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Experimental behaviour of restrained reinforced concrete columns subjected to equal biaxial bending at elevated temperatures

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ABSTRACT

This paper experimentally investigates the effects of equal biaxial bending, restraint ratio, and concrete strength on the structural behaviour of reinforced concrete columns at elevated temperatures. Nine full-scale column specimens equally grouped into three series were designed and tested with three levels of equal biaxial eccentricities. Three specimens of the first series were loaded to failure at room temperature to verify the EC2 Pt.1.1 simplified criterion for axial resistance of columns subjected to biaxial bending. The remaining six specimens in two fire-test series of different concrete compressive strengths (55 and 29 MPa, respectively) were first loaded to 55% of their EC2 eccentricity-dependent axial resistances and were then exposed to fire conditions with different restraint ratios (3.5% and 6.0%, respectively) until failure. Experimental results were compared with analytical and numerical predictions. It was consistently shown that (i) EC2 predictions were reasonable for the tested columns; (ii) lateral deflections of the heated columns were proportional to equal biaxial eccentricities; (iii) the development of thermal-induced restraint forces increased with equal biaxial eccentricities, restraint ratio, as well as concrete strength, and was overpredicted by numerical analyses that neglected concrete spalling; and (iv) the column failure times were adversely affected by equal biaxial eccentricities.

1. Introduction

Columns subjected to a compressive axial load at biaxial eccentricities, so-called biaxial bending, are common in reality. Even the columns that are initially designed for pure compression or uniaxial bending at room temperature are potentially subjected to biaxial bending when heating occurs due to either non-uniform fire exposure or concrete spalling. Under fire conditions, a heated column may be restrained from free elongation due to the difference in fire behaviour of the surrounding structural members. Hence, biaxially-loaded columns subjected to thermal-induced restraint at elevated temperatures have to be investigated for practical design purpose.

Structural behaviour of columns at elevated temperatures has attracted a great interest for fire-safety research activities. However, to the authors' best knowledge, there have been only limited fire tests on full-scale reinforced concrete (RC) columns subjected to biaxial bending and axial restraint. Initial ambient tests and fire tests [1–8] on eccentrically-loaded columns were mostly conducted on small-scale specimens, which had cross-section sizes smaller than 229 mm and column heights shorter than 2.03 m. Since concrete is not a homogeneous material and has low thermal conductivity, testing on full-scale specimens provides better insight into the thermal and the structural responses of RC columns. In other fire tests conducted on full-scale columns [9–13], all specimens were only subjected to either pure compression or uniaxial bending of small eccentricities, but all of them were tested without any axial restraint. Meanwhile, experiments on axially-restrained columns in fire [14–17] were only performed on small-scale columns among which there was only one restrained column tested under equal biaxial bending [17]. Some research works have been conducted to investigate the effect of either biaxial bending or restraint due to framing structural members [18–22]. However, these studies were mostly on full-scale steel and composite columns. In the simplified approach for predicting fire resistance of RC columns under biaxial bending proposed by Kodur and Raut [23], increment in axial force due to thermal-induced restraint is not considered since the interaction effects arising from stiffness of adjoining members is neglected. The effect of thermal-induced restraint on uniaxially-loaded RC columns at elevated temperatures was experimentally observed by Tan and Nguyen [24]. However, there are only provisions in current codes of practice for structural fire design [25,26] considering pure compression on unrestrained RC columns. Hence, there is an urgent need to perform experiments to enhance the understanding of structural behaviour of RC columns under the

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combined effects of biaxial bending and axial restraint at elevated temperatures.

This paper presents an experimental programme on nine full-scale RC columns subjected to the aforementioned critical conditions. The main objective of this study is to investigate the effects of equal biaxial bending, restraint ratio, and concrete strength, on the structural behaviour of six axially-restrained RC columns tested at elevated temperatures. Similar trends were observed from experimental results, code predictions, and numerical analyses using computer program SAFIR [27]. Relatively good agreement between the test results and the EC2 predictions at room temperature was achieved. At elevated temperatures, as equal biaxial eccentricities increased, both lateral deflection and thermal-induced restraint forces also increased, leading to a decrease in the failure times of the test columns. Effects of axial restraint, concrete strength, and concrete spalling are also discussed in the latter part of the paper. The other objective of this paper is to ascertain if the simplified criterion in accordance with EC2 Pt.1.1 [28] is able to give reasonable predictions of the axial resistances of the remaining three RC columns that were loaded under typical levels of equal biaxial bending to failure at room temperature. These columns also served as control specimens at ambient condition for the fire test series.

2. Experimental programme

2.1. Test specimens

In this experimental programme, concrete strength was a variable of interest together with equal biaxial eccentricities and restraint ratio, as concrete spalling tends to be more severe with higher concrete strength. Nine column specimens were equally divided into three test series, namely, Sa, S2, and S3, as listed in Table 1. Three columns in the ambient series (Sa) were loaded to failure at room temperature at three typical levels of equal biaxial eccentricities, i.e., (25 mm, 25 mm), (40 mm, 40 mm) and (60 mm, 60 mm). The columns in this series were cast with 28.4 MPa-compressive-strength concrete and were reinforced with four 25 mm-diameter main bars (4T25) which had 554 MPa yield strength. Every three columns of S2 and S3, which were respectively designed with three aforementioned typical sets of equal biaxial eccentricities, were heated to failure at an identical load level of 55% of their EC2 eccentricity-dependent axial resistances. In order to investigate the effects of restraint ratio and concrete strength on structural behaviour of test specimens, the differences between S2 and S3 specimens were (i) S2 columns had a restraint ratio α_r, which was the normalised restraint stiffness K_r with respect to the column axial stiffness K_c, of 3.5% and S3 had 6.0%; and (ii) mean concrete cylinder compressive strength of S2 columns was 55.3 MPa and that of S3 was 29.3 MPa. This selection of investigated variables was due to the limitations of research time frame and laboratory condition. Based on good agreement in trend between the test and the numerical results, parametric studies can be conducted to differentiate the individual effects of each parameter, as will be presented in Section 7.

The concrete was cast with siliceous aggregates of 20 mm maximum size, silica-based sand, water/cement ratios of 0.58 (for Sa and S3) and 0.43 (for S2), and at the times of 4 months (for Sa and S3) and 24 months (for S2 series) before testing.

All the test specimens had identical geometry properties of a nominal height 3.3 m and a 300 mm × 300 mm cross-section (Fig. 1). Two concrete blocks with the dimensions of 500 × 500 × 300 (in mm) were designed at both ends of each specimen. Equal biaxial eccentricities were produced in the tests by adjusting the centroids of these blocks, where the test load was applied, relative to the centroid of the column cross-section (Fig. 1(b)). According to EC2 Pt.1.1 [28], all the column specimens were slender since their slenderness of 40.9 is higher than the slenderness limitation of 26.9, which is determined based on equal bending moments applied at the column ends.

For Sa specimens, sixteen strain gauges were mounted on longitudinal bars (M1 to M4), on stirrups (L1 to L4), and on concrete surfaces (C1 to C8) at the column mid-height cross section (Fig. 1(c)). The steel and concrete strain gauges used were KFG-5-120-C1-11L8M3R and TML PL-60-11-5LT with gauge factors of 2.07 and 2.12 (±1%), respectively.

For S2 and S3 specimens, fourteen butt-welded chromel–alumel K-type thermocouples were instrumented at three cross-sections viz. ‘A’, ‘B’ and ‘C’, along the specimens to record temperature profiles at various points during the tests (Fig. 1(a) and (d)). Heat-resistant nickel–chromium alloy wires in 1 mm diameter were used to form stand frames within column cross-sections by tightening to reinforcing bars. At their designed positions thermocouples were fixed to the frames and reinforcing bars by using the heat-resistant wires as well.

2.2. Test set-up and instrumentation

A photograph of the test set-up for a Sa specimen loaded under equal biaxial bending at room temperature is shown in Fig. 2. The test specimen was installed in a self-reaction test rig and was subjected to an axial load at one end from a 5000 kN servo-hydraulic actuator fixed onto a steel bulkhead of the test rig. The other end of the specimen was connected to another bulkhead through a knuckle bearing block so that the column could be tested in pinned and pinned-on-roller end conditions. The knuckle bearing blocks were connected to the column end blocks and to the test rig by 16 mm-in-diameter bolts (Fig. 1(a)).

In the ambient tests conducted on Sa specimens, instrumentation was mainly for deflection measurement. At two ends and the mid-height of the test specimen, a total of twelve linear variable differential transformers (LVDTs) were used to measure axial

Table 1
Test specimens.

Series	Specimens	Eccentricities (mm)	Concrete strength	Main bars	Properties of steel bars	μ_{fi}	α_r
Sa	Ca-1-25	25, 25	f_c = 28.4 MPa	4T25	f_y = 554 MPa		
	Ca-2-40	40, 40			f_u = 663 MPa		
	Ca-3-60	60, 60			E_s = 201 GPa		
S2	C2-1-25	25, 25	f_c = 55.3 MPa	6T20	f_y = 550 MPa		
	C2-2-40	40, 40			f_u = 649 MPa	55%	3.5%
	C2-3-60	60, 60			E_s = 196 GPa		
S3	C3-1-25	25, 25	f_c = 29.3 MPa	4T25	f_y = 554 MPa		
	C3-2-40	40, 40			f_u = 648 MPa	55%	6.0%
	C3-3-60	60, 60			E_s = 201 GPa		