Structural and seismic performance of RC columns with L-shaped hoop details

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Abstract. This paper aims at developing L-shaped hoop detail and evaluating structural and seismic performance of reinforced concrete columns when the developed hoop detail is applied. L-shaped hoop is introduced in this study to save construction time period by improving constructability. RC columns are fabricated having test parameters of concrete strength (24MPa and 35MPa) and hoop details (general hoop and L-shaped hoop). Axial and seismic loading tests are performed, and the test results of maximum column strength and load-strain curve of the column are similar regardless of hoop types. In addition, seismic test results show that hysteresis loops and energy dissipation capacity of the column specimens using two different hoop types (general hoop and L-shaped hoop) are similar.

1. Introduction

Korean Building Code (KBC 2016[1]) recommends details of seismic hoop as shown in figure1 to increase seismic performance with 135° anchorage hooks. However, it is hard to place such design hoops at the top of longitudinal bar and pull them down to fixed position. Considering that a height of one story is about 4-5m, such hoop design needs to be improved.

The previous studies with alternative hoop details have been reported by Kim G Y [2], Kim C G et al. [3-5], Eom T S [6-7], Kim D H [8], and Ko S H [9]. Kim G Y suggests two kinds (C-shaped hoop and L-shaped hoop) of hoop as alternatives. Both hoops show similar axial and seismic performance in their test, but it is reported that C-shaped hoop is sometimes loosened when the cover of the concrete is failed. Therefore, this study choose L-shaped hoop (figure 2) for the evolution of axial and seismic performance.

The L-shaped hoop used in the study is prefabricated in L shape and has 135° anchorage hooks at both ends. Because it is relatively easy for workers to open the tie of the hoop momentarily as long as the diameter is 10mm, the L-shaped hoop can be placed at designated location directly without being pulled down from the top of the longitudinal bar. Thus, the L-shaped hoop can improve the constructability and shorten construction period.

This study aims at evaluating structural and seismic performance of reinforced concrete columns by carrying out axial and seismic tests on the columns applied with the developed hoop detail.

Figure 1. General hoop. Figure 2. L-shaped hoop.
2. Test program
The experimental parameters are hoop detail (general and L-shaped type) and designed concrete compressive strength, $f_c$ (24MPa and 35MPa). Considering these parameters, total eight specimens (4 for axial loading test specimens, and 4 for seismic test specimens) are fabricated as tabulated in Table 1. [10-13]

| Specimen     | $f_c$  | Hoop type         |
|--------------|--------|-------------------|
| A (C)$^b$24-08 | 24MPa  | General type      |
| A (C)$^b$35-08 | 35MPa  |                   |
| LA (C)$^b$24-08 | 24MPa  | L-shaped type     |
| LA (C)$^b$35-08 | 35MPa  |                   |

$^a$ A: Axial loading test specimen  
$^b$ C: Seismic test specimen

2.1 Test specimens
There are two types of test specimens, which are for axial loading test and for seismic test. Axial loading test specimens are fabricated in straight rectangular shape and seismic test specimens are fabricated in reversed T shape.

Figure 3 shows details of specimens for axial loading tests. The cross section is 400x400mm$^2$ and the height of the test specimen is 1400mm. Thickness of 5mm steel plates are welded on both ends of specimen to prevent eccentricity during loading. In order to prevent excessive cracking in the region close to the loading point, three layers of carbon fiber sheet is attached to the ends of the specimens at a width of 250mm. Figure 4 shows details of specimens for seismic test. Test specimens are composed with column section at upper part, and foundation section at the bottom. Cross section of column is 400x400mm$^2$ and that of foundation is 1400x800mm$^2$. The height of the column is 1500mm and the total height of specimen is 2000mm.

For longitudinal bars and hoops of all the specimens, D22 and D10 are used respectively, which means that the nominal diameter of longitudinal bar is 22mm and that of hoop is 10mm. Concrete mix proportion and strength are tabulated in table 2 and mechanical properties of longitudinal bars and hoops are tabulated in table 3. The nominal yield strength of longitudinal bar is 500MPa and the nominal yield strength of hoop is 400MPa. However, in our study, strength measured from tensile strength tests are found as 504.92MPa and 467.41MPa for longitudinal bars and hoops, respectively.

![Figure 3. Axial loading test specimen.](image)

![Figure 4. Seismic loading test specimen.](image)
Table 2. Concrete mix proportion and strength.

| $f_c$ (MPa) | $f_{ck}$ (MPa) | Mixed proportion |
|-------------|----------------|------------------|
|             |                | Max. aggregate size (mm) | Slump (mm) | W/C (%) | Fine aggregate (%) |
| 24          | 33.50          | 25                | 150        | 49.7    | 49.5              |
| 35          | 43.60          | 25                | 150        | 39.5    | 47.5              |

Table 3. Steel material property.

| Bar type          | $f_y$ (MPa) | $\varepsilon_y$ (mm/mm) | $E_s$ (GPa) |
|-------------------|-------------|-------------------------|-------------|
| Longitudinal bar  | 504.92      | 0.0028                  | 179.90      |
| Hoop              | 467.41      | 0.0026                  | 179.74      |

2.2 Test setup and loading plan

For the axial loading test, the load is applied using a 1000 ton capacity hydraulic machine until the column is failed as shown in figure 5. Strain gauges are attached to longitudinal bars and hoops. Figure 6 illustrates the test setup for the seismic loading test. Axial load (N) is applied to the columns by actuator placed on the top of the column. During seismic loading, axial load N, sustained to be around 10% of the axial strength of the column. As the axial load is sustained, the cyclic lateral loading is applied in a form of controlling the displacement at a height of 1200mm from the column base. The total of 11 steps of seismic loading are planned and the same loading magnitude is repeated for three times at each step as shown in figure 7. After the each step, the load is increased about 1.25~1.5 times to the drift ratio of previous step, according to ACI 374.1 [14]. Strain gauges are attached at longitudinal bars and hoop sides parallel to the lateral force direction in plastic hinge section, where in the range of 400mm from the column bottom.

![Figure 5. Axial loading test setup.](image)

![Figure 6. Seismic test setup.](image)

![Figure 7. Seismic loading plan.](image)
3. Test results

3.1 Axial loading test results

3.1.1 Maximum column strength

Based on the results obtained from the axial force tests, $P_{\text{test}}$ is defined as failure load at the time of failure. For the case of columns having concrete strength of 24MPa (A24-08 and LA24-08), the difference of maximum loads between the columns with the general hoop and L-shaped hoop is only 0.1%. For the case of columns having concrete strength of 35MPa (A35-08 and LA35-08), the difference of maximum load between the columns with the general hoop and L-shaped hoop is 4.4%. Therefore, the test specimens show similar axial strengths regardless of general or L-shape hoop types. To compare the test result with the theoretical value, column strength ($P_{\text{theo}}$) is calculated according to the concrete design code from KBC 2016 [1] as shown in Equation (1). In the equation, $A_g$ and $A_w$ denote cross sectional areas of the column and longitudinal bars, respectively. Compressive strength measured 28 days after the curing is generally regarded as standard compressive strength ($f_{ck}$) and the yield strength of longitudinal bar obtained by steel tensile strength test ($f_y$ in table 3) is used.

$$P_{\text{theo}} = 0.85f_{ck}(A_g - A_w) + f_yA_w$$ (1)

As listed in Table 4, theoretical values, $P_{\text{theo}}$, are very close to the values of test results, $P_{\text{test}}$, which shows that not only L-shaped hoop functions similar to general hoop but also axial strength of the column having L-shaped hoop is predictable using the classical design code. The maximum difference of axial strength between the $P_{\text{theo}}$ and $P_{\text{test}}$ is about 3.3%.

| Specimen  | $P_{\text{theo}}$(kN) | $P_{\text{test}}$(kN) | $P_{\text{test}} / P_{\text{theo}}$ |
|-----------|-----------------------|------------------------|-------------------------------------|
| A24-08    | 6031.55               | 6200.426               | 1.028                               |
| LA24-08   |                       | 6191.509               | 1.027                               |
| A35-08    | 7378.56               | 7298.728               | 0.989                               |
| LA35-08   |                       | 7655.720               | 1.033                               |

3.1.2 Load-strain curve of hoop

![Figure 8. Load-strain curve of mean of 4 sides of hoops.](image1)

![Figure 9. Load-strain curve of hook side of hoops.](image2)

The relationships between axial load and strains obtained from the axial loading tests are illustrated in figure 8 and figure 9. Strain values are measured from the gauges attached to the hoops. For the
analysis, averaged values of strains obtained from different locations of hoops are used. The solid line of 0.0026 of strain represents the point where D10 bar is yielded.

From figure 8 and figure 9, it can be seen that the graphs show increase of hoop strain as the column is axially loaded and the axial load-strain relationships of general hoop and L-shaped hoop are very similar to each other. In addition, strains of hoops do not reach 0.0026, which means hoops are not yielded until the specimen is failed.

Figure 9 shows axial load versus strain obtained from a gauge attached to the hook of the hoop. The graph shows that the strains of hook are smaller than those measured from other locations of hoops and they are not yielded as well. This means that the hooks are fully tied until the specimens fail regardless of hoop type.

3.2 Seismic test results

3.2.1 Hysteresis loops of columns
Seismic loading is terminated when the specimens show severe damage at the plastic hinge area. At the moment, all the specimens show similar failure mode, such that flexural and diagonal shear cracks occur in plastic hinge area of the specimens.

The hysteresis loops obtained from the seismic loading test are illustrated in figure 10 and figure 11. From the graphs, the hysteresis behaviors of the specimens using the L-shaped hoop and general hoop are similar to each other in terms of stiffness and maximum shear load. For all the specimens, shear force reaches its maximum value at the 6th loading step (drift ratio of 1.5%) regardless of hoop types. After the 6th loading step, maximum shear force decreases steadily until the final loading step, which means the specimens show ductile behaviors.

3.2.2 Energy dissipation
Energy dissipation analysis is important as it represents energy absorption capacity of columns under seismic loading. Accumulated energy dissipation is obtained from the area inside the hysteresis loops shown in figure 10 and figure 11.

As tabulated in table 5, the energy dissipation capacity of specimens using the general hoop or L-shaped hoop have almost the same energy dissipation capacity until 6th loading step (drift ratio of 1.5%), where the maximum shear force occurs. In the 6th loading step, the accumulated energy dissipation of C24-08 and LC24-08 are very similar with 1.01% difference. For the C35-08 and LC35-08, difference of accumulated energy dissipation in 6th loading step is 2.03%.

At the 7th and 8th loading step, the energy dissipation capacity is similar regardless of hoop types for the columns having concrete strength of 24MPa. However in the last loading step (drift ratio of 3.5%), the energy dissipation capacity of the C24-08 is 11.5% higher than that of LC24-08.
For the columns having concrete strength of 35MPa, the energy dissipation capacity of C35-08 is higher than LC35-08. However, in the last loading step, due to the yielding of the longitudinal bar, C35-08 cannot withstand the axial force sufficiently and the cumulated energy dissipation decreases. On the other hand, in the case of the specimens using the L-shaped hoop, accumulated energy dissipation steadily increase with the loading cycle.

Table 5. Accumulated energy dissipation.

| Drift ratio (%) | Loading step | Accumulated energy dissipation (kN·mm) |
|----------------|--------------|--------------------------------------|
|                | C24-08       | LC24-08 | C35-08 | LC35-08 |
| 0.25           | 1            | 0.527   | 0.507  | 0.550   | 0.550   |
| 0.35           | 2            | 0.712   | 0.755  | 0.725   | 0.850   |
| 0.5            | 3            | 1.156   | 1.308  | 1.216   | 1.316   |
| 0.75           | 4            | 2.183   | 2.459  | 2.303   | 2.377   |
| 1              | 5            | 3.728   | 3.619  | 3.387   | 3.742   |
| 1.5            | 6            | 7.447   | 7.372  | 7.948   | 8.109   |
| 2              | 7            | 11.976  | 10.973 | 14.049  | 12.083  |
| 2.5            | 8            | 18.656  | 17.346 | 23.440  | 19.165  |
| 3.5            | 9            | 39.205  | 34.662 | 16.350  | 42.939  |

3.2.3 Yield step of hoop.

In this study, strains of the hoops at 50mm and 250mm away from the bottom of the column are focused because the earliest yielding step occurs in those area compared to other locations. All hoops are yielded after the 6th loading step where the maximum shear forces occur. In addition, all hoops are yielded after the yielding of the longitudinal bars. Hooks are yielded later than 8th loading step which means that the hooks have been tied with no significant deformation.

Table 6 shows yield step of hoop. For the hoops located on the first layer (1H1 and 1H2), it can be seen that the general hoops are yielded at the same or later steps than the L-shaped hoops are yielded. For the hoops located on the second layer (2H1 and 2H2), yield steps of general hoops and L-shaped hoops are similar.

Table 6. Yield step of hoop.

| Specimen | 1H1 | 1H2 | 2H1 | 2H2 | Gauge location |
|----------|-----|-----|-----|-----|----------------|
| C24-08   | x   | 9   | 8   | 7   |                 |
| LC24-08  | 7   | 7   | 8   | x   |                 |
| C35-08   | x   | x   | 8   | 9   |                 |
| LC35-08  | x   | x   | 9   | 9   |                 |

\[ x^a : \text{Not yielded} \]
\[ x^b : \text{Not measured} \]
3.2.4 Failure mode
Figure 12~15 show crack patterns of the tested specimens after the test. There is no significant difference in failure mode among the tested specimens regardless of hoop types. For all specimens, flexural and diagonal shear cracks occurred in the plastic hinge zone. In addition, the concrete cover in the plastic hinge zone was gradually spalled off as cracks at the bottom of the column are developed with load.

Between the columns having concrete strength of 24MPa (C24-08 and LC24-08), concrete failure at the bottom of the column and diagonal shear cracks are more obvious in C24-08 than LC24-08. On the other hand, the crack patterns of specimens are similar between the columns having concrete strength of 35MPa (C35-08 and LC35-08). Thus, one can say that there is no significant difference in failure modes due to different hoop types.

4. Summary and conclusion
- The axial strengths of the columns using the general hoops or the L-shaped hoops are similar with 4.4% of maximum difference.
- The hysteresis loops of the specimens with the same designed concrete compressive strength show almost same behavior between the specimens using general hoop and L-shaped hoop. All specimens show maximum shear force at 6th loading step (drift ratio of 1.5%) and shows ductile behavior afterwards.
- The energy dissipation capacity of all the specimens is very similar to each other until 6th loading step (maximum shear load). Only for the specimen of C35-08, energy dissipation capacity is relatively small due to the earlier failure than that of specimen LC35-08.
- The hoops located in plastic hinge section are yielded after the yielding of longitudinal bar. Yield step of general hoop and L-shaped hoop is similar, which confirms that seismic performance of general hoop and L-shaped hoop is similar.
- For the failure mode of all the tested specimens, diagonal shear crack is dominant and cross-sectional area of the concrete at the bottom of the column is gradually reduced. The crack patterns of the all specimens are similar to each other, which means there is no significant difference in failure mode among the specimens having different hoop types.

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