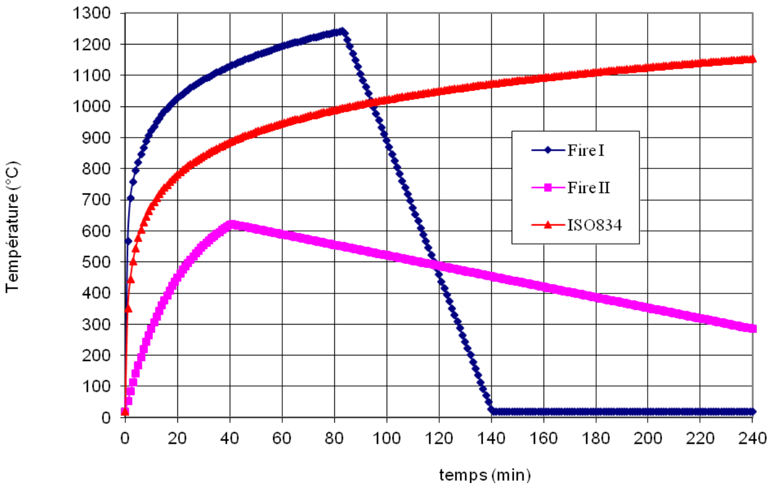

Figure 4: Various fire scenarios

4 RESULTS AND DISCUSSIONS

Geometrical and loading details of the column are shown on figure 5 having an initial sinusoidal imperfection of $\omega_o = \ell/1000$. It is sufficiently slender with an initial deflection as to induce second order effects. Additionally, a compressive load of P_0=740 kN is applied with an eccentricity e_0 of 15 mm. The column is pinned at both ends with the loaded end free to elongate axially. It is heated on all the four faces while keeping the applied load constant. The column is assumed to be made of normal concrete with a compressive strength f'_c = 30 MPa, tensile strength f_t= 3.5 MPa, and reinforced with steel rebars having a yield strength f_y = 400 MPa. The concrete cover relative to the stirrups is taken as equal to c= 30 mm for all the columns. In the analysis, the column is also assumed to be exposed to fire from all sides, and the materials' properties suggested by the EC2 are adopted. The fire resistance is evaluated based on the conventional material failure criterion previously defined particularly expressed by crushing of concrete and/or yielding of the steel. Fire induced spalling is supposed not occur since the column is made of normal concrete (NC), which exhibits a relatively high permeability. This provides an easy mechanism for the water vapor to escape from the concrete. Thus, with increasing temperatures the pore pressure continuously dissipates in the column, and there is no significant vapor pressure build-up. This is agreement with reported test results, which clearly show negligible spalling in NC members during fire exposure [15].

To investigate the effect of transient creep on its behavior, the column is analysed under two different cases. In the first case, transient creep is considered implicitly through the use of the variations of the material properties with temperature as recommended by the Eurocode [10]. In the second case, transient creep is considered explicitly as an additional strain component. The obtained results are shown in the form of the progression with time fire exposure of the axial displacement, u, of the loaded end and the lateral deflection, v, of the middle of the column.

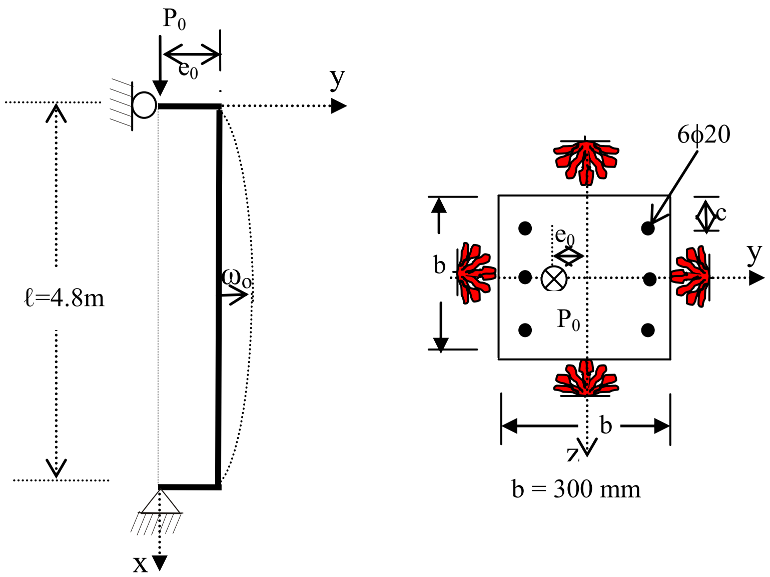

Figure 5: Geometrical details of the column

4.1 Effect of fire scenario

Figures 6 and 7 show the results with fire exposure for the three fire scenarios when transient creep is considered implicitly through the use of Eurocode's properties. It can be seen that the lowest fire resistance is obtained for the column exposed to the severe fire design Fire I. It is about 38 min in Fire I, 62 min in ISO834 and 180 min in Fire II. This is due to the rapid increase in temperature for Fire I as can be seen from figure 4. A reduction (or recovery) in the displacements is also noticeable particularly for the moderate fire design FireII as a result of the decay phase. Hence, the result reveals that in many applications, the fire resistance values computed based on standard fire exposure may not be conservative if the resulting fire has a decay phase similar to the one of design Fire I used in this study.

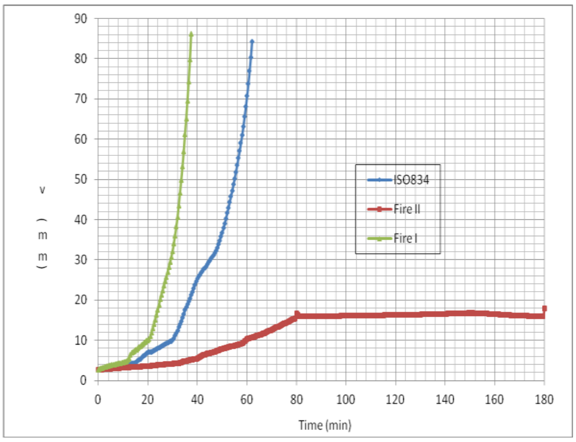

Figure 6: Effect of fire scenario on the deflection

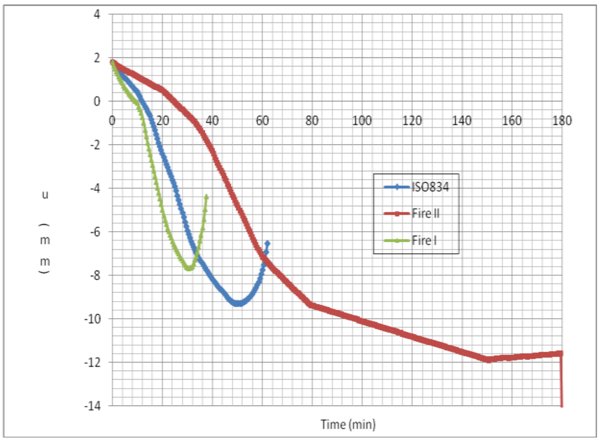

Figure 7: Effect of fire scenario on the axial displacement

4.2 Effect of transient creep

Figure 8 shows the model’s predictions under the severe fire design (Fire I) when transient creep is considered explicitly with: k = 0, k = 1.8 and k = 2.35. Temperature dependent material properties used are those derived originally by Anderberg and Thelandersson which also reported in [5,4] since Eurocode’s material data with temperature presents some ambiguity on whether these properties include transient creep or not. This can be explained by the fact the transient creep strains counteracts the thermal expansion and thus creating additional compressive stresses. Noting that the column is under a state of bending due to the influence of the eccentric load applied initially prior to the beginning of the fire. The increase in compressive stresses results in more plasticization of the compressed zone and more cracking in the tensile zone, and hence in a reduction of the overall stiffness of the beam. The sudden increase in the lateral displacement v indicates the onset of buckling which precipitates the failure of the column.

The results are also compared with the implicit model when the properties recommended by Eurocode are used. As shown in figure 9, it can be seen that the results agree better when transient creep is taken into account. The value of k = 1.8, which is the least recommended, was found to give the best agreement

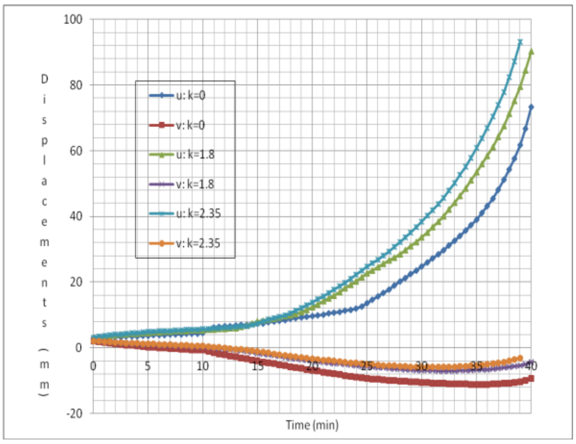

Figure 8: Effect of transient creep on the column response

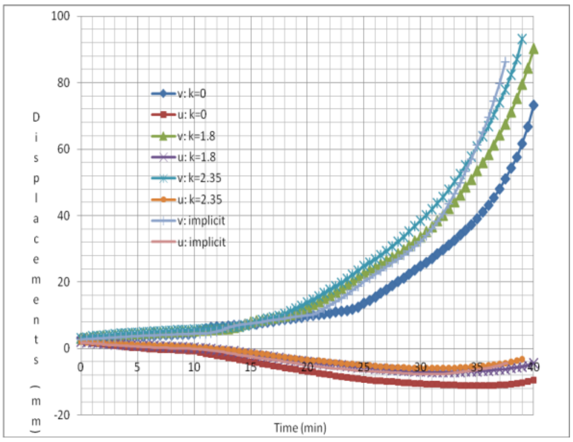

Figure 9: Model predictions using both the Eurocodes’s properties and transient creep

5 CONCLUSIONS

- The transient creep on the fire response of RC columns is investigated using two different approaches. In the first approach transient creep is considered explicitly as an additional component of the total strain, while in the second approach, the phenomenon is taken into account implicitly through the use of concrete data properties with temperature as recommended by the Eurocode.
- The transient creep modelled as an additional strain component is a more robust

approach since it provides an insight into the response of the column. The value of the transient creep strains coefficient k = 1.8 is found to give the best agreement comparatively to the implicit model.

- The transient creep effects counteracts the thermal expansion and thus creating additional compressive stresses, which clearly explains the rapid failure of the column at elevated temperatures where transient creep strains are important.
- The conventional methods of evaluating fire resistance, computed based on standard fire exposure, may not be conservative if the resulting fire has a decay phase similar to the severe fire scenarios as the one used in this study.

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