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Dynamic response of a full-scale reinforced concrete building frame retrofitted with FRP column jackets

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ABSTRACT

Many existing reinforced concrete buildings designed in accordance with pre-1971 codes are generally dominated by weak column-strong beam behavior under seismic loading due to inadequate reinforcement detailing. This behavior can lead to premature failure under seismic loads from damage concentrated in the first story of the structure. This paper presents the results of an experimental investigation into the seismic response of a full-scale, two-story non-ductile reinforced concrete frame. The frame was retrofitted with a fiber-reinforced polymer jacketing system on the first story columns to mitigate seismic vulnerability. Shake weight testing was performed to investigate the dynamic performance of the retrofitted building structure in terms of the modal response, inter-story drift, and effectiveness of the fiber-reinforced polymer jacketing system. The results demonstrate that the retrofit scheme helped develop a more uniform story drift distribution, working to counter the soft-story mechanism commonly found in reinforced concrete frames designed during this period.

1. Introduction

Past seismic events (e.g. the 1989 Loma Prieta earthquake, and the 1994 Northridge earthquake) have demonstrated that many existing reinforced concrete (RC) frame buildings constructed prior to 1971 have a structural vulnerability to seismic loading. This vulnerability can be attributed to inadequate reinforcement detailing in frame columns, including: (1) large spacing of small-diameter transverse reinforcement, leading to poor concrete confinement and inadequate lateral support of longitudinal reinforcing; (2) 90° L-shaped corner hooks for rectangular column ties, resulting in loss of confinement and longitudinal reinforcement support after concrete cover spalling; and (3) inadequate lap splice lengths, causing low lateral resistance at high bending moment areas [1–9]. Inadequate detailing in combination with a low $\Sigma M_c/\Sigma M_b$ ratio (where M_c and M_b are the moment capacities of columns and beams in the structure) often results in weak column-strong beam (WCSB) behavior in non-ductile RC frames. This damage or collapse mechanism is concentrated on specific stories when subjected to seismic loads, often resulting in premature failure in the structure [1–6]. In order to prevent the failure of seismically deficient RC columns, a number of column jacketing techniques have been developed using a range of materials and fabrication techniques including steel, fiber reinforced polymer (FRP) wraps, and prefabricated FRP shapes [10–20]. Among the retrofit schemes, the prefabricated FRP jacketing system is expected to have significant advantages related to constructability in terms of quality control and the speed of installation [17,18]. Thus, a prefabricated FRP jacketing system was selected for this study to retrofit seismically vulnerable columns in a non-ductile RC frame.

To investigate the effectiveness of this retrofit approach, a series of dynamic tests were performed on a full-scale, non-ductile RC frame retrofitted with prefabricated FRP jackets on the first story columns. A hydraulic linear shaker was installed on the roof to generate an excitation in the structure. The dynamic response of the retrofitted test frame was evaluated in terms of natural frequency, inter-story drift, and column and beam rotations. Furthermore, the relative effectiveness of the FRP jacketing system was investigated by comparing the dynamic responses between as-built and retrofitted RC frames.

2. Previous work

2.1. Column jacketing systems

Column jacketing systems have been developed to strengthen seismic capacities of existing structures. Priestley et al. [10,11] pro-

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posed the use of steel jackets for seismically vulnerable bridge columns and validated the effectiveness of the retrofit through experimental studies. The test results showed that the retrofit of steel jackets enhanced the shear strength of columns and prevented premature failure. However, using steel jackets on RC columns can result in the addition of significant weight, increased construction time, and potential future corrosion issues [12,13]. Given the problems associated with the use of steel in these types of applications, FRP jacketing systems have been proposed as an alternative to improve the seismic performance of RC columns. The typical structural behavior for RC columns with and without the FRP jacketing system is illustrated in Fig. 1. As shown in Fig. 1(a), the FRP jacket confines the dilation of concrete columns under axial compression, and provides a radial passive stress (σ_R). Consequently, the confinement effect resulting from σ_R contributes to the enhancement of concrete compressive strength (f'_{cc}) and ultimate axial strain (ε_{cu}). Through this confinement effect, the seismic response for an RC column retrofitted with the FRP jacketing system can be improved as shown in Fig. 1(b) with additional flexural capacity as well as an increase in stiffness and ductility [21–24]. However, the confinement effect is significantly affected by the cross section shapes of the columns [9,25–29]. To evaluate the effectiveness of FRP jacketing systems with respect to cross section, Haroun et al. [9] tested circular and rectangular RC columns retrofitted with FRP jacketing systems. The test results showed that the square sections were less effective than their circular counterparts because the rectangular section was not uniformly confined by the FRP jackets and the confinement effect was greatly reduced [25–29]. To maximize the confinement effect, section enlargement from a rectangular or square shape to a circular or elliptical shape was accomplished using FRP jackets with non-shrink grout filling the annular space. ElGawady et al. [30] demonstrated that the application of shape enlargement with circular FRP jackets in the plastic hinge region of rectangular RC columns significantly improved the displacement ductility, energy dissipation and lap-splice capacity of RC columns with deficient lap-splices. A typical retrofit scheme with an enlarged section that is fully-confined by FRP jackets for RC columns is shown in Fig. 2.

To demonstrate the effectiveness of FRP jacketing systems related to shear failure, flexural failure and lap-splice failure of seismically vulnerable RC columns, Seible et al. [14–16] conducted quasi-static tests for column specimens retrofitted with a variety of FRP jackets. The test results showed that FRP jacketing systems could be effective to prevent certain failure modes in non-ductile RC columns. Based on these experimental studies, a retrofit design process of FRP jacketing systems was proposed and validated by Seible et al. [31,32]. Xiao et al. [17,18] applied prefabricated FRP jackets to existing circular RC columns to enhance the shear strength and lap-splice capacity of non-ductile RC bridge columns designed according to pre-1970s codes. The test results indicated that the prefabricated FRP jacket completely prevented shear failure and contributed to stable ductile behavior without any significant degradation in stiffness and strength. Additionally, the use of prefabricated FRP jacket delayed the premature lap-splice failure. A number of studies of non-ductile RC building columns were conducted to investigate the effectiveness of FRP jacketing systems for the most common possible failure modes (i.e. axial-flexural failure [7], lap-splice failure [8] and shear failure [33]). In each case, the jacket design was based on the procedure proposed by Seible et al., [31,32]. Through an extensive experimental investigation, the FRP jackets provided a sufficient confinement pressure to improve the flexural, shear and lap-splice capacities of the RC columns as well as increase the longitudinal reinforcement buckling resistance.

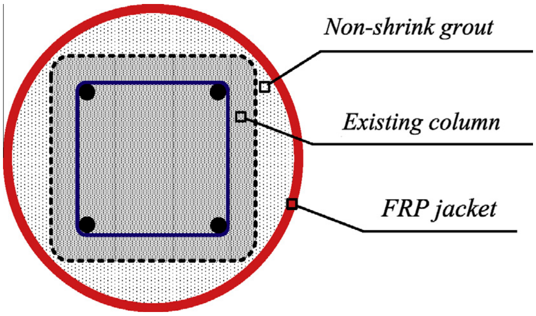

Fig. 2. Typical FRP jacketing retrofit for RC column.

2.2. Dynamic testing of RC frames

To investigate the seismic response and modal properties for RC building structures, a variety of shake table tests e.g. [2,5,34–36] have been performed to simulate seismic loading. However, the size, weight and strength of test specimens were necessarily limited in these types of experiments due to the capacities of available shake table equipment [37–39]. Consequently, previous experimental studies typically employed reduced scale specimens in their testing programs. In addition, to measure the modal properties of real structures and calibrate analytical models, prior researchers conducted field testing of full-scale RC structures subjected to ambient and low-level forced vibrations [40,41]. In order to overcome those limitations, the National Science Foundation George E. Brown Jr. Network for Earthquake Engineering Simulation (NEES) established the University of California, Los Angeles

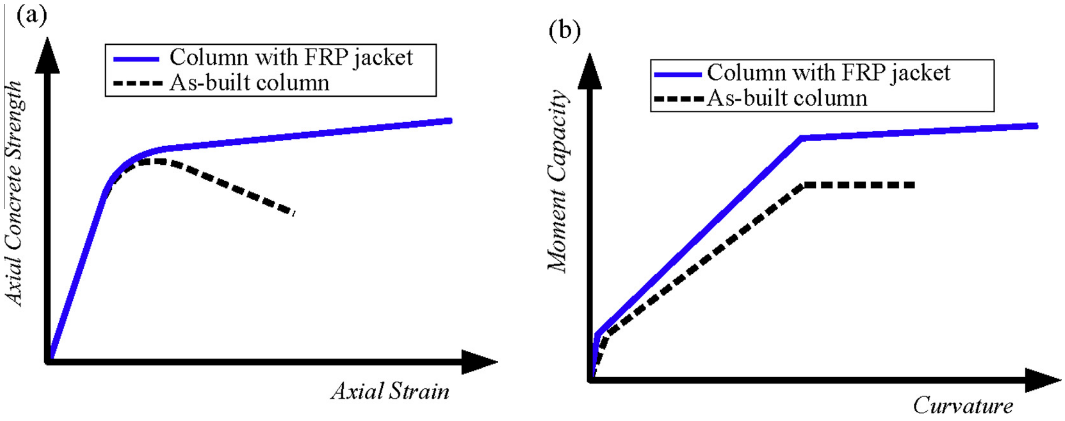

Fig. 1. Typical behavior of RC columns with and without FRP jacketing system: (a) Axial stress-strain response; (b) Moment-curvature response.