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Complete List of Authors:	Kim, Tae-Hoon; Samsung C and T Corp Construction and Engineering Group, Construction Technology Team Kim, Ick-Hyun; University of Ulsan, Department of Civil and Environmental Engineering Lee, Jae-Hoon; Yeungnam University Shin, Hyun Mock; Sungkyunkwan University - Suwon Campus, Civil and Architectural Engineering
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Hollow bridge columns with triangular confining reinforcement

Tae-Hoon Kim ^{a,*}, Ick-Hyun Kim ^b, Jae-Hoon Lee ^c, and Hyun Mock Shin ^d

^a Principal Researcher, Construction Technology Team, Samsung Construction & Trading Corporation, 145, Pangyoyeok-ro, Bundang-gu, Seongnam-si, Gyeonggi-do, 13530, Korea

^b Professor, Department of Civil and Environmental Engineering, University of Ulsan, 93, Daehak-ro, Nam-gu, Ulsan-si, 44610, Korea

^c Professor, Department of Civil Engineering, Yeungnam University, 280, Daehak-ro, Gyeongsan-si, Gyeongsangbuk-do, 38541, Korea

^d Emeritus Professor, Architectural and Civil Engineering Department, Sungkyunkwan University, 2066, Seobu-ro, Jangan-gu, Suwon-si, Gyeonggi-do, 16419, Korea

* Corresponding author: Tae-Hoon Kim (e-mail: neopilot@naver.com)

Abstract

The purpose of this study is to assess the structural performance of hollow bridge columns with triangular confining reinforcement. The proposed triangular reinforcement details were equal to the conventional reinforcement details in terms of required structural performance. The triangular confining reinforcement is also economically feasible and rational, and facilitate shorter construction periods. Three hollow cast-in-situ concrete and three precast concrete bridge columns were tested. The behavior of the hollow columns is discussed in terms of their lateral load-drift relationship, cumulative dissipated energy, and lateral load-strain curves. The nonlinear finite element analysis program RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology) was used to analyze hollow bridge columns,

and adopted a modified joint element for the precast concrete bridge columns. The results showed that the proposed innovative reinforcement details were superior to the conventional reinforcement details, in terms of the required structural performance.

Key words: structural performance; hollow cast-in-situ bridge columns; hollow precast bridge columns; triangular confining reinforcement; economically feasible

1. Introduction

Hollow column cross-sections are widely used because they offer the advantages of high bending and torsional stiffness, reduced substructure weight, and resulting in savings in foundation costs. For these reasons, reinforced concrete bridge columns with hollow cross-sections are widely designed and constructed for highway, high-speed rail, and other bridge columns (Lignola et al. 2011; Kim et al. 2013, 2014; Han et al. 2014; Liang et al. 2015; Kim et al. 2018).

Traditional hollow reinforced concrete bridge columns are designed based on economic considerations of the cost saving associated with reduced material and design moments compared with increased construction complexity of hollow column cross-sections, and hence increased labor costs (Zahn et al. 1990; Yeh et al. 2001; Delgado et al. 2008; Kim et al. 2012a).

Hollow reinforced concrete columns were used with two layers of confinement reinforcement placed near the inside and outside faces, as well as cross-ties placed through the wall thickness. In the previous studies performed by the authors (Kim et al. 2013, 2014), a new configuration of confining reinforcement was proposed to solve the problem of construction complexity of conventional hollow column cross-sections. The proposed triangular reinforcement details were expected to help the column to exhibit sufficient ductility and design strength. The triangular confining reinforcement also plays a role in preventing longitudinal reinforcement buckling.

The main aim of this study is to expand the application of the triangular confinement modules to hollow bridge columns with a hollow ratio (inner / outer diameter ratio) to 0.8. Additionally, current study extends the application of precast concrete bridge columns along with the triangular confinement modules.

Precast segmental bridge columns provide the benefits of increasing construction speed and quality, reducing environmental pollution, and decreasing life cycle costs. Recently, various studies have been carried out abroad on the inelastic behavior and performance of precast segmental bridge columns (Billington et al. 2001; Chou and Chen 2006; Kim et al. 2010; Dawood et al. 2012; Kim et al. 2017). Billington et al. (2001) proposed substructures by developing attractive and rapidly constructed substructure systems for short- and moderate-span bridges. Chou and Chen (2006) verified a method to estimate the experimental flexural displacement using two plastic hinges in the segmental column. Kim et al. (2010) investigated the performance of precast concrete segmental bridge columns with a shear resistant connecting structure. Dawood et al. (2012) presented a detailed three-dimensional finite-element (FE) model for segmental precast posttensioned (SPPT) bridge piers. Kim et al. (2017) established

the behavior of hollow precast segmental prestressed concrete bridge columns under cyclic loading.

In this paper, hollow cast-in-situ concrete and precast concrete bridge columns are tested under a constant axial load and a quasi-static, cyclically reversed horizontal load. Many parameters can influence the overall hollow cross-section response, such as the reinforcement details, the shape of the cross-section, the spacing of the transverse reinforcement, and the material strength of the concrete and reinforcement.

An assessment method for the performance of hollow bridge columns with triangular confining reinforcement is proposed. The proposed method uses the computer program, RCAHEST, developed by the authors (Kim et al. 2007, 2008, 2010, 2012b, 2013, 2014, 2017, 2018). A joint element is modified in order to predict the inelastic behaviors of segmental joints for hollow precast bridge columns.

2. Triangular confining reinforcement for hollow bridge columns

Hollow bridge columns have become popular in bridge construction during the last few decades. Hollow cross-sections are often used for tall bridge columns to reduce their mass, seismic inertia forces, and foundation forces (Kim et al. 2012b).

Figure 1 shows the developed hollow bridge column cross-sections with triangular confining reinforcement details. In conventional practice, a number of layers of longitudinal and transverse steel are placed near both the outside and inside faces of the hollow circular cross-section of bridge columns, and are tied through the wall thickness with cross-ties. Normally, a 135-degree bend or full hook should be specified for at

least one end of the cross-tie. These hollow column cross-sections have increased construction complexity, and hence increased labor costs (see Fig. 1(a)).

In the previous studies performed by the authors (Kim et al. 2013, 2014), the developed reinforcement details for material quantity reduction consist of a stable triangular structure that combines outside transverse reinforcement and triangular cross-ties. The transverse steel placed near the inside face and the cross-ties may not significantly contribute to the confinement of the concrete wall in the hollow cross-section (Zahn et al. 1990; Hoshikuma and Priestley 2000). The details involve applying a sparsely spaced inner reinforcement in circular hollow cross-sections, in order to control non-structural cracks (the serviceability limit state) (see Fig. 1(b)).

This paper presents a new design concept of hollow cast-in-situ concrete and precast concrete bridge columns with triangular confining reinforcement. These innovative reinforcement details offer economic feasibility and rationality, and facilitate shorter construction periods (see Fig. 1(c)). Figures 1(c) and (d) also show the design concept of the proposed hollow precast concrete bridge columns with triangular confining reinforcement. A segmentally precast concrete bridge column consists of relatively small, easily handled segments. After all the precast column segments were erected, longitudinal reinforcement was inserted in the sheath prefabricated in the segments, which were then mortar grouted. The use of precast segmental construction for concrete bridges has increased in recent years due to the demand for shorter construction periods and the desire for innovative designs that yield safe, economical and efficient structures (Kim et al. 2010).

The proposed triangular reinforcement details with corrugated sheaths are both structurally and constructionally efficient, facilitating shorter construction periods by

prefabricating triangular modules and reducing steel congestion. The use of the triangular modules can meet the tolerance of 3 mm required for segmental precast columns, which has been often troublesome for regular precast columns. Each pre-fabricated triangular module can also stand alone prior to fabricating a whole bridge column cage. The developed pre-fabricated triangular confinement modules have many structural and constructional advantages such as: superior concrete confinement; seismic performance; increased moment capacity with outer longitudinal rebars; reduced construction time; stability of steel cage modules; minimized tolerance (particularly for precast segmental columns); reduced steel congestion; and material efficiency.

3. Experimental investigation

3.1 Test specimens and procedure

An experimental investigation was conducted to evaluate the performance of hollow bridge columns with triangular confining reinforcement.

Three cast-in-situ and three precast hollow column specimens were tested under cyclic lateral loads while being simultaneously subjected to constant axial loads. It is considered appropriate to use the current code provisions (AASHTO 2014; MCT 2015) on the concrete confinement for the plastic hinge regions in the design of hollow bridge columns for use in moderate to low seismic regions by the following equation:

- (1) For a circular column: $\rho_s = 0.12 \frac{f'_c}{f_{yh}}$
- (2) For a rectangular column: $A_{sh} = 0.12 a h_c \frac{f'_c}{f_{yh}}$

where ρ_s = volumetric ratio of transverse reinforcement; f'_c = concrete compressive strength; f_{yh} = yield strength of transverse reinforcement; A_{sh} = cross-sectional area of column tie reinforcements; a = vertical spacing of hoops; and h_c = core dimension of tied column in direction under consideration.

Table 1 lists the materials properties used in cast-in-situ and precast column specimens, and Figures 2 and 3 show the geometric details. The cast-in-situ circular column has a 1400 mm outer diameter and 1050 mm inner diameter. The precast rectangular column has a 1000×1000 mm cross-section with 500×500 mm hole in the center.

The first character of the specimen ID refers to the shape of the cross-section (Circular or Rectangular), the second character refers to the configuration type (Conventional or Triangular) and the third character represents the spacing of the confining steel (80 mm or 120 mm). In addition, the character N indicates that minimum inner lateral reinforcement was used.

A schematic representation of the test set-up for column specimens is shown in Fig. 4. The load was applied at the column top by a servo-controlled 3500 kN capacity hydraulic actuator with a ± 600 mm stroke reaching off the laboratory strong wall.

The same procedures were used for each test. The column specimens were tested under a $0.1f'_cA_g$ and $0.07f'_cA_g$ constant compressive axial load to simulate the gravity load from bridge superstructures (see Table 1). The displacement was represented by using drift ratio. The specimens were subjected to two cycles at each

lateral displacement amplitudes of 0.25, 0.5, 1.0, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.5, 5.0, 5.5 and 6.0 percent until failure.

Measurements were then manually triggered based on the lateral actuator running in displacement control. Strains of the longitudinal and transverse reinforcement were measured with the strain gauges attached at the positions shown in Fig. 5. The strain gauges placed at several locations in the region were affected by significant inelastic flexural behavior.

3.2 Results of experiments

The drift responses for the column specimens are shown in Figs. 6 and 7. Figures 6 and 7 also show the nominal strength of the columns and the damage of the specimens beyond end of test. The nominal strengths obtained from the design code (AASHTO 2014; MCT 2015) are conservative for six hollow column specimens with proposed and conventional reinforcement details.

It was observed from the test, the similarity in the shape of the hysteresis curves of specimens. The physical phenomena that similarly occurred during all tests include: cracking, yielding, spalling of cover concrete, buckling, and fracture of rebars.

Flexural cracks perpendicular to the column axis developed first in regions close to the bottom end of the three cast-in-situ columns (drift 0.50%). The flexural cracks became inclined and extended due to the influence of shear, typically at a stage exceeding the first yield of longitudinal reinforcing bars (drift 1.50%). Plastic hinges were fully formed at the bottom end of the columns, which contributed to the development of ductility (drift 3.00%).

Minor concrete cracking was found on the surface of the column during the test of the

three precast columns. The joint opening between the foundation and the first column segment increased as the applied lateral displacement increased. Almost the entire joint opening was concentrated at the joint between the foundation and the first column segment. Other joints had not obviously opened by the end of the test.

The concrete cover at the base of the cast-in-situ and precast column specimens had spalled off and hence the transverse reinforcement is clearly seen. Note that the core concrete inside stirrups remained effective in carrying the compressive load. Subsequent displacement steps in the negative direction beyond this point were accompanied by a significant decrease in lateral load.

Figures 6 and 7 also show a good seismic performance of the proposed hollow cast-in-situ concrete and precast concrete bridge column with respect to reference specimens: CC-80 and RC-80. This is because more effective confinement is provided by links having triangular reinforcement details than that provided by 90-degree hooks. The opening of the 90-degree-hooks in the cross-ties, longitudinal bar buckling, core crushing, fracturing of hoops or cross-ties occurred at large strain values. The triangular confining reinforcement was evaluated to ensure that longitudinal reinforcement buckling failure would not occur. Internal damage was also monitored as shown in Figs. 6 and 7, further widespread damage in the conventional specimen series rather than in the proposed specimen series.

All six hollow cast-in-situ concrete and precast concrete bridge column specimens exhibited ductile behavior under cyclic loading. The ductility ratios ranged from 4.9 to 6.6 (see Table 2). The displacement ductility is defined as the ratio between the limit point and the yielding point. The yielding point was defined as the displacement corresponding to the intersection of the horizontal line passing through $0.75V_{max}$ on

the load-displacement envelope curve and the straight line passing through $0.75V_{max}$ from the origin, and the limit point was defined as the displacement corresponding to $0.85V_{max}$ after the maximum load (Park 1998).

The hysteretic energy dissipation of the column specimens was evaluated based on the cumulative dissipated energy (see Figure 8). The dissipated energy was determined by integrating the areas bound by all the hysteretic loops and it was found that the hysteretic energy dissipation increased as column drift increased. The proposed triangular reinforcement detail exhibited hysteretic behavior with satisfactory hysteretic energy dissipation, as shown in Figure 8. For specimens CC-80 and CT-80, the cumulative dissipation energy was 2104182 kN-mm (drift 5.0%) and 2708244 kN-mm (drift 5.5%), respectively.

Figure 9 shows the typical measured steel strains in the transverse reinforcement for hollow cast-in-situ concrete specimens with innovative details. It was found that the transverse reinforcement was subjected to low demand, with strains typically not reaching above 2,000 microstrain. This indicates that the triangular confining reinforcement was adequate to prevent fracture of the transverse reinforcement.

As shown in the figures, the effect of negative confinement (cracking of the inner concrete cover) is diminished, because the confining action of the inner transverse reinforcement is transferred by the links' tensile actions towards the outer transverse reinforcement, providing improved confinement of the concrete region in-between. It was also observed that the presence of inner transverse reinforcement does not significantly contribute to the strength and ductility of the confined section. The inner concrete cover tended to crack and spall off at higher levels of axial strain, leading to the observed reduced ductility. This adverse effect has been referred to as 'negative

confinement' (Papanikolaou and Kappos 2009).

4. Analytical investigation

4.1 Description of numerical simulation

A two-dimensional finite element model for the hollow cast-in-situ concrete and precast concrete bridge columns with triangular confining reinforcement was developed in this study.

The model was created and analyzed using the general-purpose finite element software, FEAP (Taylor, 2000). The proposed structural element library for RCAHEST (Kim et al. 2007, 2008, 2010, 2012b, 2013, 2014, 2017, 2018) is built around the finite element analysis program shell named the Finite Element Analysis Program (FEAP). The details of the nonlinear material model used were provided in previous research.

The elements developed for the nonlinear finite element analyses of reinforced concrete bridge columns are a reinforced concrete plane stress element and an interface element. The nonlinear material model for the reinforced concrete comprises models for concrete and models for the reinforcing bars.

Models for concrete may be divided into models for uncracked concrete and for cracked concrete. For cracked concrete, three models describe the behavior of concrete in the direction normal to the crack plane, in the direction of the crack plane, and in the shear direction at the crack plane, respectively. A modified elasto-plastic fracture model is used to describe the compressive behavior of concrete struts in

between cracks in the direction of the crack plane. The basic and widely-known model adopted for crack representation is based on the non-orthogonal fixed-crack method of the smeared crack concept.

The post-yield constitutive law for the reinforcing bar in concrete considers the bond characteristics, and the model is a bilinear model. The transverse reinforcements confine the compressed concrete in the core region and inhibit the buckling of the longitudinal reinforcing bars.

This study adopted the model proposed by Mander et al. (1988) for normal strength concrete of below 30 MPa and adopted the model proposed by Sun and Sakino (2000) for high strength concrete of above 40 MPa. An analytical model was proposed for confined intermediate strength concrete from 30 MPa to 40 MPa. The model incorporates all relevant parameters of confinement with a smooth transition from 30 MPa to 40 MPa (Kim et al. 2008, 2010, 2012b). The stress-strain relationship for confined concrete is given by

$$(3) \quad \frac{f'_{cc}}{f'_{co}} = \frac{(f'_{co} - 30)}{10} sk_{Sun\&Sakino} + \frac{(40 - f'_{co})}{10} sk_{Mander} \quad \text{for } 30 \text{ MPa} < f'_{co} \leq 40 \text{ MPa}$$

$$(4) \quad \frac{\epsilon_{cc}}{\epsilon_{co}} = \frac{(f'_{co} - 30)}{10} nk_{Sun\&Sakino} + \frac{(40 - f'_{co})}{10} nk_{Mander} \quad \text{for } 30 \text{ MPa} < f'_{co} \leq 40 \text{ MPa}$$

where f'_{cc} = confined concrete compressive strength; f'_{co} = unconfined concrete compressive strength; sk = confining parameter of strength; ϵ_{cc} = peak strain of confined concrete; ϵ_{co} = peak strain of unconfined concrete; nk = confining parameter of strain.

The models consider the yield strength, the distribution type, and the amount of longitudinal and transverse reinforcing bars to compute the effective lateral confining stress and the ultimate compressive strength and strain of the confined concrete (Kim et

al. 2008, 2010, 2012b). This is similar to the formula suggested by Mander et al. (1988) for the triaxial stress condition, but the reduced confinement effectiveness coefficient corresponding to the ratio of the inside-to-outside diameters of the bridge column cross-section is applied.

Figures 10 and 11 show the finite element discretization and the boundary conditions for hollow cast-in-situ concrete and precast concrete bridge columns specimens, respectively.

The 8-node isoparametric elements were used and in the cross-section where the load is applied, a total of two 8-node elastic elements were used to prevent local concrete failure. The 6-node interface elements between the footing and column were applied to model the effects of localized discontinuous deformation. Accordingly, with the stiffness changing rapidly in the column and footing, local discontinuous deformation occurs that is part of the anchorage slip, shear slip at the joint plane, and penetration at the joint plane.

The joints between the precast segments were also modeled using modified six-node joint elements. In the joint model, the inelastic behavior of the joint elements is governed by normal and tangential stiffness coefficients. In the simulation, the modified joint elements representing these segmental joints had also cracked and opened. Experimental evidence indicates that the failure of this material can be described by a Coulomb type relationship. The angle of internal friction and cohesion are respectively 45° and 5.88 MPa.

Figures 10(a) and 11(a) also show a method for transforming a hollow cross-section into rectangular strips when using plane stress elements. For rectangular cross-sections, equivalent strips are calculated. After the internal forces are calculated, the

equilibrium is checked.

In this transformation of a hollow cross-section to a rectangular cross-section, a cross-section with minimum error was selected through iterative calculations concerning the moment of inertia for the cross-section and area of concrete and reinforcements, to ensure that the behavior was similar to the actual behavior of bridge columns with hollow cross-sections (Kim et al. 2018).

For the physical properties of reinforcements and concrete, the same values as those used in the experiment were applied, as shown in Table 1.

4.2 Comparison with experimental results

The lateral load-displacement responses for column specimens are shown in Figs. 12 and 13. The analytical results show reasonable correspondence with the experimental results; comparative data is summarized in Table 2. In predicting the results for the specimens, the mean ratio of experimental to analytical maximum strength was 0.96, with a Coefficient of Variation (COV) of 3%. Also, the mean ratio of experimental to analytical ductility capacity was 0.91, with a COV of 6%.

The predicted ultimate strength was slightly larger than the actual strength of the hollow bridge columns with triangular confining reinforcement. Also, the predicted displacement ductility was slightly overestimated compared to the actual column displacement ductility.

The experimental hysteretic curves also shown in Figs. 12-13 exhibit asymmetry. It was found that the main reasons were slip between base plate and column foundation, initial axial load eccentricity. However, the analytical hysteretic curves exhibit symmetry.

Figure 14 compares the strain at each Gaussian integration point in the lower part of the column at failure, obtained from a nonlinear finite element analysis of the specimens. In Figure 14, the horizontal axis represents the outside and inside diameter of each specimen while the vertical axis represents the strain in the lower part of the column at each Gaussian integration point. The neutral axis locations predicted by the analytical results are also shown. As shown in Figure 14, the neutral axes of the hollow circular column specimens with proposed reinforcement details (CT-80 and CNT-80) are located towards the centroid of the section. Also, the neutral axis of the hollow circular column specimen with conventional reinforcement details (CC-80) is located towards the centroid of the section. However, the neutral axes of the hollow rectangular column specimens (RC-80, RT-80, and RT-120) were located in the wall at failure.

5. Assessment of seismic performance

An analytical evaluation was developed to assess the damage states and performance levels of solid reinforced concrete bridge columns (Kim et al. 2007). Explicit descriptions of the different performance levels are defined to employ specific engineering criteria (ATC 1996; FEMA 1997). This can be accomplished through engineering limit states that can be expressed by limiting the values of quantities such as damage indices (see Table 3). These damage indices were derived from a parametric study using finite element analysis (Kim et al. 2007). The state of damage in structures is often quantified by damage indices that are usually scaled to be zero in

the case of an undamaged structure, and unity in the case of collapse.

Table 4 provides an example of such descriptions that might be associated with the three performance levels. For the “fully operational” performance level, the column is designed to remain almost undamaged, and repair is not required. For the “delayed operational” performance level, the column is expected to sustain some damage that impairs its full use and that might require repair. Finally, for the “stability” performance level, the column can be expected to resist severe damage requiring partial or complete replacement of the column (Kim et al. 2007, 2018).

The proposed assessment procedure predicts the damage state and performance level for hollow cast-in-situ concrete and precast concrete bridge column specimens as shown in Fig. 15, and describes the damage close to that observed in the test, as shown in Table 5. As shown in Fig. 15, vertical gray lines indicate drift ratios corresponding to three performance levels: fully operational, delayed operational and stability.

It can be also seen from Fig. 15 that the T specimen series provided the expected performance prior to the C specimen series. As a result, the proposed triangular reinforcement details were determined prior to the conventional reinforcement details in terms of required structural performance.

Table 5 also shows the evolution of the damage index and include the physical damage occurring during the test. The used damage index shows a reasonable gradual progression of damage throughout the load history. In general, a good agreement was found between these values and those obtained from the experimental results of the hollow cast-in-situ concrete and precast concrete bridge columns.

The sequence of damage was similar for all hollow cast-in-situ concrete and precast concrete bridge columns. Concrete cracking, longitudinal reinforcement yielding,

initial spalling of the concrete cover, complete spalling of the concrete cover, longitudinal reinforcement buckling, and longitudinal reinforcement fracture were observed in sequence.

It is expected that, by using the proposed assessment procedure, the seismic performance of hollow cast-in-situ concrete and precast concrete bridge columns with triangular confining reinforcement can be predicted accurately, enabling more rational and reliable design of hollow bridge columns.

6. Conclusions

This paper presents a new design concept of hollow cast-in-situ concrete and precast concrete bridge columns with triangular confining reinforcement. An experimental and analytical study was conducted to investigate the structural performance of hollow bridge column specimens. From the results of the studies, the following conclusions were reached.

- An experimental and analytical study was conducted to quantify performance measures and examine one aspect of detailing for a set of developed triangular confining reinforcement. It was concluded that the design concepts and construction methods are promising solutions to the application of hollow cast-in-situ concrete and precast concrete bridge columns with triangular reinforcement details.
- The triangular reinforcement details for material quantity reduction might be an

excellent alternative to conventional reinforcement details for easier, more reliable, and more rapid construction. In-depth discussion revealed that the pre-fabricated triangular confinement modules for precast concrete bridge columns would offer many structural and constructional advantages, such as better concrete confinement, seismic performance, increased moment capacity with outer longitudinal reinforcement, reduced construction time, stability of steel cage modules, minimized tolerance, reduced steel congestion, and material efficiency.

- All six analyses predicted the experimental failure loads fairly well. The mean ratio of experimental to analytical maximum strength was 0.96, with a Coefficient of Variation (COV) of 3%. Also, the mean ratio of experimental to analytical ductility capacity was 0.91, with a COV of 6%.
- The proposed assessment procedure should be carried out on hollow cast-in-situ concrete and precast concrete bridge columns with triangular confining reinforcement to evaluate the seismic performance level. Such an analysis for the study of the seismic response of hollow bridge columns would lead to realistic and safe design.
- More efforts should be directed to include certain procedures in the current design codes to direct the engineers toward an acceptable method for evaluating the structural performance in hollow bridge columns. Future work by the authors will include a hollow bridge columns with triangular confining reinforcement under higher axial loads.

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Fig. 3. Hollow precast concrete bridge column specimens (Unit: mm) (a) RC-80, (b) RT-80, and (c) RT-120.

Fig. 4. Loading setup for column specimens.

Fig. 5. Instrumentation of the test specimen (Unit: mm) (a) hollow cast-in-situ column, and (b) hollow precast column.

Fig. 6. Lateral load-drift relationship for cast-in-situ column specimens (a) CC-80, (b) CT-80, and (c) CNT-80.

Fig. 7. Lateral load-drift relationship for precast column specimens (a) RC-80, (b) RT-80, and (c) RT-120.

Fig. 8. Hysteretic energy dissipation (a) cast-in-situ column, and (b) precast column.

Fig. 9. Lateral load-strain curves of transverse reinforcement for cast-in-situ column specimens (IT1 or IT2) (a) CC-80, (b) CT-80, and (c) CNT-80.

Fig. 10. Finite element model for cast-in-situ column specimens (a) transformation of a hollow circular column to an idealized equivalent rectangular column, and (b) finite element mesh for analysis.

Fig. 11. Finite element model for precast column specimens (a) transformation of a hollow rectangular column to an idealized equivalent rectangular column, and (b) finite element mesh for analysis..

Fig. 12. Comparison of results from the experimental results (cast-in-situ column specimens) (a) CC-80, (b) CT-80, and (c) CNT-80.

Fig. 13. Comparison of results from the experimental results (precast column specimens) (a) RC-80, (b) RT-80, and (c) RT-120.

Fig. 14. Strain at each Gaussian integration point from analytical results.

Fig. 15. Assessment of performance level for specimens (a) cast-in-situ column, and (b) precast column..

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Table 1. Properties of cast-in-situ and precast column specimens.

Specimen	Cylinder concrete strength (MPa)	Longitudinal reinforcement (D19)		Transverse reinforcement (D13)			Cross-tie (D13)		Axial force
		f_{yl} (MPa)	ρ_l (%)	f_{yh} (MPa)	Space (mm)	Ratio (Compared to AASHTO)	f_{yh} (MPa)	Space (mm)	
CC-80	28.1				Outer @80, Inner @80	Outer 0.0047 (49%), Inner 0.0047 (49%)		18 @80	
CT-80	24.3	408.3	1.5	405.7	Outer @80, Inner @80	Outer 0.0047 (49%), Inner 0.0047 (49%)	405.7	12 @80	0.1
CNT-80	27.4				Outer @80, Inner @400	Outer 0.0047 (49%), Inner 0.0009 (10%)		12 @80	
RC-80			1.53		Outer @80, Inner @80	Outer 0.0083 (52%), Inner 0.0083 (52%)		12 @80	
RT-80	47.0	408.3		405.7	Outer @80, Inner @400	Outer 0.0100 (63%), Inner 0.0020 (13%)	405.7	8 @80	0.07
RT-120			1.38		Outer @120, Inner @360	Outer 0.0067 (42%), Inner 0.0022 (14%)		8 @120	

<Note> CNT-80, RT-80, RT-120: Minimum inner lateral reinforcement was used.

Table 2. Experiment and analysis results for cast-in-situ and precast column specimens.

Specimen	Experiment		Analysis		Ratio of experimental and analytical results	
	V_{max} (kN)	μ_{Δ}	V_{max} (kN)	μ_{Δ}	V_{max}	μ_{Δ}
CC-80	774.3	4.9	791.0	5.6	0.98	0.88
CT-80	762.4	5.5	787.7	5.9	0.97	0.93
CNT-80	776.6	5.1	785.3	5.6	0.99	0.91
RC-80	726.7	5.4	787.3	6.6	0.92	0.82
RT-80	699.4	5.8	754.3	6.1	0.93	0.95
RT-120	697.3	6.6	738.4	6.7	0.94	0.99
Mean					0.96	0.91
Coefficient of Variation (COV)					0.03	0.06

Table 3. Failure criterion and damage index (Kim et al. 2007).

Material	Type of failure	Failure criterion (ϵ_{cu} or ϵ_{tu})	Damage index ($DI_{compressive}$ or $DI_{tensile}$)
Concrete	Compressive and shear	$0.004 + \frac{1.4\rho_s f_{yh} \epsilon_{sm}}{f'_{cc}}$	$1 - ftg_c \left(\frac{2\epsilon_{cu} - \epsilon_{cs}}{2\epsilon_{cu}} \right)^2$
Steel	Tensile	0.10	$1.20 \left(\frac{\epsilon_{ts}}{2ftg_r \epsilon_{tu}} \right)^{0.67}$

<Note> $ftg_c = 1 - 0.3AD_c$, $ftg_r = 1 - 0.3AD_r$

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Table 4. Description of performance levels (Kim et al. 2007).

Performance level	Service	Repair	Damage	
			State	Index
Fully operational	Fully service	Limited epoxy injection	Hairline cracks	≤ 0.1
Delayed operational	Limited service	Epoxy injection Concrete patching	Open cracks Concrete spalling	≤ 0.4
Stability	Not useable	Replacement of damaged section	Bar buckling/Fracture Core crushing	≤ 0.75

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Table 5. Comparative evaluation of progressive damage for column specimens.

Drift (%)	CC-80		CT-80		CNT-80		RC-80		RT-80		RT-120	
	Exp.	Ana.	Exp.	Ana.	Exp.	Ana.	Exp.	Ana.	Exp.	Ana.	Exp.	Ana.
0.25		0.00		0.00		0.00		0.00		0.00		0.00
0.50	First cracking	0.04	First cracking	0.04	First cracking	0.04	First cracking	0.04	First cracking	0.04	First cracking	0.04
1.00		0.07		0.07		0.07		0.08		0.08		0.08
1.50	Open cracks	0.24	Open cracks	0.23	Open cracks	0.19	Open cracks	0.18	Open cracks	0.21	Open cracks	0.21
2.00		0.33		0.32		0.29		0.25		0.27		0.28
2.50		0.36		0.36		0.35		0.30		0.32		0.33
3.00	Spalling	0.43	Spalling	0.45	Spalling	0.43	Spalling	0.40		0.37	Spalling	0.38
3.50		0.53		0.54		0.53		0.41	Spalling	0.39		0.45
4.00	Buckling	0.68	Buckling	0.69	Buckling	0.66		0.48		0.49		0.51
4.50		1.00		1.00		1.00		0.54		0.50		0.58
5.00	Fracture	1.00		1.00		1.00	Buckling	0.72	Buckling	0.63	Buckling	0.75
5.50	-	-	Fracture	1.00	Fracture	1.00		1.00		1.00		1.00
6.00	-	-	-	-	-	-	Fracture	1.00	Fracture	1.00	Fracture	1.00

Fig. 1. Hollow bridge columns with triangular confining reinforcement (a) conventional reinforcement details, (b) proposed reinforcement details, (c) construction method, and (d) precast segmental columns.

Fig. 2. Hollow cast-in-situ concrete bridge column specimens (Unit: mm) (a) CC-80, (b) CT-80, and (c) CNT-80.

Fig. 3. Hollow precast concrete bridge column specimens (Unit: mm) (a) RC-80, (b) RT-80, and (c) RT-120.

Fig. 4. Loading setup for column specimens.

Fig. 5. Instrumentation of the test specimen (Unit: mm) (a) hollow cast-in-situ column, and (b) hollow precast column.

CL : triangular confining reinforcement (inclined line);
OT : outer transverse reinforcement; OL : outer longitudinal reinforcement; IL : inner longitudinal reinforcement; CT : triangular confining reinforcement (base line); IT : inner transverse reinforcement

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(a)

(b)

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