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Assessment of probabilistic seismic performance of RC columns jacketed by FRP winding wires using analytical models

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ABSTRACT

This study assessed the seismic vulnerability of reinforced concrete columns jacketed by fiber-reinforced polymer (FRP) wires. To achieve this goal, four column specimens subjected to cyclic load tests were selected to validate the analytical model of existing and FRP retrofitted columns in OpenSees; the specimens included two existing columns with lap-spliced and continuous longitudinal reinforcement and two FRP wire-jacketed columns with lap-spliced and continuous longitudinal reinforcement. Two types of material models (‘Concrete’ versus ‘Pinching’) were used to simulate the concrete material models of columns. Based on the validation results, the advantages and disadvantages of using of two material models were considered. Additionally, to compare the seismic performance of the columns subjected to ground motions, their fragility curves were developed. Comparison results revealed that the retrofitting effect using the ‘Pinching’ model is superior, but use of the ‘Concrete’ model is also acceptable. However, the ‘Pinching’ model is more vulnerable than the ‘Concrete’ model for specimens exhibiting limited ductility.

1. Introduction

The performance of reinforced concrete (RC) structures, which are widely used in construction and industry, can be enhanced [1–4]. External jacketing methods for reinforced concrete columns that do not have sufficient seismic capacity against seismic attacks, such as RC columns with lap splice, are considered effective to increase their displacement ductility and flexural strength [5–8]. In recent, the steel reinforced polymers (SRP) were introduced to enhance strength and ductility of RC members with advantages of high stiffness and ductility of steel wires comparing to fiber reinforced polymers [9]. The most widely used conventional jackets are steel tubes or fiber-reinforced polymer (FRP) sheets [10–12]. Several studies, however, have reported disadvantages of such jackets, although they have shown excellent performance to protect RC columns from earthquakes, namely, grouting for steel jackets and epoxy application for FRP sheet jackets [13–15]. Recently, to overcome the above disadvantages of the conventional jackets, the employment of wires for jacketing RC columns has been introduced. The first wire-type jacket was fabricated from shape memory alloy (SMA) wires [16–19]. In the method, the recovery stress of prestrained SMA wires due to the shape memory effect was used to tightly hold the wires on the column’s surface. Thus, grouting or epoxy was not needed to attach the wires on the column. The second wire-type jacket was introduced using fiber-reinforced polymer (FRP) wires [20,21]. The FRP wires for the method should be tensioned to obtain tight contact with the column; the tension could be provided by manual drawing using a frictional device. For easy pretension of the FRP wire, glass FRP (GFRP) wires with a low Young’s modulus have been considered for practical installation [22]. In particular, multiple layers for the FRP wire jackets can be quickly installed since epoxy application under the wires is not needed. For FRP sheet jackets, epoxy must be applied under each layer, and the leads to a time delay for hardening of the applied epoxy. GFRP wire winding jackets presented by Choi et al. [22] showed excellent performance in increasing the displacement ductility and flexural strength of RC columns with a lap-splice at the bottom. The flexural strength of a column jacketed by the GFRP wires reached that of an RC column with continuous reinforcing steel bars, and its displacement ductility was greater than that of a column with continuous reinforcement. The wires in both methods were stressed; thus, they contacted the concrete surface without a gap and provided confining pressure immediately when the concrete inside bulged out.

Experimental tests such as concrete cylinder compressive tests and

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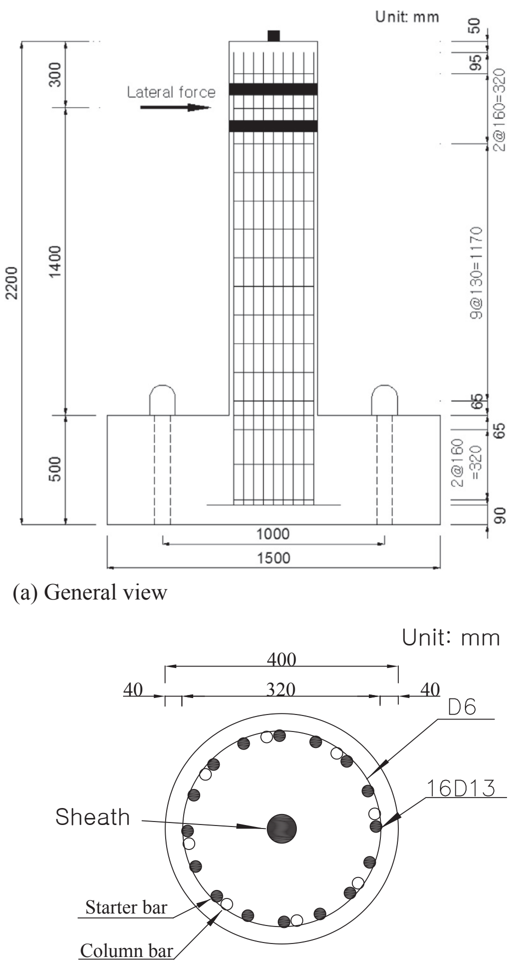

(a) General view

(b) Cross-section of the column

Fig. 1. Schematic view of a specimen.

Table 1
Description of RC column specimens.

Specimen	Diameter/ Height (mm)	Longitudinal reinforcement		Transverse reinforcement		Jacket
		No. of bars/ Volumetric steel ratio	Lap Splice (%)	Volumetric confinement steel ratio	Space (mm)	
SP-Ref	D = 400	#16-D13	50	ρ_s = 0.46%	160	Non
SP-FRP	H = 1400	ρ_s = 1.61%				Full
CN-Ref			0			Non
CN-FRP						Full

flexural tests of RC columns were conducted to examine the performance of the two wire jacketing methods. In addition, for the SMA wire jacketing method, an analytical model developed using the OpenSees program [23], and the seismic performance of RC columns jacketed by SMA wires were assessed using the developed analytical model through nonlinear time history analyses. Similarly, for FRP wire winding jackets, an adequate analytical model is necessary for their practical applications, such as design of the jackets and evaluation of their seismic performance. Analytical models of the SMA wire-jacketed RC columns were created using 'Pinching' material of the OpenSees to calibrate the hysteretic behavior of the RC columns. The analytical models showed hysteretic behaviors that corresponded well with those of experimental tests. However, the pinching material did not have a solid scientific basis since it was calibrated to adjust the hysteretic curves of the RC columns. Thus, it is doubtful that the analytical model with the pinching material can be generalized for practical applications. Thus, another analytical model of FRP wire-jacketed RC columns is needed for practical use.

Therefore, this study aimed to provide adequate analytical models for the behaviors of FRP wire-confined RC columns and to compare their hysteretic curves with experimental results. In addition, through nonlinear seismic time history analyses, this study assessed the probabilistic seismic performance of the two analytical models and the strengths and weaknesses of the models are discussed.

2. Experimental tests of RC columns

2.1. Specimens

The RC column specimens included two 50% lap-spliced reinforcement and two continuous reinforcement. The lap-splice means that the steel reinforcement is cut at the bottom of the RC column for convenience of construction, and the two reinforcing bars are overlapped for connection. The 50% indicates that half of the total reinforcing bars are lap-spliced and the others are continuous while the continuous reinforcement indicates that all reinforcing bars are in continuity without lap-splice. Each column was 400 mm in diameter and 1400 mm in height with an aspect ratio of 3.5 (see Fig. 1). Sixteen D13 longitudinal reinforcing bars were applied with a volumetric ratio of 1.61%, and D10 bars were placed with a spacing of 160 mm for the transverse reinforcement with hoop-ties. The thickness of the cover concrete was 40 mm. The yield strength of the longitudinal reinforcement was 325 MPa, and the compressive strength of the concrete was 27 MPa. Table 1 presents the details of the specimens. A constant axial load of $0.1f_c'A_g$ equal to 334 kN, where f_c' (25 MPa) and A_g were the peak strength of the concrete and the cross-sectional area of the columns, was introduced by prestressing the force. A more detailed explanation was provided by Choi et al. [22].

2.2. GFRP wire winding jacket

Glass-fiber reinforced polymer (GFRP) wire with a diameter of 1.0 mm was used for the jacketing. The ultimate strength and corresponding strain of the GFRP wire were 1332.0 MPa and 2.41×10^{-2}, respectively, and its Young's modulus was 55.3 GPa. The first layer of the FRP wire was wrapped from the bottom to the length of 400 mm, and the second layer was applied at the length of 300 mm. The third one covered the length of 200 mm. Thus, the FRP wire jackets looked like step, and the jacket is named as stepping jacket. The stepping jackets were applied to the lap-spliced and continuous reinforcement columns; the jacketed column with lap-splice was denoted by SP-FRP and the jacketed column with continuous reinforcement is CN-FRP hereafter. The other two columns were not jacketed and were used for reference; they are denoted as SP-Ref and CN-Ref. The GFRP wires were coiled around a large reel as shown in Fig. 2(a). In this study, a device with rubber pads clamped by bolts was prepared for the winding (see Fig. 2(b)). The device provided tension in the wire due to friction between the wire and pads when the wire was stretched by drawing. Super glue was applied to hold the wire during the winding (see Fig. 2(c)). This procedure guaranteed the wire's tight attachment to the