EFFECT OF IMPERFECTIONS ON CONCRETE COLUMNS SUBJECTED TO FIRE TAKING INTO ACCOUNT SECOND ORDER EFFECTS

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Abstract

Concrete structures are inherently subjected to effects of imperfections. Generally speaking, imperfections consist of geometric imperfections, fabrication imperfections and boundary imperfections (Simitses 1986). These imperfections could be caused by industrial manufacturing processes, uncontrollable initial eccentricities, connection eccentricities, etc. These imperfections lead to second-order effects and weaken the load-bearing capacity and the stability of structural members. Considering the effects of imperfections, an estimated eccentricity is usually adopted in the calculation procedure. In EN 1992-1-1, an equivalent initial eccentricity is proposed for the imperfection of columns. Based on this simplification, imperfections are incorporated as an initial eccentricity in a first order calculation and are further used to obtain interaction diagrams taking second order effects into account. Furthermore, EN 1992-1-1 (2004) points out that allowance should be made in the design for uncertainties associated with the prediction of second order effects. To our knowledge, however, no parametric study has been investigated so far on the effect of imperfections on columns exposed to fire. Therefore, it is essential to study parameters that influence the effects of imperfections in order to quantify model uncertainties.

The objective of the paper is to examine the influence of imperfections on columns subjected to fire. The most important influencing parameters with respect to imperfections are identified with respect to the analysis of columns in case of fire.

Keywords: imperfections, concrete columns, ISO 834 fire, analytical methods, second order effects

1 Introduction

In the last two decades, Lie (1984) firstly considered an estimated eccentricity as the effect of imperfections to compare with the experimental data of concrete columns exposed to fire and combined with concentrated axial loads and later on (1996) in case of steel columns filled with reinforced concrete. Then, Becque and Rasmussen (2007) carried out the interaction of local and overall buckling of stainless steel I-shaped columns with experimental and numerical methods. Further, Schillinger et al. (2010) developed a finite element based methodology for the stochastic buckling analysis of imperfect I-section beam-columns. Karmazinova and Melcher (2013) expanded the research to steel-concrete composite columns.

First, this paper introduces an analytical method to indicate the influence of imperfections on columns for different slenderness ratios at ambient temperature. Further, the influence of an ISO 834 standard fire is investigated. Fire durations, slenderness ratios, eccentricities, reinforcement ratios as well as dimensions of cross-sections are included in a parametric study on imperfections. Recommendations on when imperfections have to be considered explicitly are presented.

2 Basic Assumptions and Calculation Method

The fire analysis consists of two parts: the thermal analysis and the structural analysis. With respect to making a coherent calculation system, a cross-sectional calculation tool is adopted for both of the analysis. The material models are the same as provided in EN 1992-1-2 (2004). In order to simplify the calculation, assumptions are made: 1) plane sections remain plane; 2) the cross-sectional temperatures of a reinforcing bar are calculated as the temperature at the centroid of the bar; 3) the tensile strength of the concrete is not considered.

As the first step of the calculation, the cross-section of the calculated column is divided into small fibres. A 1 mm × 1 mm square is set as a basic segment in the current calculation. Then, all the nodes in the corner and in the middle of the side of the segment (Fig. 1) are chosen as calculated nodes.

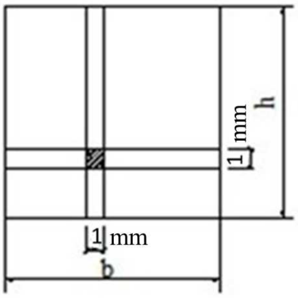

Fig. 1 Calculation model discretization

The heat transfer in the form of the node temperature is obtained by Fourier's law for conduction, Newton's law for convection and Stefan-Boltzmann's law for radiation. Further, the mechanical strains are calculated as the difference between the total strains and the thermal strains in case of different curvatures (see Equation (1)).

$$\varepsilon_{\mathrm{mech}} = \varepsilon_{tot} - \varepsilon_{\mathrm{th}} = \varepsilon_0 + k_0\eta - \varepsilon_{\mathrm{th}} \qquad (1)$$

where ε_{tot} is the total strain, ε_{th} is the thermal strain, ε_0 is the strain at the centroid point, k_0 is the curvature around the neutral axis and η is the distance to the centroid point.

Finally, the initial eccentricities as well as the effect of possible imperfections are taken into account to calculate deflections of the columns. As a result, the interaction curves of columns for different slenderness ratios are obtained. It is noteworthy that the imperfection of the column in the current calculation is considered as an eccentricity $e_i = l_0 /400$ provided in EN 1992-1-1 (2004), where l_0 is the effective length of the column.

3 A Parametric Study

First, a simply supported column at ambient temperature is analyzed: the cross-section is 300 mm × 300 mm, with one diameter 32 mm reinforcement bar in each corner and concrete cover 25 mm; concrete compressive strength $f_{ck} = 55$ MPa, reinforcement yield strength $f_y = 500$ MPa and modulus of elasticity of steel $E_s = 2 \times 10^5$ N/mm^2. The effect of imperfections on the load capacity of columns for different slenderness ratios is investigated. Fig. 3 shows the respective value of the load capacity n ($n = \frac{N_c+N_s}{f_c bh}$) of columns for the slenderness ratio (30, 40, 50, 60, 70, 80) in case of different first order moments. Three types of first order moments are studied: a low first order moment ($e = 0{,}025b$ with $e \geq 10$ mm), a moderate first order moment ($e = 0{,}25b$ with $e \leq 100$ mm) and a high first order moment ($e = 0{,}5b$ with $e \leq 200$ mm), where e is an eccentricity and b is the width of the cross-section. In Fig. 2, the columns present respective value n in case of different first order effects and the shaded bars show the relative increase due to imperfections.

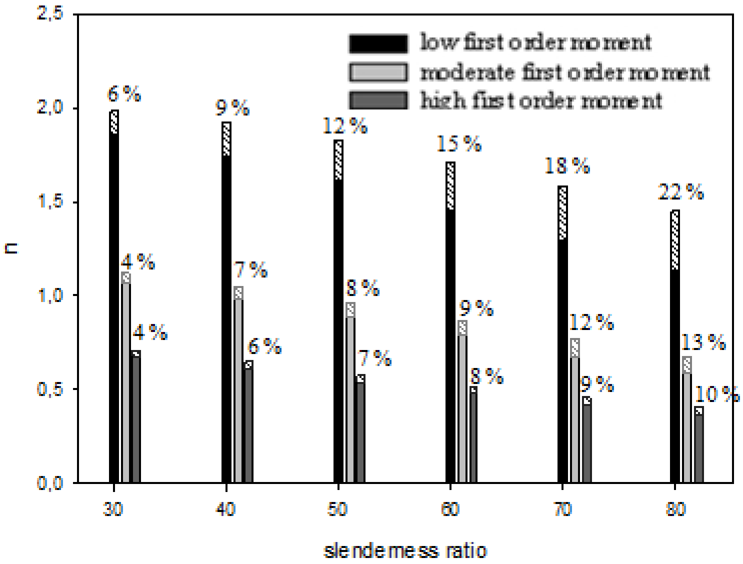

Fig .2 The effect of imperfections on the load capacity of columns for different slenderness ratios in case of a low first order moment, a moderate first order moment and a high first order moment (ambient temperature)

From the figure, we can see that the influence of imperfections on columns becomes more apparent with the increment of the slenderness ratios at ambient temperature. It is noticed that this influence increases from 6 % (slenderness ratio 30) to 22 % (slenderness ratio 80) in case of the low first order moment. It indicates that imperfections cannot be neglected in case of slender columns, especially when combined with a low first order moment at ambient temperature.

Next, an ISO 834 standard fire is adopted to investigate the effect of imperfections in fire combinations. Four groups of parametric variations are considered among which fire durations, slenderness ratios, eccentricities, reinforcement ratios as well as dimensions of cross-sections (Table 1).

Table 1

Parametric study on the influence of imperfections

Comparison Group No.	Dimensions (mm × mm)	Reinforcement ratio	Slenderness ratio	Fire duration (min)
1	300 mm × 300 mm	0.5	60	0, 30, 60, 90
2	300 mm × 300 mm	0.5	40, 50, 60, 70	60
3	300 mm × 300 mm	0.1, 0.5, 1.0	60	60
4	150 mm × 150 mm 300 mm × 300 mm 600 mm × 600 mm	0.5	60	60

In the comparison of the first group, interaction digrams are shown in Fig.3 taking into account different fire durations.

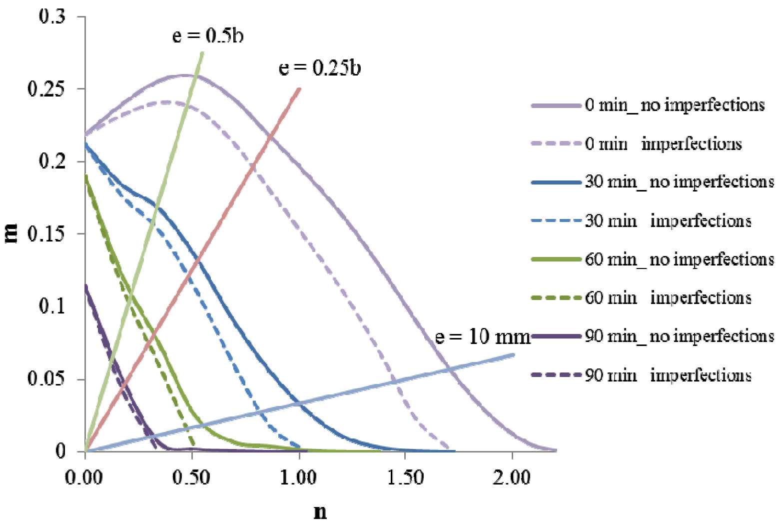

Fig. 3 Interaction diagrams of a column in case of an ISO 834 fire at 30 min, 60 min and 90 min of fire exposure (Group No.1)

Fig. 3 shows the interaction diagrams (m = $\frac{M_c+M_s}{f_c b h^2}$ and n = $\frac{N_c+N_s}{f_c b h}$) of a column at different fire durations of an ISO 834 standard fire. The effect of imperfections (Fig.3), in case of a low first order moment, first has a slight increase from 15% (at 0 min) to 20% (at 30 min), and then drops from 20 % (at 30 min) to 6 % (at 90 min). However, for other cases, the influence of imperfections is getting lower with the temperatures of columns increasing. The imperfections have almost no influence on interaction curves when the ISO 834 fire lasts 90 minutes.

The second group presents the effect of slenderness ratios (Fig.4).

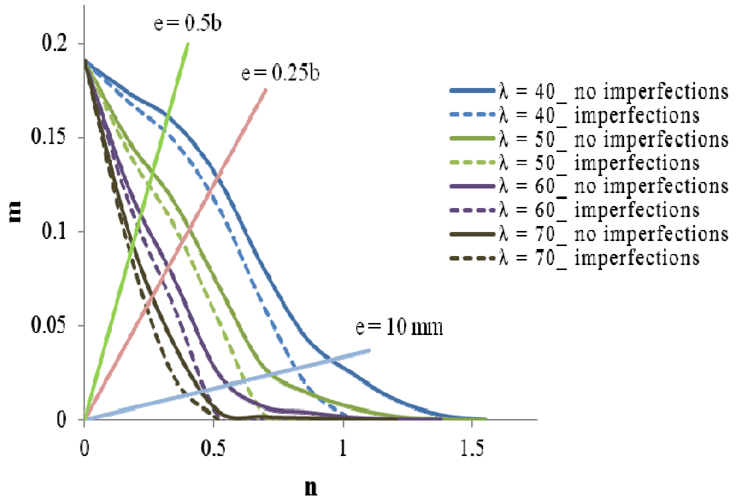

Fig. 4 Interaction diagrams of columns (slenderness ratios 40, 50, 60, 70) exposed to an ISO 834 fire after 60 min fire exposure (Group No.2)

Fig. 4 indicates that the effect of imperfections increases slightly with the increasing slenderness ratios. Compared with the differences caused by imperfections at the ambient temperature, the effect of slenderness ratios, however, is not that apparent after 60 minute standard fire exposure.

Fig. 5 shows the effect of reinforcement ratios on the influence of imperfections.

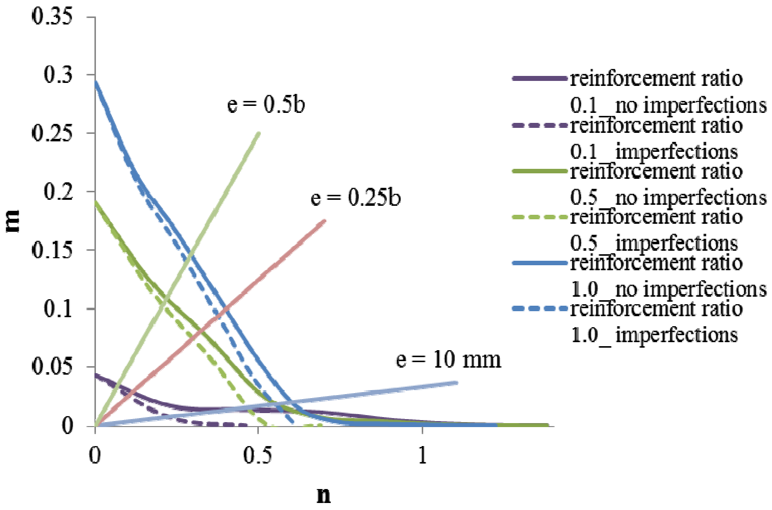

Fig. 5 Interaction diagrams of columns (reinforcement ratio 0.1, 0.5, 1.0) exposed to an ISO 834 fire after 60 min of fire exposure (Group No.3)

In Fig. 5, it is clear that the influence of the imperfections on the maximum allowable bending moment of fire exposure decreases with an increasing reinforcement ratio when the first order moment is low (e = 0,025b with e ≥ 10 mm). However, this phenomenon does not match in case of the high first order moment (e = 0,5b with e ≤ 200 mm) and this change in Fig. 5 is not apparent anyway. Hence, the reinforcement ratio is not an important parameter on the imperfection study.

The influence of imperfections for different sizes of the cross section is quantified in Fig.6.

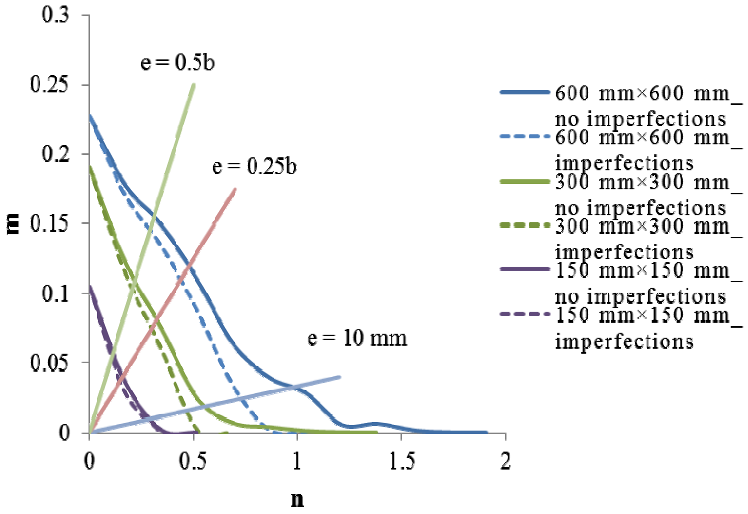

Fig. 6 Interaction diagrams of columns (cross-section 600 mm×600 mm, 300 mm×300 mm, 150 mm×150 mm) exposed to an ISO 834 fire after 60 min of fire exposure (Group No.4)

Firstly, it is observed that in Fig.6 imperfections have more effects on columns with a larger cross-section if other properties are kept the same. Secondly, imperfections are very important when the initial eccentricity is very low or the column is concentrically loaded. In the case of the column with cross-section 600 mm×600 mm, the ideal load capacity under compression is more than twice as the one considering imperfections. Hence, it is quite dangerous to neglect the imperfections when the fire resistance design of columns is required.

4 Analysis and Conclusions

In general, no matter how the configurations of the columns are and no matter whether the columns are at ambient temperature or exposed to fire, the imperfections have apparent effects on the load capacities of columns under compression. Furthermore, the resistance without considering imperfections could be overestimated by a factor 2 compared to the case when considering imperfections at elevated temperatures. Two main reasons can be given for this effect. First, the imperfection is considered as an initial eccentricity, which causes an additional bending moment under a large axial load. Secondly, the maximum allowable bending moments of columns decrease fast with the temperatures of columns increasing. As a result, the bending moment caused by imperfections will present an increasing proportion of the total bending moment in case of the fire loads.

According to the comparisons of studies on parameters, the following observations are made:

(1) Fire duration (temperature)

The effect of imperfections is generally getting smaller in function of the fire duration time because relative importance is higher compared to the non-eccentric loading. However, this effect cannot be neglected in case of slender columns combined with the low first order moment.

(2) Slenderness ratio

The higher the slenderness ratio becomes, the more influence the imperfections have. Nerveless, due to the second order effects, this influence decreases in function of the fire duration time.

(3) Eccentricity

This paper investigates the effect of eccentricities in form of a low, moderate and high first order moment. The results indicate that imperfections have more effects on columns in case of the low first order moment. The reason for this is that the bending moment contributed by imperfections has a relatively high influence on the first order moment if the eccentricity is low. To some extent, eccentricity is one of the most important parameters on the study of the effect of imperfections.

(4) Reinforcement ratio

According to the Fig. 5, the reinforcement ratio is for only of minor importance for the imperfection study.

(5) Dimension of the cross-section

The effect of imperfections is more apparent on a bigger cross-section in case of the same slenderness ratio because the assumed eccentricity (l_0 /400) for a certain slenderness ratio has a minimal influence if the dimensions of the cross-section are small and the additional bending moment caused by imperfections is negligible.

Finally, with respect to the axial load design under compression, imperfections have to be taken into account. Further, fire durations and eccentricities act important roles on the effect of imperfections. The slenderness ratios as well as dimensions of the cross-section have a significant effect on imperfections in some conditions.

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