Engineering Structures 162 (2018) 60–71

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

Quasi-static tests of RC columns under variable axial forces and rotations

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A R T I C L E I N F O

Keywords:
Variable axial forces
Variable rotations
Reinforced-concrete columns
Quasi-static test
Seismic behaviour

A B S T R A C T

The behaviour of reinforced-concrete (RC) elements subjected to axial force and rotation variations in conjunction with lateral displacement variation is considered a highly important topic, but only a few experimental studies investigating this topic have been performed. In this paper, five full-scale RC rectangular columns were tested by quasi-static testing (QST) to investigate the effects of large variation axial forces and rotations on the seismic behaviour of columns. Furthermore, the effects of variable axial forces and rotations on the seismic performance of RC columns in terms of the failure modes, hysteretic loops, skeleton curves, ductility factors, stiffness degradations and energy dissipations are presented and analysed. Based on the QST results, the axial force and rotation variations have significant effect on the seismic behaviour of RC columns. Generally, the variable axial forces and rotations may cause a distinct asymmetrical failure phenomenon in the specimens and reduce the lateral strength and ductility factor. Thus, RC columns should be well designed to account for the adverse effects of variable axial forces and rotations.

1. Introduction

1.1. Background and motivation

Recently, concerns regarding the seismic performance of reinforced-concrete (RC) columns have increased [1,2]. Earthquake overturning moments and bi-directional lateral loading may subject the exterior and/or corner columns of an RC frame to a varying axial load (force) [3]. This topic had been investigated by Aycardi et al. [4] and Bracci et al. [5] twenty years ago. Four RC column specimens loaded with low and high levels of axial forces were examined under reversed cyclic loading, furthermore, one analytical modelling method was presented for better capturing the seismic performance of RC columns. Nishida et al. [6] analysed the seismic behaviour of the 1st-floor side columns of a 12-story RC frame. In RC frame structures with buckling-restrained braces (BRBs), the variation levels and amplitudes of the column axial force that is induced by the BRBs under an earthquake wave may substantially increase. Although most studies agree that BRBs are energy-dissipating members that enhance structural stiffness, energy dissipation and ductility [7,8], the unbalanced force of BRBs may have a non-negligible effect on the behaviour of RC frames [9], and axial loads, particularly the biaxial action, may have a major impact on the deformation capacity of RC columns [10,11]. Several methods of designing RC frames using BRBs have been investigated [12–14]. An energy-based seismic design procedure was proposed to protect the structure against collapse [12]. A performance-based plastic design method for RC-BRBFs was investigated and achieved the intended performance levels [13]. A simplified method of predicting the response of damped RC structures using BRBs has been proposed [14]. However, few design methods consider the negative effects of BRBs on RC columns.

Several research projects investigating the influence of the axial load ratio on the capacity of RC columns have shown that the axial load ratio is critical for estimating the RC column seismic performance [15–17]. Therefore, the effects of the axial load variation on the RC columns should also be evaluated. Abrams [18] conducted experimental tests using ten RC columns that were subjected to reversals of lateral deflection and axial force and concluded that the strength, stiffness, deformation capacity and hysteretic properties were drastically changed by the variations in the axial loads. The seismic performance of beam-to-column connections subjected to a varying axial column force was investigated by Agbabian et al. [19]. Due to the

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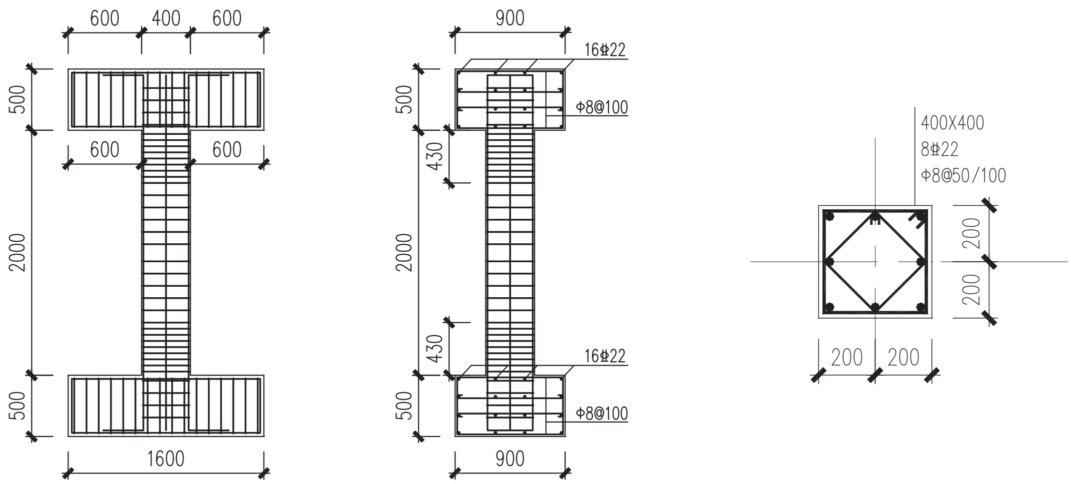
https://doi.org/10.1016/j.engstruct.2018.02.004
Received 16 August 2017; Received in revised form 29 January 2018; Accepted 1 February 2018
0141-0296/



(a) Specimen dimensions and reinforcement layout (b) Cross-section details

Fig. 1. Dimensions and reinforcement details of the RC column specimens.

importance of axial force variations, a new arrangement of longitudinal reinforcing bars was investigated to improve the ductility in the RC exterior columns [20]. The effects of variable axial loads on the seismic behaviour of bridge piers were investigated using six large-scale reinforced-concrete circular columns, and the magnitude and loading pattern of the axial force had significant effects on the seismic behaviour of the columns [21]. Six full-scale RC rectangular columns were tested to investigate the effects of variable axial loads on the hysteretic behaviour of RC columns under biaxial horizontal loading, and the axial load variation was shown to have significant effects on the hysteretic behaviour of RC columns [22].

Recently, researchers have concluded that axial loads with different variation patterns have significant effects on the behaviours of columns. Saatcioglu and Ozcebe [23] have shown that axial loads significantly affect the hysteretic response of columns. The column capacity changes concurrently with the level of the axial load, the axial compression reduces the column response, and bi-directional load cycles can severely degrade the strength and stiffness. By testing twelve identical cantilever-type column specimens, whose damage was controlled by flexure, Bousias et al. [24] concluded that most of the observed effects of multidirectional loading on the inelastic cyclic behaviour had an adverse effect on the structural seismic response (e.g., a reduction in strength and stiffness with biaxial bending, ratcheting deflections due to axial load variations, etc.). However, certain effects are clearly beneficial to the structural response (e.g., increased hysteretic energy dissipation due to the coupling of two bending directions). Saadeghvaziri [25] investigated the effects of a non-proportionally varying axial load on the response of RC cross-sections and concluded that the history of the axial load significantly affected the moment-curvature and axial load-bending moment interaction diagrams of RC columns. Similarly, Galal and Ghobarah [26] proposed an inelastic biaxial model that considered the effect of the axial load variation on the lateral deformation and studied the effects of eight different axial load variation patterns on the lateral deformation of RC columns. Bechtoula et al. [27] subjected eight large-scale and eight small-scale cantilevered RC columns to various vertical and horizontal loading patterns. The damage, i.e., concrete spalling, was more severe in the large-scale columns than that in the small-scale columns.

1.2. Scope

Recently, studies have paid more attention to the effects of variable axial forces on the seismic performance of columns, and several new failure mechanisms have been disclosed. However, these studies have been focused on the performance of small-scale cantilever columns under small-magnitude variable axial forces without rotations on the top of the specimens. The seismic performance of RC columns subjected to large variation magnitudes of axial forces and rotations should be investigated using large- or full-scale specimens. Therefore, this paper investigates the effects of large variation magnitudes of axial loads and rotations on the seismic performance of RC columns by performing quasi-static tests (QSTs) using five RC column specimens in order to provide reference data for the proper design of RC columns. First, the five RC column specimens and corresponding QST procedure are introduced in Section 2. Second, the experimental results of the failure mode, hysteretic behaviour, skeleton curve, ductility factor, stiffness degradation and energy dissipation in the five column specimens subjected to different variation magnitudes of axial loads and rotations are presented in Section 3. Finally, the conclusions are summarized in Section 4.

2. Experimental procedure

2.1. Specimen description

Five rectangular RC columns with identical geometric characteristics and reinforcement details were constructed according to the Chinese Code [28]. The interstory height and cross-section of the column specimens were 2000 mm and 400 mm × 400 mm, respectively. Each column was cast between a square concrete foundation beam and a top beam with plan dimensions of 1600 mm × 900 mm and a height of 500 mm. The longitudinal reinforcements in each column consisted of 8 22-mm-diameter HRB400 grade ($\sigma_y = 420.1$ Mpa) deformed bars arranged symmetrically around the perimeter. The reinforcement stirrups in each column had a grade of HRB300 and a yield strength of 320.1 Mpa. The concrete in each column had a class of C40 and a cube compressive strength of 37.2 MPa. The dimensions and details of the specimens are shown in Fig. 1.

2.2. Test set-up

In this paper, we investigated the effects of large variation magnitudes of axial forces and rotations on the seismic performance of RC columns using QSTs. Thus, the boundary conditions on the top of the specimens must be accurately simulated to boost the performance of the RC column tests. The three-DoF testing system at the Structural and