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A numerical approach for modeling the fire induced restraint effects in reinforced concrete beams

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Abstract

In this paper, a model to predict the influence of fire induced restraints on the fire resistance of reinforced concrete (RC) beams is presented. The three stages, associated with the fire growth, thermal and structural analysis, for the calculation of fire resistance of the RC beams are explained. A simplified approach to account for spalling under fire conditions is incorporated into the model. The validity of the numerical model is established by comparing the predictions from the computer program with results from full-scale fire resistance tests. The program is used to conduct two case studies to investigate the influence of both the rotational and the axial restraint on the fire response of the RC beams. Through these case studies, it is shown that the restraint, both rotational and axial, has significant influence on the fire resistance of the RC beams.

Keywords: Fire resistance; Computer program; Fire induced restraint; High temperature; High-strength concrete; Reinforced concrete beams; Spalling; Numerical model

1. Introduction

Reinforced concrete (RC) structural systems are quite frequently used in high-rise buildings and other built infrastructure due to a number of advantages they provide over other materials. When used in buildings, the provision of appropriate fire safety measures for structural members is an important aspect of design since fire represents one of the most severe environmental conditions to which structures may be subjected in their life time. The fire resistance of the RC members is generally established using prescriptive approaches which are based on either the standard fire resistance tests or the empirical calculation methods.

The RC beams can develop significant restraint under fire exposure. The degree of restraint is mainly dependent on the support conditions and will determine the fire behavior and resistance of the RC beams. The end restraints can be rotational, axial or both. Rotational restraints, under fire conditions, can improve the fire response of an RC beam through moment redistribution between span (positive moment) and support (negative moment) sections within the length of the beam. Therefore, rotational restraints increase the fire resistance of the RC beams. Even if the moment redistribution has been considered in the design at room temperature, rotational restraints are expected to have positive effect on the fire resistance of the RC beams. This is because the critical span section will experience higher strength loss (due to tension steel being closer to the fire exposure surface) than the critical support section (due to low thermal conductivity of the concrete which keeps the temperatures of the tensile reinforcement at the support section lower). Furthermore, the curvature ductility of an RC beam under fire conditions is higher than that at room temperature, which allows for higher moment redistribution under fire exposure.

The effect of the axial restraints on the fire resistance of the RC beams depends on the vertical location of the restraint force. Generally, the axial restraint force in an RC beam is expected to be below the neutral axis of the RC beam section as a result of the higher temperature rise in the bottom fibers of the beam as shown in Fig. 1. This can

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Nomenclature

b	beam width
c	clear concrete cover
C_t	total compressive force
d	effective depth of the beam
$f_{c,20}$	concrete strength at room temperature
$f_{c,T}$	concrete strength at temperature T
f_y	yield strength of steel
k_2	a constant for the transient strain calculations and it ranges between 1.8 and 2.35
K_g	global stiffness matrix for strength analysis
L	length of the beam
L_s	length of the beam segment
P_f	equivalent nodal load vector due to applied loading
P_s	equivalent nodal load vector due to P–δ effect
t	time
T	temperature
T_0	initial temperature
t_h	time, h
T_f	fire temperature
T_t	total tensile force
T_∞	fire or ambient temperature depending on the boundary, Γ
w	applied distributed load
y	the distance from the geometrical centroid of the beam
Z	Zener–Hollomon parameter for the creep strain
δ	nodal displacements
$\Delta\varepsilon_{th}$	change in the thermal strain
$\Delta\varepsilon_{tr}$	change in the transient strain
ε_c	strain at the topmost fibers of concrete
ε_{cr}, ε_{me}, ε_t, ε_{th}, ε_{tr}	creep strain, mechanical strain, total strain, thermal strain and transient strain
ε_{crs}, ε_{mes}, ε_{ths}, ε_{ts}	creep strain, mechanical strain, thermal strain and total strain in steel
ε_{t0}	creep strain parameter
κ	curvature
θ	temperature-compensated time
σ	current stress in concrete or steel

improve the fire resistance of the RC beam through the arch action associated with the axial restraints, which increases the strength and the stiffness of the beam under fire exposure. However, axial restraints may lead to spalling of the concrete which in turn might reduce the fire resistance of the RC beams. Thus, it is essential to investigate and quantify the influence of the fire induced restraint forces and moments on the fire response of the RC beams. At present, there are limited approaches or methodologies to properly model the fire induced restraint effects in the RC beams.

This paper presents the development of a computer model for tracing the fire response of the restrained RC beams under the realistic fire, loading and failure scenarios. The model is capable of predicating the fire induced restraint effects in the RC beams for any material properties, fire scenario, loading and support conditions. The model is based on a macroscopic finite element approach and uses a series of moment–curvature relationships for tracing the fire response of the RC beams. The model is verified against experimental data by comparing the predicted temperatures, deflections and fire resistance times with the measured ones from fire tests. Results from case studies are presented to illustrate the influence of the fire induced restraint forces and moments on the fire resistance of the RC beams.

2. Fire response of RC beams

A review of literature indicates that limited fire resistance tests have been conducted on the RC beams. Most of these tests were conducted on unrestrained beams and thus there is limited information on the fire response of the restrained RC beams in the literature. The most notable fire tests are those carried out by Lin et al. [1] and by Dotreppe and Franssen [2]. Both the tests were conducted on the axially unrestrained beams. Lin et al. [1] tested 11 305 mm × 355 mm RC beams under ASTM E119 [3] standard fire exposure. Their study investigated the influence of a number of factors including beam continuity, moment redistribution and aggregate type on the behavior

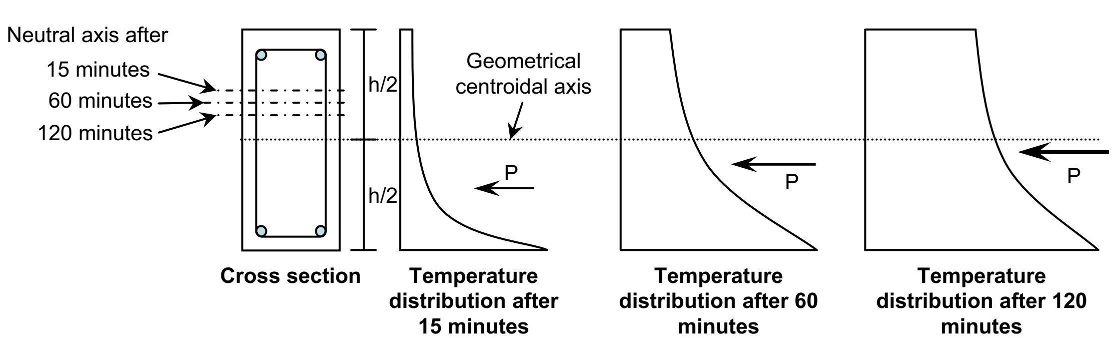

Fig. 1. Schematic diagram showing the thermal gradients and the position of axial force as a function of time of fire exposure.