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Cyclic loading test for reinforced concrete columns with continuous rectangular and polygonal hoops

Tae-Sung Eom [a], Su-Min Kang [b,*], Hong-Gun Park [c], Tae-Woo Choi [c], Jong-Min Jin [d]

[a] Department of Architectural Engineering, Dankook University, 152, Jukjeon-ro, Suji-gu, Yongin-si, Gyeonggi-do 448-701, South Korea
[b] Department of Architectural Engineering, Chugbuk National University, 52, Naesudong-ro, Heungdeok-gu, Cheongju, Chungbuk 361-763, South Korea
[c] Department of Architecture, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea
[d] Daehan Steel Co., 15th Floor, HSBC Building, 37, Chilpae-ro, Jung-gu, Seoul 100-161, South Korea

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ABSTRACT

A re-bar fabrication method using continuously wound rectangular or polygonal ties (or continuous hoops) was developed to enhance constructability and economy of reinforced concrete columns. In the present study, cyclic loading tests were performed to investigate the structural performance of the columns with continuous hoops. The test parameters were the shape, spacing, and bar diameter of the continuous hoops, and the spacing between the longitudinal bars and the hoops. The load-carrying capacity, deformation capacity, and failure mode of the specimens were directly compared with those of a column with conventional ties. On the basis of the test results, the effects of the continuous hoops were evaluated. Further, requirements for the vertical spacing of transverse reinforcement were studied to restrain the post-yield buckling of longitudinal bars in the plastic hinge zone.

1. Introduction

ACI 318-11 [1] and KCI 2012 [2] require strict transverse reinforcement details for the earthquake design of reinforced concrete beams, columns, and beam–column connections. The transverse reinforcement details are more complicated by the use of close spacing, crossties, and 135-degree seismic hooks. Thus, the reinforcement work requires elaborate efforts and construction time even for skilled workers (see Fig. 1(a)).

To ease the complicate reinforcement work, various re-bar fabrication methods have been considered. Particularly, in Europe, the use of welded meshes, welded bar cages, and circular-shaped spirals has been increased for the transverse reinforcement of beams, columns, and walls. Recently, continuously wound ties (or continuous hoops) in the form of polygonal helixes (i.e. rectangle, hexagon, octagon, etc.) were developed by using coiled bars and bending-and-cutting machines [3,4]. For easy shipping, the continuous hoops are compressed and tied after fabrication. In construction site, the compressed continuous hoops are released in the position of fabrication (see Fig. 1(b)).

When compared to conventional hoops using crossties and hook anchorages, the continuous hoops have several advantages. The construction time can be reduced because the ties enclosing longitudinal bars can be installed by simply releasing the compressed continuous hoops, as shown in Fig. 1(b). Various tie shapes including rectangular, T-shaped, hexagonal, and octagonal ones can be fabricated without difficulty. Furthermore, since hook anchorages are not necessary, the amount of coiled bars that is required for ties can be decreased and re-bar congestion can be alleviated.

Recently, many studies have been performed to investigate the structural performance of beams and columns with continuous rectangular hoops. Karayannis and Chalioris [5] and Karayannis et al. [6] proposed various details of continuous rectangular hoops to enhance the shear capacity of beams. The test results showed that the shear capacities of the beams with the continuous hoops were increased by 14.7–21.7% due to the bar inclination, when compared to conventional stirrups. De Corte and Boel [7] tested twenty four beams with continuous rectangular hoops, and compared the shear capacities with those of beams with conventional standard stirrups. The results showed that the shear capacity of the continuous hoops agreed with the predictions of current design codes such as EC2 [8], ACI318-11 [1], and JSCE [9]. Kakaletsis et al. [10] performed cyclic loading tests on reinforced concrete frames with continuous rectangular hoops. The structural

* Corresponding author. Tel.: +82 1092084116; fax: +82 43 263 2635.
E-mail addresses: tseom@dankook.ac.kr (T.-S. Eom), ksm0626@paran.com (S.-M. Kang), parkhg@snu.ac.kr (H.-G. Park), ksm@snu.ac.kr (J.-M. Jin).

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Nomenclature

A_b	cross-sectional area of reinforcing bar
A_g	gross area of column section
A_{sh}	total cross-sectional area of a layer of tie including crossties
D_b	diameter of longitudinal bar
E	effective modulus of reinforcing bar
E_D and E_{ep}	energy dissipations per load cycle by actual behavior and elastic-perfectly plastic behavior, respectively
E_p	post-yield stiffness of reinforcing bar
E_r	reduced modulus of reinforcing bar
E_s	elastic modulus of reinforcing bar
I_0	second-order moment of inertia of bar section
K	effective buckling length factor
N	axial compressive load applied to a column
P_{cr}	Euler buckling load of a reinforcing bar
P_n and P_{n0}	nominal strengths of column with or without second-order effect, respectively
P_u	maximum test strength
c	clear cover of hoop
c_b	spacing between longitudinal bars and continuous hoop for re-bar fabrication
d_b	diameter of hoop bar
f_y	yield strength of reinforcing bar
f'_c	compressive strength of concrete
l_h and l'_h	bar lengths of a layer of continuous and conventional hoops, respectively
l_x and l_y	dimensions of continuous and conventional hoops
s	spacing of hoop
δ	lateral drift ratio of column
δ_y	yield drift ratio of column
δ_u	maximum drift ratio at failure of column
κ	energy dissipation ratio of column
μ	displacement ductility ratio of column
ρ_v	shear reinforcement ratio of column
σ_{cr}	post-yield buckling stress of reinforcing bar

performances of the continuous rectangular hoops (e.g. load-carrying capacity, deformation capacity, stiffness, and energy dissipation capacity) were comparable to those of conventional stirrups. Chalioris and Karayannis [11] studied torsional capacity of beams with continuous rectangular hoops. The torsional behavior was significantly influenced by the directions of twisting and hoop-winding. Karayannis et al. [12] performed cyclic loading tests on columns and exterior beam–column connections with continuous rectangular hoops. The joint shear capacity of the beam–column connections, and the load-carrying and energy dissipation capacities of the columns were improved by the use of continuous rectangular hoops.

From the viewpoint of structural safety and design, the continuous hoops are reliable particularly under cyclic loading because there is no risk of unfolding of hook anchorages. Because of continuity of the continuous hoops, confinement effect may be better than that of the conventional ties. Furthermore, since 135-degree hook anchorages are not necessary, longitudinal bars can be concentrated at the corners of the rectangular hoops, which can increase the flexural capacity of columns. On the other hand, a spacing between the longitudinal bars and ties is required for an easier reinforcement work of continuous hoops. Because of the spacing, the structural capacity of the continuous hoops and the columns such as shear strength, confinement effect, and restraining effect against longitudinal bar buckling may be degraded.

In the present study, to study the effects of the continuous hoops, column specimens with the continuous hoops were tested under cyclic lateral loading. The structural performance including load-carrying capacity, deformation capacity, and energy dissipation capacity was directly compared with a column with conventional hoops. From the test results, the effect of the shape and spacing of the continuous hoops was investigated. Further, the effect of the spacing between the longitudinal bars and ties was studied.

2. Details of continuous hoops

Fig. 2(b) shows three representative layouts of the continuous hoops for columns: for small size cross sections, rectangular hoops can be used (see **Detail A** of Fig. 2(b)); and for large size cross sections with many longitudinal bars, rectangular-rhombic or rectangular-octagonal hoops can be used (see **Details B** and **C** of Fig. 2(b)). When the rhombic and octagonal hoops are used, conventional crossties can be removed. The shape of the continuous hoops can vary according to the shape of the cross sections and the arrangement of the longitudinal bars. At the start and end of the continuous hoops, a seismic hook or one additional turn of hoop is required for anchorage [1].

Since hook anchorages are not necessary, the quantity of the continuous hoops can be decreased. Table 1 compares the bar lengths per hoop, l_h, of the conventional ties (including crossties) and the continuous hoops. For the continuous hoops, three hoop shapes in Fig. 2(b) were considered: **Details A** (rectangular hoop), **B** (rectangular-rhombic hoop), and **C** (rectangular-octagonal hoop). The conventional ties that are the counterpart of **Details A**, **B**, and **C** of the continuous hoops are shown in Fig. 2(a), in which the rhombic and octagonal shapes are substituted by conventional tie

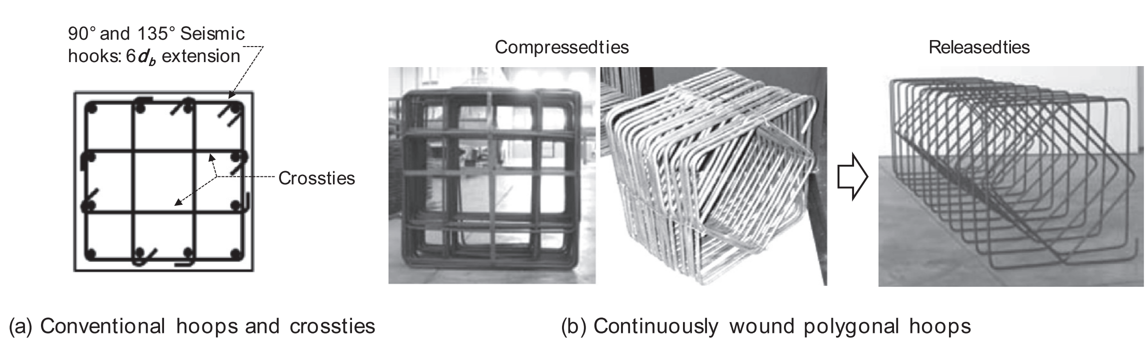

Fig. 1. Transverse reinforcement of reinforced concrete columns.