EFFECT OF RESTRAINTS ON THE RESPONSE OF RC COLUMNS IN A PARAMETRIC FIRE

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Abstract: The effect of induced restraint on the fire response of reinforced concrete (RC) columns is addressed in this work. A finite element model, capable of analysing the behaviour of restrained RC columns from pre-fire stages to collapse in fire is developed for the analysis of RC structure elements subjected to natural or parametric fire conditions. The advantage of the procedure is its ability to consider realistic constitutive relations for concrete and steel including wide range phenomena such as transient creep, plasticity, cracking, and degradation of material properties, all within the framework of large displacements and small strains theory. The model is used to investigate the effect of the degree of axial restraint, fire scenario, failure criteria, compressive load level, slenderness and eccentricity on the fire response of restrained RC columns. Through the results of the parametric study, it is shown that the fire parameters significantly influence the fire resistance of RC columns. It's also shown 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 study.

1 INTRODUCTION

The performance of reinforced concrete structures in a fire scenario depends particularly on the behaviour of the columns subjected to fire. These structural elements are of great importance to the structural integrity of the building because they contribute to its load-bearing capacity and global stability. The fire resistance of RC members is generally established using prescriptive approaches which are based on either standard fire resistance tests or empirical calculation methods [1].

In buildings which have been subject to fire, it is usual to find beams which show large permanent deflections in the horizontal plane as a consequence of axial restraint. The effect of these axial restraints on the fire resistance of beams depends on the vertical location of the restraint forces. Generally, the axial restraint force improves the fire resistance of RC beams through the arc action [2,3]. RC columns can also develop significant restraint forces during fire exposure. The degree of restraint is dependant on the support conditions and will determine the behaviour and fire resistance of RC columns.

At present, there is limited information on the fire induced restraint effects in RC columns. The available studies in the literature [4,5,6,7] were mainly experimental, and do not fully take into account the combined and inter-dependent effect of different parameters; such as axial restraint under various loading and fire scenarios. Thus, there have been only limited studies on evaluating the fire performance of RC columns (mostly unrestrained, fully restrained or weakly restrained) [7,8]. Furthermore, much of the current knowledge on the fire behaviour of RC columns is based on standard fire resistance tests under standard fire exposure. There have been limited research studies on evaluating the fire performance of RC columns under realistic (design) fire scenarios. Thus, there is no reliable experimental data, mathematical models, or design specifications for predicting the fire resistance of RC columns under design fire scenarios. Additionally, 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 realistic load levels, degree of restraint are not accounted for. Furthermore, compartmentation characteristics such as opening size, behaviour and eventual failure of an RC column, are not taken into consideration.

This work presents the effect of various parameters such as fire scenario, load level, degree of restraint, slenderness and eccentricity on the behaviour of RC columns exposed to fire. The numerical studies are carried out using a macroscopic finite element model specially developed by the authors for the analysis of RC columns under fire conditions [9].

2 NUMERICAL MODEL

A two-dimensional Euler-Bernoulli beam-column element based on the finite element displacement method approach is used to describe the deformation behaviour of RC columns under fire conditions. The element has two nodes: each with two displacements and one rotational degree of freedom. The axial displacement is interpolated using a quadratic Lagrange polynomial while the lateral displacement is interpolated using a cubic Hermite polynomial. For the quadratic interpolation function, an additional internal node has been added with a degree of freedom in the axial direction. For the determination of the internal force vector and the stiffness matrix, the cross-section of each element is subdivided into layers or sub-layers forming a two dimensional mesh.

2.1 Main steps of fire resistance analysis

The fire resistance analysis is carried out by incrementing time in steps, but initially the structure is analysed at ambient temperature under services loads only just prior to the beginning of a fire. At each time interval, the analysis is performed through three main steps:

- establishing the temperature due to fire exposure;
- carrying out the heat transfer analysis to predict cross sectional temperature distribution;
- Performing strength and deflexion analysis, which is carried out, through two sub-steps:
  - performing the structural analysis of the column to compute displacements, strains, stresses and thus internal forces,
  - calculating the axial restraint force in the column.

The computer model generates various critical output parameters, such as temperatures, stresses, strains, displacements and fire induced axial restraint forces at various given fire exposure times. These parameters are then used to check against pre-determined two sets of failure criteria, in which the failure of an RC column is said to occur when:

1- The column is unable to resist the specified applied service load (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- The restraining forces regain the value of the initial applied load (restraining forces failure criteria).

2.2 Thermal and structural analysis

The fire temperature in the compartment is established using specified standard or design fire scenarios. The fire temperature is then used to carry out the hydrothermal analysis to evaluate cross sectional temperatures in each element of the column. The hydrothermal analysis is based on the work of Di Capua et al. [10] which assumes that under realistic conditions, and if only the temperature field is required, the heat transfer problem can be solved in an uncoupled way. The model requires the knowledge of the initial moisture content as it accounts for the latent heat due to the evaporation of water by introducing a water vapour fraction, which is a function of temperature. In practical situations, however, the water content is not only unknown but variable. The initial moisture content is taken equal to 6%, which, according to Eurocode 1 [11], corresponds to a peak value of the specific heat equal to 3700 J / kg. ° K. The generated temperatures in each element form the input to the structural analysis, which includes the computation of the axial restraint force in the column. Gaussian and Simpson rules are used respectively to integrate the stiffness matrices and internal forces along the longitudinal and transverse directions. Furthermore, the formulation is based on a co-rotational approach and it makes use of a tangential operator derived by integrating the stress-strain rates of concrete and steel at elevated temperatures [9,12]. It includes geometrical nonlinear effects resulting from large displacements, and material nonlinearities due the degradation of the elastic and inelastic properties with temperature. The concrete model also accounts for cracking and crushing, as well as transitional thermal creep, which is computed by using the approach proposed by Anderberg and Thelanderson [13]. The details of the material model and its numerical implementation can be found in reference [20]. The transitional creep is accounted explicitly as an additional component of the total strain, or implicitly through the use of the materials' properties recommended by the Eurocodes 2.

2-3 Axial restraint forces

The reaction of a structure to the heating of a column can be compared to that of a spring, whose stiffness depends upon the physical and geometric properties of the structure (fig. 1).

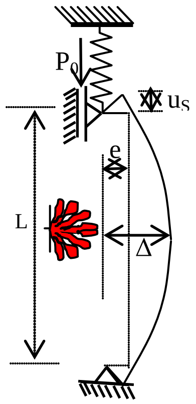

Figure 1: Model of a restrained column

Based on this simple concept, a computer program initially developed to calculate the fire resistance of single columns [9], was adapted, so it can be used to reproduce the development of the induced restraining forces that arise when a column forming part of a structure is heated. Noting that the elastic restraint due to the rotation at the top and bottom of the column was not considered in order to isolate the effects of the axial restraint. The elastic matrix stiffness of the spring element can be simply written as:

$$\begin{pmatrix} K_s & 0 & 0 & -K_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ -K_s & 0 & 0 & K_s & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix} \quad (1)$$

where K_s represents the axial stiffness of the surrounding structure. The non-dimensional axial restraint ratio k of the column is defined by a relation between K_s and the elastic axial stiffness of the column K_C:

$$k = \frac{K_S}{K_C} \quad (2)$$

where

$$K_C = \frac{EA}{L} \quad (3)$$

The values of k can vary in such a way to represent the various types of boundary conditions commonly encountered in practice ($k = 0$: unrestrained column; $k = 1$: fully restrained column and $0<k<1$: real situations). The axial restraint force is accounted for in the model in the phases of expansion, which develop compression forces, and contraction, which generally develops tensile forces. The force, P_k developed in the spring is the axial restraint force resulting from the permanent compatibility between the axial displacements of the top of the heated column and the displacements of the spring representing the rest of the structure, together with the condition of internal equilibrium between the axial forces acting on the column and on the spring. It can be expressed by the relation:

$$P_k = K_s u_S \quad (4)$$

where u_S is the corresponding axial displacement developed in the spring.

2.4 Restraining forces failure criteria

The fire behaviour of columns with thermal restraint is categorised by an initial increase in the restraining forces followed by a decreasing phase reaching values less than the initial applied load P_0, [4,14], as shown on figure 2. The fire resistance of a structural member like a column represents the time during which that member can fulfil its load bearing functions; that is: resistance the applied design load.

When the restraining forces decrease to a level below the initial force P_0, the load difference must be supported by the surrounding structure, because in the descending branch the restraining force always represents the maximum force that the column can. In this context, it seems reasonable to define the fire resistance (R_f) as the time it takes to reach the initial force. It was experimentally verified that columns subject to thermal restraint have a reduced fire resistance compared to coulumns having free elongation [7].

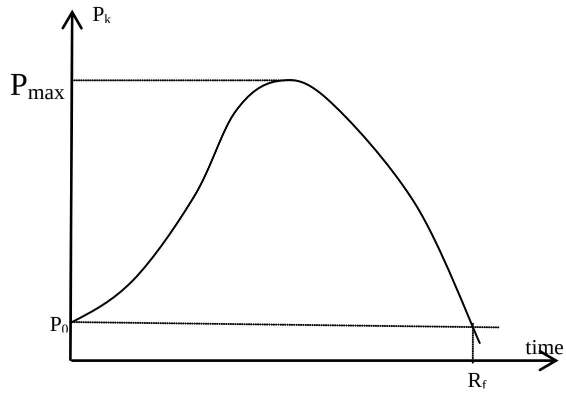

Figure 2: Typical development of the restraining forces

3 PARAMETRIC STUDIES

To investigate the influence of various factors on fire induced restraints in a RC columns exposed to fire, a set of RC columns were analysed. The studied parameters are: fire scenario, load level, degree of restraint, slenderness, and eccentricity. All the analysed columns have the same cross section dimensions as illustrated in figure 3, and a sinusoidal imperfection along the column axis of ω_o = L/1000. A length L = 4.8 m corresponding to a slenderness ratio, λ = 55.43, and an initial compressive load P_0 = 740 kN with an eccentricity e_0 = 15 mm are considered for all the columns studied except for those used to study the effect of slenderness and the eccentricity. The support conditions for all the columns are supposed to be similar to those in figure 3, but with different values of stiffness ratio k. The values of the stiffness ratio are varied in such a way that they represent the types of boundary conditions commonly encountered in practice. Three values were considered, one low (5%), one intermediate (20%), and one high (50%) The stiffness ratio of 5% represents a very soft boundary condition while a value of 50% represents a very stiff boundary condition such as the one produced by a shear wall. Such values of stiffness ratio correspond to axial restraint stiffnesses in the range of 0 to 168.75 kN/mm. The effect of the axial restraint force is largely dependent on the location of the axial restraint force with respect to the column depth. However, in this work, the axial reaction is assumed to develop at the geometrical centroid of the concrete cross section. The location of the axial restraint force is assumed to be constant during fire exposure. Four load levels namely; 30%, 52%, 65% and 85% are used in the analysis. Load level is defined as the ratio of the applied load during the fire to the capacity of the column at ambient conditions calculated according to Eurocode 2. The corresponding initial compressive loads are respectively equal to 430, 740, 933 and 1200 kN. These load levels are selected to represent realistic load encountered in practical applications. The columns are 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 30 mm for all the columns. In the analysis, the columns are also assumed to be exposed to fire from all sides, and the materials' properties suggested by the Eurocodes 2 are adopted. The fire resistance is evaluated based on the failure criteria previously defined as when the restraining force regains the value of the initial applied load P_0. Fire induced spalling is supposed not occur in any of the analysed columns since they are made of normal concrete (NC), which exhibits a relatively high permeability. This provides an easy mechanism for the water vapour to escape from the concrete. Thus, with increasing temperatures the pore pressure continuously dissipate in the column, and there is no significant vapour pressure build-up. This is agreement with reported test results, which clearly show negligible spalling in NC members during fire exposure [3,15].

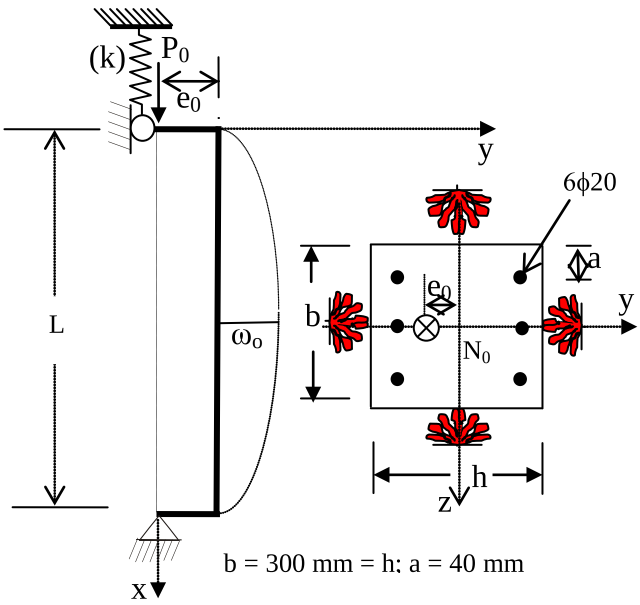

Figure 3: Cross section and elevation of RC column used in parametric studies

3.1 Effect of fire scenario and failure criteria

The effect of fire scenario is investigated under the exposure of two standard fire; namely: ISO834 [16] and ASTM E119 standard fires [17], and two design fire scenarios; namely Fire I and Fire II. There is no decay phase in the time-temperature curves for the standard fire scenarios. However, in realistic fires (represented by the two design fire), 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 Eurocode 1, and the modifications suggested by Franssen [18] and Feasey [19] are selected to represent the design fire scenarios used in the analysis. According to Eurocode 1, the design fire consists of a growth phase and a decay phase. Feasey [19] revealed that both the growth and decay phases of the fire 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 4.

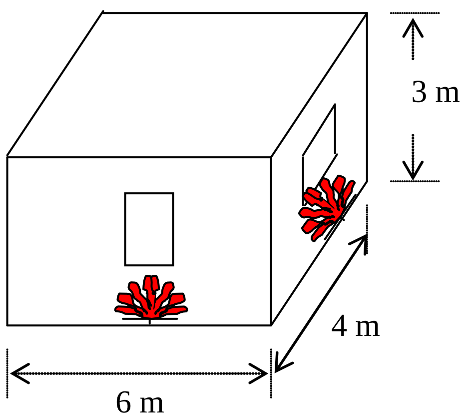

Figure 4: Compartment in fire

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 time-temperature curves for the two standard fire scenarios and the two design fire scenarios are shown in Figure 5. 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, as well as in the rebars, increases with the fire exposure time for the two standard fire scenarios. The results also show that the increase in concrete and rebar temperature is slightly larger for the ISO 834 than that for the ASTM E119 standard fire.

Table 1: Compartment characteristics used to generate design fire scenarios

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

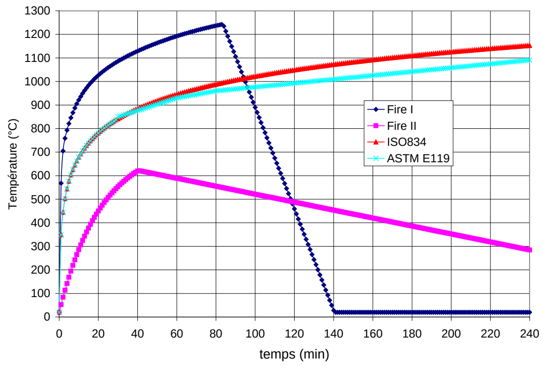

Figure 5: Various fire scenarios used in the analysis

This is due to the progressive increase in temperature of the ISO 834 fire in the first 30 min of exposure as can be seen in Figure 5. However, under the two design fire exposures, the predicted temperatures in the concrete and steel bars increase till they reach a maximum, and start to decrease. This can be attributed to the decay phase in the time-temperature curve of the design fires. Then the column cross section enters a cooling phase.

Figures 6 and 7 present the variations of the deflection and axial force with fire exposure for the four fire scenarios at load level 52 % (P_0 = 740 kN), eccentricity e_0 = 15 mm and axial restraint stiffness ratio k = 50%. The failure criterion adopted was the fire resistance time based on the material failure criteria. It can be seen that the deflection increase with time in the early stages of the fire. A reduction (or recovery) in the deflection is noticeable for the two design fires as a result the decay phases. The column also recovers part of its stiffness and strength. The recovery of deflection appears to be higher for the column exposed to the severe design Fire I than for the column exposed to the moderate design Fire II. On Figure 7, it can be seen that the axial restraint force increases with time in the early stages for the four cases as a result of the rapid increase in temperature. A slight reduction can also be noticed in the axial restraint force for the column exposed to the less severe Fire II at later stages of the fire exposure time. The results show that the fire severity has a significant effect on the fire resistance of RC columns calculated using the restraining forces failure criteria.

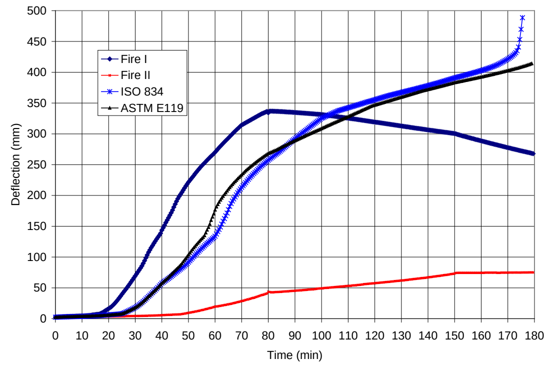

Figure 6: Effect of fire scenario on the deflection of RC columns exposed to fire (N_0 = 740kN, e_0 = 15 mm, k = 50%)

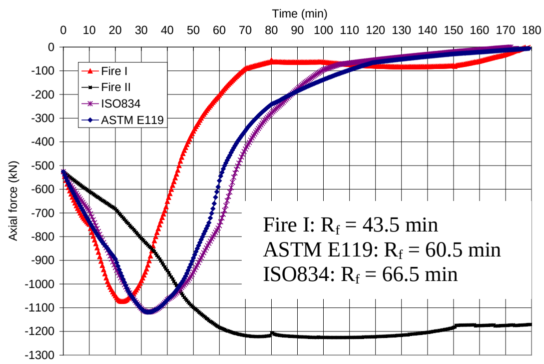

Figure 7: Effect of fire scenario on the axial force of RC columns exposed to fire (N_0 = 740kN, e_0 = 15 mm, k = 50%)

It can be seen, from figure 7, that the lowest fire resistance is obtained for the column exposed to the severe fire design Fire I. It is about 23 minutes lower than that for the column under the ISO834 standard fire exposure. This is due to the rapid increase in temperature for Fire I as can be seen from figure 5. 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.

3.2 Effect of the degree of restraint

To investigate the effect of the degree of restraint on the fire response of RC columns, five values for the axial restraint stiffness ratio; namely 0, 5, 20, 50 and 100%, were assumed for all the analysed columns. The obtained results under the severe fire scenario (Fire I) are summarized in figures 8 and 9 at a load level of 52 % (P_0 = 740 kN) and an eccentricity e_0 = 15 mm. The restraining forces failure criterion is used. It can be seen that the axial restraint stiffness significantly influences the deflection, the restraining force and the fire resistance. For low values of k, the deflection of the column increases with the axial restraint stiffness ratio. This can be attributed to the P-Δ effect which creates additional moments that increase the effect of the applied loading and thus increase deflections which leads to a lower fire resistance. However, for high values of k, and at later stages of fire exposure (beyond nearly 35 min.), the deflection of the column decreases with an increasing axial restraint stiffness ratio. It could be explained by the fact that the axial restraint force creates an arch action, which leads to the development of a counter moment that reduces the effect of the applied loading as noticed for RC beams [3]. This leads to a decrease in the deflections and thus higher fire resistance.

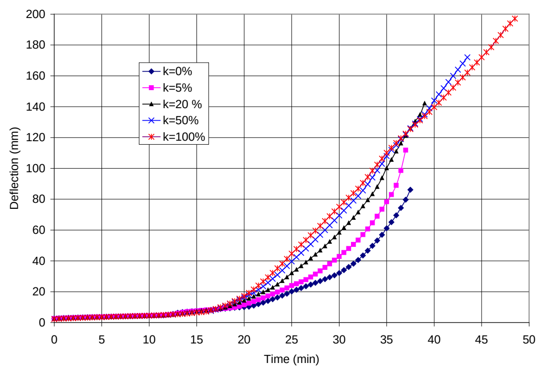

Figure 8: Effect of degree of restraint on the deflection of columns exposed to severe fire scenario

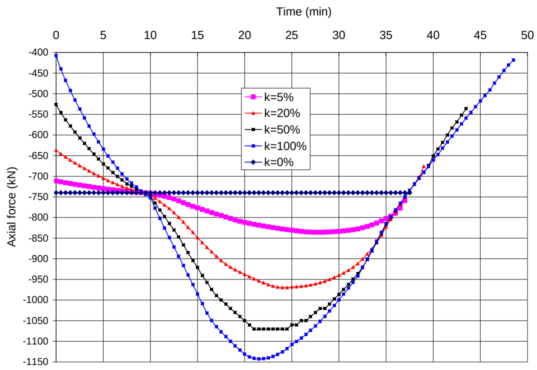

Figure 9: Effect of degree of restraint on the axial force of columns exposed to severe fire scenario

3.3 Effect of load level

To investigate the effect of load level on fire resistance, the column was analysed under four levels of loading 30, 52, 65 and 85%. In the study, the load level is calculated as the ratio of the applied initial compressive load under fire conditions to the capacity of the column at ambient temperature.

The results are shown in Figures. 10 and 11 for a column under the exposure of Fire I, having a length L = 4.8 m, eccentricity e_0 = 15 mm and axial restraint stiffness ratio k = 50%. As shown on Figure 10, the load level has a significant influence on the deflection. An increase in the load level increases the deflection significantly at later stages of the fire exposure. An increased load level causes early yielding of the steel reinforcement, and thus increases the plastic and creep strains. This leads to a lower stiffness in the column, and results in a significant increase in the deflection. Figure 11 shows a large increase in the axial restraint force followed by a slight linear recovery. This could be attributed to the softening of the column material, which increases with fire exposure time and then dominates the behaviour of the column at later stages of the fire exposure leading to a reduction in the fire axial restraint force. Results from the analysis also reveal that load level has a significant influence on the fire resistance predicted with the restraining forces failure criteria. It can be seen that increasing the load level significantly reduces the fire resistance of RC columns. This can be attributed to the fact that high load level causes early softening and weakening of the constituent materials and thereby cause early strength and stiffness reductions of the column.

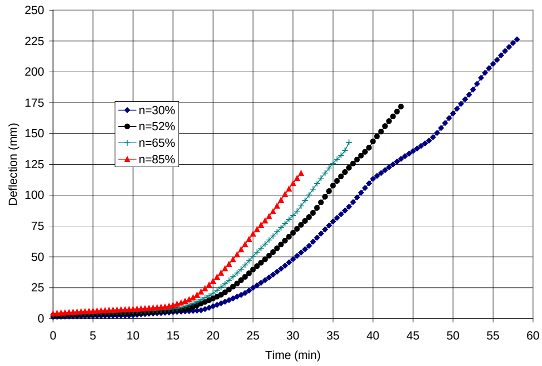

Figure 10: Effect of load level on the deflection of RC columns exposed to severe fire scenario

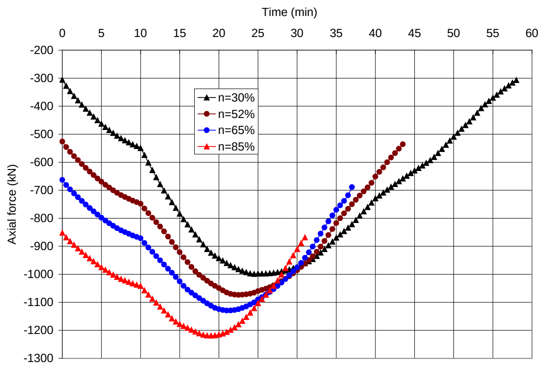

Figure 11: Effect of load level on the axial restraint force in RC columns exposed to severe fire scenario

3.4 Effect of slenderness and eccentricity

The effects of the slenderness of the column and of the eccentricity of the applied loading are also investigated. Three values for slenderness (λ) are considered, one low (24.42), one high (83.14) and one intermediate (55.43). The corresponding column's heights (L) are respectively: 2.4, 4.8 and 7.2 m. For the eccentricity (e_0) of the initial compressive load P_0, three values are also considered, e_0 = 0 mm (centred column), e_0 = 15 mm (reference eccentric loading), and e_0 = 30 mm. The values are chosen to represent the most frequently encountered in practical situations. The variation of deflection under fire exposure scenario Fire I is shown in figures 12 and 13 for an axial restraint stiffness ratio of 50%. In every case, the initial compressive load P_0 is taken constant and equal to 740 kN and the restraining forces failure criterion is adopted.

It can be seen that in general the deflection increases with fire exposure time. Figures 12 and 13 respectively show that high rates of increase in deflection can be seen for high slenderness ratios, and for high eccentric loading. This is due to the reduced flexural stiffness of slender or eccentrically loaded columns, which make the column prone to buckling under the effect of the axial restraint force. Furthermore, the reduced flexural stiffness leads to a higher deflection of the column at any fire exposure time. This will increase undoubtedly the secondary moments developed due to the P-Δ effect on the axial restraint force, and in turn will cause larger deflections, which will ultimately lead to an early failure of the column. Figure 12 shows that the fire resistance decreases from more than 150 min to 25 min when the slenderness ratio increases from 27.42 to 83.14. Meanwhile, Figure 13 shows a reduction of nearly 30 % when the eccentricity increases from 0 to 30 mm.

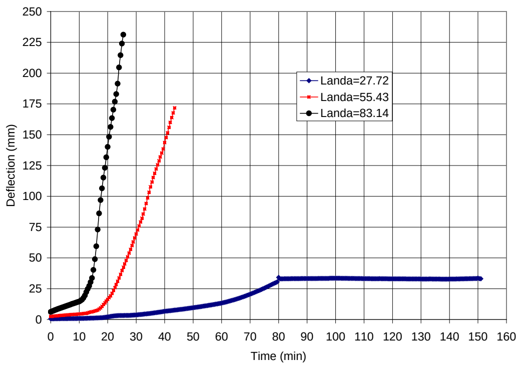

Figure 12: Effect of selenderness on the deflection of RC columns exposed to severe fire scenario (P_0 = 740 kN, e_0 = 15 mm)

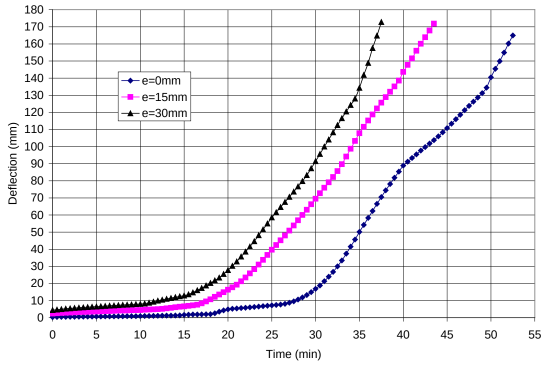

Figure 13: Effect of eccentricity on the deflection of RC columns exposed to severe fire scenario (P_0 = 740 kN, λ = 55.43)

4 CONCLUSIONS

Based on the results of this study, it was found that the effect of restraint on fire response of reinforced concrete column is significantly influenced by fire scenario, degree of restraint, failure criteria, load level, slenderness and eccentricity. In addition, the following conclusions can be drawn:

- 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 used in this study;
- load level has a considerable influence on the performance of RC columns in real fire. An increase in the load level results in a significant reduction in the fire resistance;
- increased slenderness ratios and eccentricity of the applied load lead to a significant reduction in the fire resistance because of the reduced flexural stiffness of slender columns, which makes them prone to buckling under axial restraint forces;
- failure criteria have a significant influence on the fire resistance of reinforced concrete columns since the conventional failure criteria based on crushing of the concrete and yielding of steel may not be conservative under some fire scenarios;
- based on restraining forces failure criterion, the fire resistance of reinforced concrete columns increases by increasing the axial restraint stiffness of the columns.

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