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Experimental and numerical study of strengthening non-ductile RC columns with and without lap splice by Carbon Fiber Reinforced Polymer (CFRP) jacketing

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ABSTRACT

This paper presents an effective method for strengthening non-ductile reinforced concrete columns by applying an externally bonded Carbon Fiber Reinforced Polymer (CFRP) fabrics to enhance the shear capacity and confinement. Six rectangular reinforced concrete columns designed for gravity load only were tested under quasi-static cyclic loading. Three columns were provided with short lap-splice length of longitudinal reinforcements at the plastic hinge location to study the effect of lap splice. The experimental results indicate that, by means of CFRP jacketing, the shear strength under reversed cyclic loading is significantly improved as compared to the un-strengthened columns tested in the previous studies. In addition, owing to the confinement from CFRP, the columns exhibit a dramatically improved displacement capability. The nonlinear analysis of columns is also conducted by means of nonlinear fiber section frame element. The key attribute of the nonlinear analysis is to include the effect of lap splice of longitudinal reinforcement through the lap-spring spring model formulated according to the tri-uniform bond stress model. By combining the stress-strain models of concrete, steel reinforcement, lap-splice's bond model, anchorage bond slip and nonlinear shear spring into the fiber section frame element, the numerical results shows a good agreement with experimental ones.

1. Introduction

In May 2014, the Mae Lao earthquake recorded at M_w 6.3 hit Chiang Rai province in Northern Thailand. This earthquake is regarded as the largest earthquake that has ever been recorded in Thailand. The quake has brought about widespread damages to many concrete structures in the affected area. Several existing reinforced concrete (RC) columns were severely damaged due to the lack of non-seismic reinforcement detailing as shown in Fig. 1. These columns were traditionally designed without seismic consideration according to the old non-seismic building design code in Thailand [1]. Some typical non-ductile characteristics of these columns included (1) low amount of transverse reinforcements with large center-to-center spacing, (2) small column dimension, and (3) short lap splice length of around 15–25 times bar diameter at the column base.

Due to the lack of proper seismic reinforcement detailing, a lot of severe damages to RC columns were found. Typical failures included broken column, reinforcement yielding and buckling, concrete spalling and crushing, shear failure and lap splice failure. In many cases, the failure was caused by a combination of these failure modes. These failures clearly demonstrated that insufficient non-seismic reinforcement detailing according to the existing design code could render poor structural performance during moderate or major earthquakes. These columns were considered non-ductile and susceptible to catastrophic collapse since their strength degraded rapidly under lateral cyclic loading with limited lateral drift capacity.

In literature, there have been a number of researches that attempted to seismically upgrade non-ductile RC columns. Some of the widely accepted retrofitting measures are jacketing of column by various means such as steel plate jacketing [2] and reinforced concrete jacketing [3–5]. Although these conventional techniques have been successfully used in the past, the installation works are quite labor intensive and the corrosion of steel may be a serious consideration for long-term performance. To avoid these drawbacks, alternative composite materials such as Fiber Rein-

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Fig. 1. Failure of RC columns found in 2014 Mae Lao earthquake.

forced Polymer (FRP) have been recently applied owing to its light weight, superior strength-to-weight ratios, corrosion resistance and easy installation.

The use of FRP composites to seismically strengthen RC columns have recently received wide interest among a number of researchers [6–10]. However, the experiment and numerical research works on seismic retrofit of non-ductile columns with short lap splice length have been quite comparatively few [11,12]. Haroun and Elsanadedy [13] conducted an experimental study on thirteen RC columns strengthened with carbon fiber reinforced polymer (CFRP) and E-glass FRP for enhancing flexural strength of reinforced concrete bridge columns with poor lap-splice detailing. They found that both FRP materials could improve flexural strength and ductility. To date, an in-depth understanding on the behavior of RC columns with various shear span-to-depth ratio together with intensive numerical studies on column with poor lap-splice behavior have been relatively few in literature.

With this background, this paper aims to conduct an experimental and numerical study on the behavior of RC columns with and without short lap-splice strengthened with CFRP jacketing. The column specimens were designed to have various shear span-to-depth ratios to capture a range of failure modes from flexural to shear failure. The short lap splices were included in some specimens to examine the lap splice failure in conjunction with flexural and/or shear failure. The column specimens were subjected to quasi-static cyclic lateral loading to observe the performance of CFRP-confined columns in comparison to the unconfined (control) specimens.

Another objective of this paper is to discuss the effect of CFRP jacketing to prevent the gravity load collapse of the column. The gravity load collapse is defined as the instant at which the column loses its axial load carrying capacity. This can be determined during the test by installing the load cell and Linear Variable Displacement Transducer (LVDT) at the top of column to monitor the sustained axial loading and vertical displacement. The gravity load collapse occurs when the load cell cannot maintain the sustained axial load together with the axial displacement starts to get considerably large during cyclic loading. When this occurs, the column is defined to collapse under gravity loading.

The scope of this paper is also extended to the numerical study of the seismic performance of reinforced concrete columns with and without lap splices of longitudinal reinforcing bars and with and without the confinement from CFRP jacketing. The numerical framework is based upon a nonlinear finite element analysis. A