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Seismic performance evaluation of RC columns reinforced by GFRP composite sheets with clip connectors

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HIGHLIGHTS

- ▶ GFRP strengthening device that has aluminum clip connector is proposed.
- ▶ It can be used for retrofitting in-situ column with minimal disturbance to adjacent walls.
- ▶ This device improved the column shear behaviors and ductility.
- ▶ Finite element analyses are performed to confirm the efficiency of the device.

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ABSTRACT

This paper performs experimental and numerical studies on the seismic performance of non-seismically detailed RC columns retrofitted with the proposed GFRP strengthening device. The primary goal of this study was to improve the shear strength and ductility of weak-in-shear columns. It was proposed a strengthening device that was consisted of a prefabricated GFRP composite sheet and aluminum clip connectors. This device was designed to speed up the installation time and to minimize the disturbance to adjacent walls and non-structural components. Efficiency of the proposed GFRP strengthening installation is evaluated through a series of experiments on non-strengthened and strengthened 3:4 scale RC column specimens. Comparisons between experimental results of the non-strengthened and strengthened column specimens are conducted in terms of column strength, ultimate displacement ductility, amount of hysteretic dissipated energy, and column shear behavior. So, comparisons focused on ultimate displacement ductility and hysteretic dissipated energy. A series of finite element analyses are performed to confirm the efficiency of the proposed GFRP strengthening device.

1. Introduction

In the past and recent destructive earthquakes (e.g. the 1967-Caracas earthquake, the 1968-Tokachi-Oki earthquake, the 1999-Izmit earthquake, the 2008-Wenchuan earthquake, and the 2009-Honduras earthquake, etc.), many reinforced concrete (RC) frame buildings designed and constructed in accordance with the old seismic design practices had been observed to be severely or completely damaged. A majority of those buildings collapsed due to column failure. Under seismic attack, inadequate seismic designed columns are particularly vulnerable since they are subjected to complex combination of forces (axial load, flexure and shear, and possibly torsion). Collapse of a single column or of a group of columns can lead to at least partial collapse of a building. Column shear failure is the most critical failure mode due to its non-ductile manner; therefore, seismic retrofitting of columns in shear is urgently required for existing old RC frame buildings to withstand future earthquakes. Since the destructive 2011-Tohoku earthquake with a magnitude of 9.0 (M_w), the Korean government has expressed deep concerns over potential damages caused by devastating earthquake such as that occurred in Japan, especially to existing old buildings and infrastructures. Large amounts of government budgets have been allocated to seismic retrofitting of those structural systems, particularly school buildings. In accordance with the Korean post-earthquake emergency plan, a school building must also be functional as a shelter. Unfortunately, existing old school buildings in the country had been designed to resist only gravity loads. Thus there is an urgent need to retrofit this category of public facility. Three seismic retrofitting methods have so

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far been proposed: base isolation, installation of a damping system, and strengthening of vulnerable structural members (e.g. columns) by external strengthening materials. From the pros and cons of the three retrofitting strategies, the last technique mentioned seems to be optimal especially under limited budget constraint. Therefore, an in-depth study on retrofitting of existing old school-building RC columns using external strengthening material is of particular interest in this work.

So far, several research works on seismic strengthening of RC columns using external materials have been conducted by various researchers. Pioneering works on this strengthening methodology have been conducted by Chai et al. [5], Priestley et al. [12], and Xiao et al. [17]. They had demonstrated that steel jacketing could drastically enhance both the strength and ductility of RC columns. However, ease of construction and installation has driven researchers to search for other alternative strengthening materials. Fiber reinforced polymer (FRP) is a relatively new type of composite material manufactured from a variety of fiber and resin and has been widely used as external strengthening material. Attractiveness of this strengthening material arises from its superior properties such as light weight, high strength and stiffness to weight ratios, and high resistance to fatigue and corrosion. One of the earliest works on the retrofitting of RC columns using FRP material was contributed by Matsuda et al. [10]. In their research work, potential plastic-hinges and main bar-cutoff regions of all bridge piers were strengthened by wrapping them with carbon fiber sheets in both transverse and longitudinal directions. Extensive investigations on behaviors of RC columns strengthened with FRP composites have been conducted subsequently by several other researchers. Priestley and Seible [11] showed that seismic performance of 2/5 scale bridge piers could be drastically improved by wrapping them with glass fiber reinforced polymer (GFRP) jackets. Saadatmanesh et al. [14] and Saadatmanesh et al. [15] performed experimental works on RC bridge columns and concluded that column strength and ductility could be enhanced by wrapping FRP strap around the column. Beneficial effects are results of increased core-concrete confinement and prevention of longitudinal-bar buckling. Ye et al. [21] performed experimental works on seismic strengthening of RC columns with wrapped carbon fiber reinforced polymer (CFRP) sheets and proposed a confinement factor and an equivalent transverse reinforcement index in accordance with Chinese seismic design code.

The aforementioned research works on column retrofitting have employed FRP materials in the form of in situ fabricated jacket. A common drawback in using in situ fabricated jackets is the on-site quality control. To overcome this weak point, several researchers have employed a prefabricated FRP jacket (e.g. [13,18–20]. When a composite jacket is prefabricated from a manufacturer, its qualities in terms of thickness, amount of epoxy, and curing process could be more easily controlled. Recently, Di Ludovico et al. [6] published the enhanced discussions for strengthening of full scale RC structures using innovative system and traditional solutions.

In this work, a novel GFRP strengthening mechanism is proposed. It consists of GFRP composite strip and aluminum connectors and can be used in situ with ease to strengthen an existing column with minimal disturbances to adjacent walls, together with speedy times of installation. Since GFRP composite strip is prefabricated, its qualities are controlled. Based on the number of numerical simulations, the best shape of aluminum connection part is first designed. The performance of designed connection part is then examined by tension test. Experimental works on five RC column specimens are conducted in this research to assess the efficiency of the proposed GFRP strengthening device arrangements in enhancing column seismic performance. These column specimens in the experiment are designed to resist only gravity loads according to the 1980s Korean building code and represent 3/4 models of RC columns of an existing old school building. Two column specimens are tested under as-built conditions while three others are tested after installation of proposed strengthening device. Comparisons between experimental results of the non-strengthened and strengthened column specimens are conducted in terms of column strength, ultimate displacement ductility, amount of hysteretic dissipated energy, and column shear behavior. A series of finite element analyses are also performed to evaluate the efficiency of the proposed GFRP strengthening device.

2. GFRP composite strips with connectors

The GFRP strengthening device proposed in this work is shown in Fig. 1. It consists of two parts: GFRP composite strips, and aluminum connectors. Detailed descriptions of these two parts are as follows:

2.1. GFRP composite strip

Five GFRP test coupons are prepared with ASTM specification (ASTM-D3039) as shown in Fig. 2a and tested under tensile loading to evaluate their mechanical properties using a MTS universal testing machine [4]. The mechanical properties of each composite ply were 73 GPa Young's modulus, 2600 MPa maximum tensile strength, 3.2% elongation, and 2.6 g/cm^3 density. Laminated load transfer tabs are adhesively bonded to both ends of each specimen in order to allow the load to be transferred from the grips of the testing machine to the GFRP test coupons without any damage. All tests were performed by displacement control and the loading rate based on ASTM-D3039 was 5 mm/min. The sampling rate is 1.0 Hz. The GFRP test coupons were made of eight composite plies and formed using autoclave machine. Each GFRP test coupons was 14.9 mm in width, 1.96 mm in thickness, and 2 g/cm^3 unit weight. Within each composite ply, 80% of the glass fibers are placed along longitudinal direction while 20% are distributed in transverse direction. The tension-test setup is shown in Fig. 2b and all testing results are presented in Table 1. As shown in Fig. 2c, the stress–strain responses of GFRP test coupons are essentially linear. For five coupon tension tests, the average values of the tensile strength and elastic modulus are 447.7 MPa and 38,300 MPa, respectively.

2.2. Aluminum connector

The connecting device, shown in Fig. 3, for the GFRP composite strip composes of two parts. All dimensions of the connecting

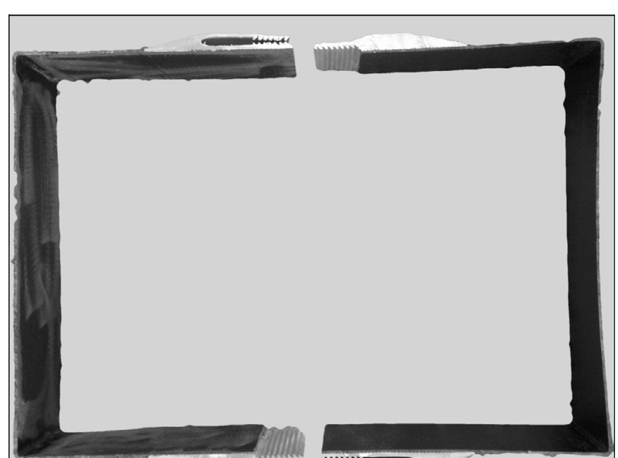

Fig. 1. Proposed column strengthening device.