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Seismic improvement of RC beam–column joints using hexagonal CFRP bars combined with CFRP sheets

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ABSTRACT

Under severe earthquake conditions, the lack of strength and ductility in reinforced concrete beam–column joints with non-seismic details raises serious concerns for overall structural safety. In this study, experimental research was carried out in order to try and improve the seismic strength and performance of reinforced concrete exterior beam–column joints by applying embedded carbon fiber-reinforced polymer (CFRP) bars combined with CFRP sheets. CFRP bars have a flat-typed hexagonal cross-section. Specimens of reinforced concrete exterior beam–column joints were manufactured based on a newly developed strengthening method by applying embedded CFRP hexagonal bars combined with externally bonded CFRP sheets, and tested for comparison with the specimen of a conventional reinforced concrete exterior beam–column joint. The newly developed design approach could minimize damage and improve the overall structural performances of beam–column joints under cyclic load reversals.

1. Introduction

Due to the increasing number of severe earthquakes, structural members should have sufficient seismic performance in strength and deformation capacities. Several attempts have been made to improve the strength and deformation of non-seismic detailed reinforced concrete structures. Under severe seismic loads, beam–column joints may become more critical structural elements than other structural elements since the beam–column joints are weaker and more liable to be compromised than other structural elements when regarding structural safety.

The behavior of beam–column joint was first investigated at the Portland Cement Association Laboratories by Hanson and Conner [15], and the ACI-ASCE Committee 352 (Joints and Connections in Monolithic Concrete Structures) published its first design recommendation for beam–column joints in 1976 [2]. Numerous researchers have studied the behavior of beam–columns in many countries and provided abundant data applicable to the design of reinforced concrete beam–column joints [3,9,11,17,21,22]. The following works have contributed to updating the design recommendations (ACI 318-05) [4]. For cases of seismic design and improvement of beam–column joints, Abdel-Fattah and Wight investigated moving the zones of beam plastic hinges for an earthquake-resistant design of reinforced concrete buildings [1]. Ha et al. studied the seismic improvement of reinforced concrete beam–column joints by applying X-type reinforcement details [13]. Ha and Cho also experimented a developed strengthening method of reinforced high-strength concrete beam–column joint using advanced steel reinforcement details [12].

On the other hand, composite materials have been widely employed to retrofit concrete structures due to their advantages in high performance and strength as structural materials such as FRP materials that are lighter, easier to assemble, and more durable than alternative repair systems. Concrete wrapped by FRP jackets improved the strength and ductility of the confined concrete columns [10,18], and several applications of externally bonded FRP sheets or plates have been examined in order to improve the shear and bending behaviors of reinforced concrete beams [5–7]. Ombres predicted intermediate crack debonding failure in FRP-strengthened reinforced concrete beams by a non-linear local deformation model [19]. Pham and Al-Mahaidi studied experimentally on flexural retrofitting of reinforced concrete bridge beams using FRP composites in order to investigate the failure mechanisms and the influence several parameters on debonding modes in beams retrofitted with FRP composites [20].

To overcome the drawbacks of externally bonded FRP sheets, a near-surface mounted (NSM) method using FRP rods was also applied to strengthen reinforced concrete beams, with the advantage of the NSM technique being the possibility to anchor the reinforcement to adjacent concrete members so as to minimize debonding failures between the concrete and strengthening materials [8,16].

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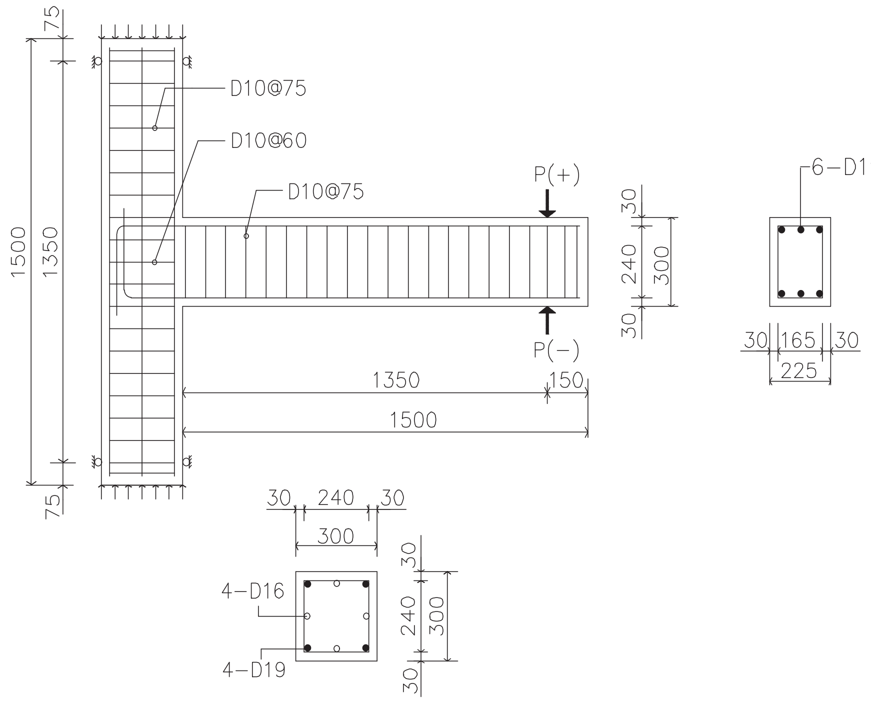

Fig. 1. Details of standard specimen, LBCJM and LBCJC.

Groove and embedding techniques using CFRP bars for the flexural strengthening of reinforced concrete beam has also been recently attempted by the authors [14], with the proposed method having two important advantages in the retrofitting of concrete beams: the failure mode of the beam was controlled by flexural failures before reaching local failures such as peeling off and the retrofitting process in the construction field was simple and easy to apply in aged reinforced concrete beam members.

The purpose of this research is to develop a new approach to improve the bending and shear capacities of non-seismic detailed reinforced concrete beam–column joints by applying embedded CFRP bars combined with externally bonded CFRP sheets. In weakly reinforced concrete buildings subjected to seismic loads, the exterior beam–column joints are prone to local damage due to the yielding of bars and crushing of the concrete in bending or diagonal cracks in shear. In this research, a series of strengthened reinforced concrete exterior beam–column joint specimens was manufactured and tested under cyclic loads in order to evaluate the improved bending and shear capacities of the strengthened exterior beam–column joints. The CFRP bars used as strengthening materials have a flat-typed hexagonal cross-section and are embedded in a concrete surface in the beam–column joints. Compared with a rectangular cross section, the hexagonal cross section of CFRP bars embedded in concrete has advantages in developing the debonding strength of the concrete surface. The use of CFRP bars and FRP sheets are the experimental variables. The experimental study reported here was undertaken to evaluate the effectiveness of the proposed strengthening concept of embedded CFRP bars combined with CFRP sheets in the seismic performance improvement of reinforced concrete beam–column joints.

2. Experimental program of exterior beam–column joints

2.1. Specimens of beam–column joints

To evaluate the performance of reinforced concrete beam–column joints by applying embedded CFRP bars combined with CFRP sheets in the joint areas, a series of experiments on exterior beam–column joints was performed under cyclic loads. The specimens were built using normal strength concrete with a compressive strength of 27.3 MPa. Five specimens of exterior beam–column joints were manufactured at a 1/2 scale of the actual structures. The standard reinforced concrete exterior beam–column joint specimens, LBCJM for the monotonic load test and LBCJC for the cyclic load test, as shown in Fig. 1, were designed according to the conventional design recommendations [4]. The specimens for strengthened details in the joints are newly designed using embedded CFRP bars combined with CFRP sheets, and the design parameters of each specimen are presented in Table 1. The specimen, LBCJ-CS1, as shown in Fig. 2, was strengthened only by externally bonded CFRP sheets. The specimen, LBCJ-CRU, as shown in Fig. 3, was strengthened by embedded CFRP bars in the top and bottom surfaces of the beam with the development length of 100 mm combined with externally bonded CFRP sheets. The specimen, LBCJ-CRS, as shown in Fig. 4, was strengthened by embedded CFRP bars in the top and bottom sides of the beam with the development length of 200 mm combined with externally bonded CFRP sheets. As shown in Fig. 5, CFRP bars have a flat-typed hexagonal cross-section used in all the specimens. In

Table 1
Design parameters of test specimens.

Specimen	Loading type	Strengthening	Design methods and parameter
LBCJM	Monotonic	None	• Standard specimen
LBCJC	Cyclic (T = 70 s)		• ACI Building Code and ASCE-ACI 352 Recommendation
LBCJ-CS1		Strengthening	• CFRP Sheet (1 sheet)
LBCJ-CRU			• CFRP sheet and CFRP bars(top, bottom) • Development length of 100 mm
LBCJ-CRS			• CFRP sheet and CFRP bars(side) • Development length of 200 mm