Engineering Structures 152 (2017) 683–697

Contents lists available at ScienceDirect

Engineering Structures

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

Seismic behavior of preloaded rectangular RC columns strengthened with precambered steel plates under high axial load ratios

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ARTICLE INFO

Article history:
Received 17 August 2015
Revised 13 September 2017
Accepted 24 September 2017

Keywords:
RC column
Precambered steel plate
Axial load ratio
Shear strength
Ductility
Reversed cyclic load

ABSTRACT

In the past 20 years, numerous tests have been conducted to demonstrate the effectiveness of additional fiber reinforced polymers (FRPs) or steel jacketing in the seismic retrofit of circular reinforced concrete (RC) columns. However, very few studies have explored the seismic retrofit of rectangular RC columns, in particular under high axial load ratios (ALRs). To address this issue, a simple and innovative approach is used in this study, in which rectangular RC columns subjected to high ALRs are retrofitted with post-compressed steel plates under severe lateral reversed cyclic loads. An experimental study is conducted to validate the effectiveness of this approach for improving the seismic performance of RC columns under high ALRs. Specimens with identical geometric and reinforcement layouts are fabricated and tested. One of the columns, which is not strengthened, is used as the control whereas the others are strengthened by using bolted steel plates. The effects of plate thickness, initial precamber and ALR on the failure mode, as well as ductility, strength degradation and energy dissipation, are investigated. The results demonstrate that this approach is effective in increasing the lateral displacement ductility capacity while maintaining the high axial load-carrying capacity of the columns.

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1. Introduction

Many metropolitan cities, including Shanghai, Melbourne, New York and Hong Kong, are located in regions of low-to-moderate seismicity. Due to land scarcity in these areas, modern reinforced concrete (RC) buildings taller than 30 stories high are widely constructed. The structural systems of these buildings are usually in the forms of moment resisting frame, shear wall and frame-wall dual systems. A survey [1,2] carried out on the axial load ratios (ALRs; defined as the applied axial load to axial load capacity of a concrete section) in medium-rise residential buildings in Hong Kong found that the ALRs in the reinforced concrete (RC) columns could increase up to 0.52 under seismic load. Prior to the implementation of new concrete design codes in Hong Kong [3], a large number of tall multi-story RC buildings were designed without any provision for ductility design and details. These non-seismically detailed RC columns, when subjected to high axial loads, are prone to fail in a brittle manner with very limited deformability [4–6].

Due to the hilly terrain in Hong Kong, many multi-story buildings are located on steep slopes (see Fig. 1). The columns that support these buildings often have varying heights. However, shorter and stiffer columns tend to attract a greater portion of seismic load and could suffer from significant damage during earthquakes [7].

To improve the structural safety of existing buildings, it is necessary to conduct the seismic retrofitting of RC columns under high ALRs. To achieve this goal, external jackets or collars made of FRPs [8–18] or steel [19–27] are added to increase both the amount of shear reinforcement and the lateral confinement of concrete; the latter can effectively prevent the concrete cover from spalling, provide lateral support to the longitudinal reinforcement and enhance concrete strength and deformation capacities [28]. The seismic performance of RC columns can be therefore significantly enhanced by the use of these jackets.

Many tests have been conducted that demonstrate the effectiveness of additional lateral confinement in the seismic retrofit of circular columns. However, few studies have aimed to improve the seismic performance of rectangular RC columns because rectangular confining reinforcement is less effective than circular confining reinforcement, as the confinement action is mostly located at the corners. To address this problem, Chai et al. [29]

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https://doi.org/10.1016/j.engstruct.2017.09.048
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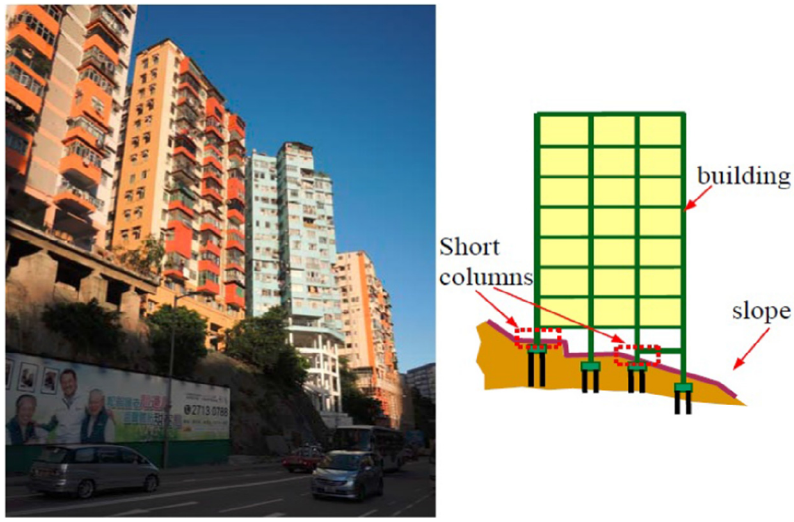

Fig. 1. Buildings on a steep slope with short columns.

and Priestley et al. [19,20] examined the effectiveness of retrofitting rectangular columns with elliptical steel jackets, filling the gap between the jacket and column with high-strength grout. Columns retrofitted with steel jackets demonstrated tremendous improvement in ductility capacity. Tsai and Lin [30] tested FRPs and steel octagonal jackets under monotonic axial loads and found that the steel-jacketed specimens exhibit not only a greatly enhanced load-carrying capacity but also excellent ductility performance. However, regardless of whether elliptical or octagonal jackets are used, the column width is significantly enlarged after retrofitting, thus resulting in the occupation of extra space which prevents the wide application of these methods.

Contemporary philosophy on performance-based seismic design requires structures to be sustainable even in severe earthquakes. Recent experimental studies [31,32] have revealed that the collapse of structures under simulated earthquake loads is mainly attributable to the failure of gravity load resisting systems after excessive lateral deformation. A reversed cyclic load test [31] on non-seismically designed columns under high ALRs showed that axial failure occurs immediately after shear failure. Research has been conducted to improve the axial load resistant retention capacity of non-seismically designed RC columns subjected to high ALRs and large lateral drift demands. Shiekh and Li [33] used confining FRP as reinforcement to retrofit square concrete columns. Their experimental results showed that the required confinement of FRP increases with the ALR and ductility demand. When the ALR is increased from 0.4 to 0.6, the required layers of FRPs are increased twofold. Kim et al. [34] performed a shake table analysis of RC structures with and without seismic retrofit. Their study aimed to prevent the loss of axial load-carrying capacity even with excessive lateral deformation. Square columns were strengthened with polyester fiber belts. This method was found to be effective in confining the columns and preventing the progression of cracking, thus modifying the failure mode of the RC columns from brittle shear failure to flexural dominant behavior.

The literature review reveals that very few studies have explored the seismic retrofit of rectangular RC columns, with special attention given to maintaining axial load-carrying capacity under severe seismic load conditions. To address this issue, we first attempted to extend the post-compressed precambered steel plates [35,36] to retrofit preloaded RC columns under reversed cyclic lateral loads. In this approach, two slightly precambered steel plates were bolted to a preloaded RC column to simulate real loading conditions. The length of the plate was slightly longer than the clear height of the column; therefore, progressive tightening of the anchor bolts can generate thrust on the beam supports due to arching actions [35]. In practical applications, the shear capacity of beams should be checked and the steel components should be protected from fire. Gypsum board details are presented in [37] for the fire protection of the strengthened columns.

Unlike other strengthening methods, this approach allows the steel plates to actively share the existing axial loads with the original column. Stress relief in the original concrete and post-stress developed in the steel plates can alleviate the stress-lagging effect and displacement incompatibility problems. By controlling the initial precamber, similar strains can be induced in the RC column and the steel plates; therefore, enhanced utilization of both components in resisting external loads and higher axial load-carrying and bending capacities can be achieved.

In this study, cyclic loading tests have been conducted to examine the efficiency of this approach in the seismic retrofitting of RC columns; the high ALR (e.g., $\varphi \geq 0.6$) in the original RC columns can be reduced to a moderate level (e.g., $\varphi = 0.3$), thus avoiding axial load failure of the original RC columns under reversed cyclic loading. Furthermore, this ALR is close to balance failure, so that the best potential of the flexural strength and deformability of the RC column can be utilised. The effects of plate thickness, initial precamber and ALR on the failure mode, as well as ductility, strength degradation and energy dissipation, have also been investigated. The testing results demonstrated that the post-compressed approach is effective in increasing the level of lateral displacement ductility while maintaining columns with a high axial load-carrying capacity. A theoretical model is therefore proposed to determine the ultimate flexural capacity of the strengthened column.

2. Experimental program

2.1. Test specimens

A total of six specimens labelled CSC1 to CSC6 were fabricated and tested. All of the specimens were characterized with a medium longitudinal steel ratio, high ALR ($\varphi \geq 0.6$) and low lateral confinement. The RC details for all of the columns are identical, as shown in Fig. 2. A longitudinal steel ratio of 2.68% and a transverse steel ratio of 0.17% in the strong axis were used for all of the specimens.

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