Canadian Journal of Civil Engineering

Seismic performance assessment of RC columns with interlocking hoops

Journal:	<i>Canadian Journal of Civil Engineering</i>
Manuscript ID	cjce-2020-0345.R2
Manuscript Type:	Article
Date Submitted by the Author:	05-Feb-2021
Complete List of Authors:	Kim, Tae-Hoon; Korea Railroad Research Institute, Advanced Railroad Civil Engineering Division
Keyword:	seismic performance, columns, interlocking hoops, damage indices
Is the invited manuscript for consideration in a Special Issue? :	Not applicable (regular submission)

SCHOLARONE™
Manuscripts

Seismic performance assessment of RC columns with interlocking hoops

Tae-Hoon Kim ^{a,*}

^a Senior Researcher, Advanced Railroad Civil Engineering Division, Korea Railroad Research Institute, 176, Cheoldobangmulgwan-ro, Uiwang-si, Gyeonggi-do, 16105, Korea

* Corresponding author: Tae-Hoon Kim (e-mail: thkim@krrri.re.kr)

Abstract

The aim of this study is to analytically assess the seismic performance of reinforced concrete (RC) columns with interlocking hoops using a novel damage index, and to provide data for developing next generation seismic design criteria. Interlocking hoops are used in rectangular or non-circular columns, the splices shall be located in the column interior. Seismic performance of RC columns is controlled by the level of confinement provided by transverse steel. Interlocking hoops are commonly used in RC columns because they can provide more effective confinement than rectangular hoops. Three RC interlocking columns were tested under a constant axial load and a cyclically reversed horizontal load. A computer program, RCAHEST (Reinforced Concrete Analysis in Higher Evaluation System Technology), is used to analyze RC structures. Novel damage indices aim to provide a means of quantifying numerically the performance level in RC columns with interlocking hoops sustained under earthquake loading. The proposed numerical method for the seismic performance

assessment of interlocking columns is verified by comparison with the experimental results.

Key words: seismic performance, columns, interlocking hoops, damage indices

Notation

A_g	gross sectional area
$DI_{compressive}$	compressive damage index
$DI_{tensile}$	tensile damage index
E_0	initial stiffness of concrete
E_s	modulus of elasticity of the bar
E_{sh}	strain hardening rates of the bar embedded in concrete
f_{ck}	compressive strength of concrete
f_{yh}	yield stress of the confining steel
f_{yl}	yield strength of longitudinal reinforcement
f_{yt}	yield strength of transverse reinforcement
f'_{cc}	confined concrete compressive strength
K_{cr}	fracture parameter for uncracked concrete
P	axial force
S	equivalent stress
V_{max}	maximum shear force

ε_{cr}^p	plastic strain for cracked concrete
ε_{cs}	compressive strain in analysis step
ε_{cu}	ultimate strain of concrete
ε_s^{av}	average steel strain
ε_{sm}	steel strain at maximum tensile stress
ε_t^{eq}	equivalent total strain
ε_{ts}	tensile strain in analysis step
ε_{tu}	ultimate strain of reinforcing bars
μ_{Δ}	ductility ratio
ρ_l	longitudinal reinforcement ratio
ρ_s	transverse confining steel ratio
$\rho_{s,req}$	required transverse confining steel ratio
σ_s^{av}	average steel stress
σ_{sh}	stress point for initiation of strain hardening of steel
σ_y	yield stress of steel
Φ_c	fatigue parameter for concrete
Φ_r	fatigue parameter for reinforcing bars

Introduction

Reinforced concrete (RC) columns with interlocking hoops have more effective confinement than rectangular hoops. The confinement provided by the transverse reinforcement is an essential factor in improving the seismic performance of RC columns in terms of strength, ductility and energy dissipation capacity. In noncircular column such as rectangular and oval column, interlocking hoops are frequently adapted as transverse reinforcement because of both better transverse confinement and easier fabrication at construction site. Interlocking hoops are also a continuous transverse reinforcement and can be fabricated automatically in a factory. This system allows for quick erection and increases the likelihood of proper concrete consolidation (Li and Belarbi 2011; Shih et al. 2013; Han et al. 2014; Yang et al. 2015; Jing et al. 2016).

The use of interlocking hoops in RC columns with rectangular or oval cross sections has several advantages. Among the many benefits of using interlocking hoops, one important advantage of the cross-section is the more effective confinement received by the two parts of concrete surrounded by the double circular hoops, which consequently leads to the enhanced ductility and energy dissipation capacity of the RC columns. Interlocking hoops confine the concrete more efficiently than rectangular hoops with cross ties, which can reduce the amount of transverse steel required for effective confinement of core concrete.

The longitudinal bar size in the interlocking portion of a seismic critical members shall be chosen to correspond to the longitudinal bar size outside the interlocking portion (Caltrans 2019). Previous studies have been conducted on the effect of several design parameters, including a comparison between interlocking hoops and ties,

horizontal spacing of interlocking hoops, quantity of transverse reinforcement, axial load ratios, longitudinal bars in the interlocking region, and cross section shape (Tanaka and Park 1993; Tsitotas and Tegos 1996; Benzoni et al. 2000; Correal et al. 2004; Lignola et al. 2011).

The main goal of this study is to provide knowledge on the seismic performance assessment of RC columns with interlocking hoops using a novel damage index. To experimentally assess the seismic performance of such complex structures is tedious, time-consuming and expensive. In this study, an analytical evaluation method for the seismic performance of interlocking columns is developed. For this purpose, three RC columns with interlocking hoops are tested under a constant axial load and a quasi-static, cyclically reversed horizontal load.

A nonlinear finite element analysis program (RCAHEST, Reinforced Concrete Analysis in Higher Evaluation System Technology), developed by the authors (Kim et al. 2003, 2005, 2009, 2014, 2017, 2019a, 2019b), was modified to develop an analytical evaluation method for the seismic performance of solid RC columns using damage index (Kim et al. 2007).

Novel damage indices aim to provide a means of quantifying numerically the performance level in RC columns with interlocking hoops sustained under earthquake loading. To assess the ability of the RCAHEST program to predict the seismic performance of RC columns, computed results using the program were compared with the test results.

Nonlinear finite element analysis program

For an accurate assessment of the inelastic behavior characteristic of RC columns with interlocking hoops, three-dimensional finite element analysis and reliable constitutive modeling are required. However, difficulties in developing a reliable three-dimensional material model and the extensive number of calculations required pose several problems in the actual problem application. The three-dimensional constitutive relationships of concrete would need to be known, and at present they are not well-defined. The main problem in using stiffness methods are the vast amounts of computer storage and time needed for a solution (Kim et al. 2014, 2017, 2019a).

Therefore, a two-dimensional finite element model of RC columns for interlocking hoops with confinement reinforcement is developed in this study. The model was created and analyzed using general-purpose finite element software, RCAHEST (Kim et al. 2003, 2005, 2007, 2009, 2014, 2017, 2019a, 2019b). RCAHEST is a nonlinear finite element analysis program used for analyzing reinforced concrete structures. The proposed structural element library RCAHEST is built around the finite element analysis program shell named FEAP, developed by Taylor (2000). The program is distributed as open source and is very useful for research, element, and architecture development.

Nonlinear material model for RC columns

The elements developed for the inelastic finite element analyses of RC columns under earthquake are a reinforced concrete plane stress element and an interface element. The nonlinear material model for the reinforced concrete is composed of models for

characterizing the behavior of the concrete, in addition to a model for characterizing 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 (see Fig. 1). A modified elasto-plastic fracture model is used to describe the compressive behavior of the concrete struts in between cracks in the direction of the crack plane (see Fig. 2). 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 as shown in Fig. 3. To account for buckling of reinforcing bars, the average stress-strain behavior after concrete crushing is assumed to be linearly descending until the 20% of the average steel stress. This relation was derived from a parametric study using finite element analysis (Kim et al. 2003). The transverse reinforcements confine the compressed concrete in the core region and inhibit the buckling of the longitudinal reinforcing bars. In this study, a lateral confining effect model was adopted and incorporated into the structural element library for RCAHEST, so that it can be used to assess the seismic performance assessment of RC columns with interlocking hoops. 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. This is similar to the formula suggested by Mander et al. (1988) for the triaxial stress condition, but the increased confinement

effectiveness coefficient corresponding to the area ratio of the interlocking hoops of the column section is applied.

Fatigue damage of RC columns subjected to seismic load seems inevitable and the fatigue damage influencing the inelastic behavior of columns may be characterized as concrete strength deterioration and low cycle fatigue of reinforcing bars (Kim et al. 2005).

A full description of the nonlinear material model for RC is given by Kim et al. (2003, 2005, 2007, 2009, 2014, 2017, 2019a, 2019b).

Analytical seismic performance assessment using a novel damage index

An analytical evaluation was developed to assess damage states and performance levels of solid RC columns (Kim et al. 2005, 2007). The state of damage in structure 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. Explicit descriptions of the different performance levels are defined to employ specific engineering criteria. This can be accomplished through engineering limit states that may be expressed by limiting values of quantities such as damage indices, as illustrated in Fig. 4.

These damage indices were derived from a parametric study of RC columns with interlocking hoops using finite element analysis. A parametric study was carried out to investigate the effect of concrete compressive strength, longitudinal bar size and spacing, tie spacing, and column cross-sectional on the buckling behavior of reinforcing bars. Each damage state may be associated with one or more engineering limit states, each of which must be evaluated to assess the performance level.

The proposed novel damage index at the element level is calculated directly from the

strain at a Gauss integral calculus point calculated for each element by nonlinear finite element analysis, this can reduce the inconvenience.

Figure 4 also provides an example of such descriptions that might be associated with the three performance levels. For the ‘fully operational’ performance level, the interlocking column is designed to remain almost undamaged, and repair is not required. For the ‘delayed operational’ performance level, the interlocking column is expected to sustain some damage that impairs its full use and that might require repair. Finally, for the ‘stability’ performance level, the interlocking column may be expected to sustain severe damage requiring partial or complete replacement of the column. This framework has been formulated in various documents on performance-based design of bridge and building structures (ATC 1996; FEMA 1997).

Numerical examples

Three RC columns with interlocking hoops were tested under cyclic lateral loads while being simultaneously subjected to constant axial loads. It is considered appropriate to use current code provisions (CEN 2004; AASHTO 2012; MCT 2015) on the concrete confinement for the potential plastic hinge regions in the design of RC columns with interlocking hoops for use in moderate seismic regions.

Description of test specimens

An experimental program was designed to obtain seismic performance data of RC columns with interlocking hoops having details typical of those currently in use in

regions of moderate seismicity in the Korea. The transverse reinforcement of the specimens was designed considering current recommendations and requirements for shear and confinement (CEN 2004; AASHTO 2012; MCT 2015).

Three interlocking column specimens were designed to represent typical existing columns as shown in Fig. 5. The columns had an oval-shaped cross section of 450 mm $\times$ 650 mm, and the clear concrete cover to the interlocking hoop reinforcement was 25 mm. The total height of the specimen was 4.0 m with an effective height of 2.4 m measured from the top of footing to the centerline of applied load, with a resulting aspect ratio of 5.3 and 3.7, respectively.

Table 1 summarizes the material properties of the test specimens. The character IC in the specimen designation stands for interlocking column. Lateral confinements were provided by interlocking hoops; and were also spaced at two different distances of 70 and 180 mm.

An axial load equivalent to 10% of the axial capacity of interlocking columns was applied during testing to simulate the superstructure dead load on the column in a bridge typically which varied between 5 and 10% of the capacity of the columns.

A schematic representation of the test set-up for specimens is shown in Fig. 6. For each test, the interlocking column footing was connected to the laboratory strong floor by high strength post-tensioning bars. The 2000 kN MTS hydraulic actuator attached to the top of the interlocking column applied the lateral displacement history. The specimens were extensively instrumented to monitor global and local response quantities.

Similar procedures were used for each test. Axial load was applied at the beginning of a test and was maintained constant during the test. The displacement history was

based on nominal drift ratio. The nominal drift ratio is defined as the ratio of maximum lateral drift to effective height of the specimen. Specimens were subjected to two cycles each at lateral displacement amplitudes of 0.25%, 0.50%, 1.00%, 1.50%, 2.00%, 2.50%, 3.00%, 4.00%, 5.00%, 6.00%, 7.00% and 8.00% until failure. The displacement cycles were repeated to measure the strength degradation. Measurements were then manually triggered based on the lateral actuator running in displacement control.

After the original tests, the damage to the RC columns with interlocking hoops was determined by visual inspection and analysis of measured data. In general, experimental results have demonstrated the advantages in strength and ductility improvement as well as economic benefit increment in applying the two interlocking hoops to columns.

Description of analytical model

Figure 7 shows the finite element discretization and the boundary conditions for 2-dimensional plane stress nonlinear analyses of the RC columns with interlocking hoops. Three-point Gaussian integrated 8-node isoparametric elements were used and in the 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 for the modeling of the effects of localized discontinuous deformation. The interface element between the footing and the column enhances the effects of the bond-slip of steel bars and the local compression. Accordingly with stiffness changing rapidly in the column and footing, local discontinuous deformation that is part of the anchorage slip, shear slip at the joint plane, and penetration at the joint

plane happens.

In particular, in the plastic hinge zone of the body of the interlocking columns, the dangerous section, was divided into elements of a smaller size for a clearer depiction of plastic behavioral characteristics after reinforcement failure. The refinement of the mesh is regarded as sufficient because the mesh sensitivity analysis has been verified in this study. Geometric nonlinearity was also included in the analysis. Geometric nonlinearity was to take into account the P-delta effect from the axial force.

Comparison with experimental results

The lateral load-drift responses for specimens are shown in Fig. 8. The analytical results show reasonable correspondence with the experimental results. There is quite different specimen (IC-1) as hysteresis curve and dissipation energy. The disparity in the data is caused by experimental error in the laboratory and simplifier assumption in numerical analysis. It was found that the main reasons were slip between base plate and column foundation, initial axial load eccentricity.

The analysis was conducted in multiple steps to simulate the actual behavior of the interlocking column specimens. Loading cycles with displacement control are applied as this allows the analysis beyond the ultimate load where the load at the maximum strain is recognized from the load displacement curve. The axial load was applied to the top of the interlocking column and remained vertical throughout the simulation and then lateral displacement was applied at the loading point.

The value given by all specimens was similar to the analytical results; comparative data is summarized in Table 2. In predicting the results of the specimens, the mean ratios of experimental-to-analytical maximum strength were 1.05 at a COV of 10%.

Also, the mean ratios of experimental-to-analytical ductility capacities were 0.95 at a COV of 4%.

As shown in Fig. 8, the analysis corresponds fairly well to the test results, including the predicted failure region. The ultimate displacement of the test results is somewhat lower, and the initial stiffness is somewhat lower, but this may be because shear was not accounted for in the flexural analysis. The predicted average ultimate strength was slightly smaller than the actual strength of the interlocking columns, however, in general, the analytical model presented herein correlated reasonably well with the experimentally observed behavior of the columns for each test. All the results support that the failure mode and ductility level of interlocking columns after yielding of longitudinal reinforcement can be estimated by the finite element analysis proposed in this paper.

The physical phenomena which occurred during the test, namely: cracking, yielding, spalling of cover concrete and buckling of rebars, are indicated. Plastic hinges were fully formed at the bottom end of the columns, which contributed to the development of ductility. From the diagrams a good seismic performance of the RC columns with interlocking hoops in terms of ductility and energy dissipation is expected.

According to the tests results, flexural and shear cracks appeared on either side of the load points with typical shear cracks at a 45° degree inclination toward the support points around the element axis. In the case of the interlocking hoops uniform cracking was observed without any signs of separation of the interlocking hoops at any point in the span length under the ultimate load.

During the negative cycles of loading, the two interlocking hoops were locked with each other increasing confinement of interlocking hoops to the core concrete which

contribute to the seismic behavior of RC columns. Figure 8 shows the load resistance on the negative cycles was higher than the positive cycles of loading at higher ductility due to the extra confinement effect caused by the locking actions of the interlocking hoops. These behaviors were also included in the nonlinear analysis.

All three RC columns with interlocking hoops exhibited ductile behavior under cyclic loading. The ductility factors ranged from 9.5 to 4.0 (see Table 2). The displacement ductility is defined as the ultimate displacement divided by the yield displacement. Decreasing the interlocking hoops spacing resulted in the increase of the concrete compressive strength in the confined concrete core, axial load carrying capacity, and ductility.

The proposed method predicts damage state and performance level for specimens as shown in Fig. 9, and describes the damage close to what was observed in the test, as shown in Table 3 and 4.

Specimen IC-1 showed better performance than IC-2 and, likewise, specimen IC-1 performed better than IC-3. The effect of interlocking hoops spacing and loading axis used in this study on the seismic performance of specimen is large.

Table 3 and 4 also shows the evolution of the damage index and includes 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 between these values and the ones obtained from the experimental results of the interlocking columns found (see Fig. 10).

The sequence of damage was similar for all RC columns with interlocking hoops. 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.

Figure 10 also presents the failure appearance of the specimens at the peak load. Horizontal minor cracks were first developed on the concrete, and, subsequently, these cracks were enlarged and resulted in crushing and spalling of the concrete cover. After the specimens reached their peak loads, the corner interlocking hoops fractured due to the lateral expansion of the concrete loaded in compression and the thrust by the buckled longitudinal bars. Consequently, the axial load-carrying capacity gradually decreased.

The onset of flexural cracking is the first visible damage indicator in the flexural damage progression. This occurs in interlocking columns when lateral load are applied to a structure. The occurrence of cracking is of some importance in assessing the stiffness changes in an interlocking column. The initiation of transverse cracking on the columns' flexural faces is the visual indicator for flexural damage state. The next visible damage indicator is shear cracking on the side faces of the column. Perhaps of more importance in the context of performance-based earthquake engineering is the identification of open residual cracks, as this may determine whether repair by epoxy injection is required (see Fig. 10 (a), (b)).

Concrete spalling on the flexural and side faces, or simply, spalling of the cover concrete is designated as the visual indicator for flexural damage state. As the demand continues to increase, the spalling will continue such that the longitudinal steel is exposed. Prior to spalling, the longitudinal reinforcement bars are surrounded by both concrete and transverse reinforcement. The occurrence and extent of spalling are important parameters for performance assessment. The onset of spalling signals a point at which more costly, time-consuming, and possibly disruptive repairs will likely

be required (see Fig. 10 (c)).

For the interlocking columns tested, loss of strength resulted from bar buckling, followed by interlocking hoops fracture, and longitudinal bar fracture. The longitudinal bars which have yielded in tension due to the flexural demand will buckle once the spalling of concrete has exposed enough longitudinal bar length to reach the critical buckling load. As a result of the buckling of longitudinal reinforcement, the transverse reinforcement often yields, eliminating the confinement of the core concrete and allowing crushing of core concrete to occur. In addition, lateral load carrying capacity is often significantly reduced at the onset of core crushing. Axial load carrying capacity is also lost when extensive bar buckling and crushing of the core concrete has occurred. The final visual damage indicator is defined as fracture of the longitudinal bars. The onset of this type of damage led rapidly to significant loss of lateral-load strength. These interlocking columns may sustain severe damage requiring partial or complete replacement (see Fig. 10 (d), (e)).

It is expected that, by using the proposed method, the seismic performance of RC columns with interlocking hoops can be predicted accurately, and this enables more rational and reliable design of columns.

Conclusions

This paper has attempted to establish a framework for assessment of the seismic performance of RC columns with interlocking hoops. An experimental and analytical study was conducted to quantify performance measures and examine one aspect of

detailing for interlocking columns. The computer program RCAHEST can be used for examining the seismic performance of existing structures. Based on the experimental and analytical studies performed in this research, the following observations and conclusions were made for columns reinforced with double interlocking hoops:

- Three RC columns with interlocking hoops were tested under a flexure dominant loading condition to investigate the applicability of transverse reinforcement requirements specified by current code. The amount of transverse reinforcement required for the confinement of the core concrete in the potential plastic hinge region of a column can be reduced considerably by using interlocking hoops. All columns failed due to flexural effects, achieving an ultimate ductility factor ranging from 9.5 to 4.0. The load resistance on the negative cycles was higher than the positive cycles of loading at higher ductility due to the extra confinement effect caused by the locking actions of the interlocking hoops.
- The results show good correlation between the experimental findings and numerical predictions, and demonstrate the reliability and robustness of the proposed analytical model. The material models used for modeling concrete and reinforcing bars in this study gave promising results for the seismic performance assessment of the interlocking columns.
- The proposed assessment procedure should be carried out on RC columns with interlocking hoops to evaluate the actual seismic performance level of the structures. It is expected that the seismic performance of interlocking columns can be predicted accurately, thereby enabling more rational and reliable design of bridge columns.
- 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 existing RC columns with interlocking hoops. Future research must be conducted to develop a more rational design model for such columns when more test data becomes available.

Acknowledgements

The research described herein was sponsored by a grant from R&D Program of the Korea Railroad Research Institute, Republic of Korea.

References

- AASHTO (American Association of State Highway and Transportation Officials). 2014. AASHTO LRFD Bridge Design Specifications, 7th Edition. AASHTO, Washington, DC, USA.
- ATC (Applied Technology Council) – 32. 1996. Improved seismic design criteria for California bridges: Provisional recommendations. Redwood City, California, USA.
- Benzoni, G., Priestley, M.J.N., and Seible, F. 2000. Seismic shear strength of columns with interlocking spiral reinforcement. 12th World Conference on Earthquake Engineering, CD.
- Caltrans. 2019. Caltrans Seismic Design Criteria. California Department of

Transportation, Sacramento, CA.

CEN (Comite Europeen de Normalisation). 2004. Eurocode 2: EN 1992-1: Design of Concrete Structures – Part 1: General Rules and Rules for Buildings. CEN, Brussels, Belgium.

Correal, J.F., Saiidi, M.S., Sanders, D., and El-Azazy, S. 2004. Seismic performance of bridge columns with double interlocking spirals. 13th World Conference on Earthquake Engineering, CD.

FEMA (Federal Emergency Management Agency). 1997. NEHRP guidelines of the seismic rehabilitation of buildings, FEMA 273, Washington, D.C., USA.

Han, Q., Zhou, Y.-L., Du, X., Huang, C., and Lee, G.C. 2014. Experimental and numerical studies on seismic performance of hollow RC bridge columns. *Earthquakes and Structures*, **7**(3): 251–269.

Jing, D.H, Yu, T., and Liu, X.D. 2016. New configuration of transverse reinforcement for improved seismic resistance of rectangular RC columns: Concept and axial compressive behavior. *Engineering Structures*, **111**: 383-393.

Kim, T.-H. 2017. Hollow precast segmental prestressed concrete bridge columns with a shear resistant connecting element. *Canadian Journal of Civil Engineering*, **44**(6): 472–484.

Kim, T.-H., Hong, H.-K., Chung, Y.-S., and Shin, H.M. 2009. Seismic performance assessment of reinforced concrete bridge piers with lap splices using shaking table tests. *Magazine of Concrete Research*, **61**(9): 705-719.

Kim, T.-H., Kim, I.-H., Lee, J.-H., and Shin, H.M. 2019a. Hollow bridge columns with triangular confining reinforcement. *Canadian Journal of Civil Engineering*, **46**(6): 467-480.

- Kim, T.-H., Kim, Y.-J., Kang, H.-T., and Shin, H.M. 2007. Performance assessment of reinforced concrete bridge columns using a damage index. *Canadian Journal of Civil Engineering*, **34**(7): 843-855.
- Kim, T.-H., Lee, K.-M., Chung, Y.-S., and Shin, H.M. 2005. Seismic damage assessment of reinforced concrete bridge columns. *Engineering Structures*, **27**(4): 576-592.
- Kim, T.-H., Lee, J.-H., and Shin, H.M. 2014. Performance assessment of hollow reinforced concrete bridge columns with triangular reinforcement details. *Magazine of Concrete Research*, **66**(16): 809-824.
- Kim, T.-H., Lee, J.-H., and Shin, H.M. 2019b. New arrangement of transverse reinforcement in rectangular solid columns. *ACI Structural Journal*, **116**(3): 207-218.
- Kim, T.-H., Lee, K.-M., Yoon, C.-Y., and Shin, H.M. 2003. Inelastic behavior and ductility capacity of reinforced concrete bridge piers under earthquake. I : theory and formulation. *Journal of Structural Engineering, ASCE*, **129**(9): 1199-1207.
- Li, Q., and Belarbi, A. 2011. Seismic behavior of RC columns with interlocking spirals under combined loadings including torsion. *The Twelfth East Asia-Pacific Conference on Structural Engineering and Construction*, **14**: 1281-1291.
- Lignola, G.P., Nardone, F., Prota, A., De Luca, A., and Nanni, A. 2011. Analysis of RC hollow columns strengthened with GFRP. *Journal of Composites for Construction, ASCE*, **15**(4): 545–556.
- Mander, J.B., Priestley, M.J.N., and Park, R. 1988. Theoretical stress-strain model for confined concrete. *Journal of Structural Engineering, ASCE*, **114**(8): 1804-1826.
- MCT (Ministry of Construction and Transportation). 2015. Korean Highway Bridge Design Code(Limit State Design), MCT, Seoul, Korea.

- Shih, T.-H., Chen, C.-C., Weng, C.-C., Yin, S.Y.-L., and Wang, J.-C. 2013. Axial strength and ductility of square composite columns with two interlocking spirals. *Journal of Constructional Steel Research*, **90**: 184-192.
- Tanaka, H., and Park, R. 1993. Seismic design and behavior of reinforced concrete columns with interlocking spirals. *ACI Structural Journal*, **90**(2): 192-203.
- Taylor, R.L. 2000. FEAP – A Finite Element Analysis Program, Version 7.2 Users Manual, Volume 1 and Volume 2. University of California at Berkeley, CA, USA.
- Tsitotas, M.A., and Tegos, I.A. 1996. Seismic behaviour of R/C columns and beams with interlocking spirals. *Advance in Earthquake Engineering*, **2**: 449-461.
- Yang, Y., Sneed, L.H., Morgan, A., Saiidi, M.S., and Belarbi, A. 2015. Repair of RC bridge columns with interlocking spirals and fractured longitudinal bars – An experimental study. *Construction and Building Materials*, **78**: 405-420.

List of Tables

Table 1. Specimen properties.

Table 2. Experiment and analysis results.

Table 3. Comparative evaluation of progressive damage for interlocking columns IC-1 and IC-2.

Table 4. Comparative evaluation of progressive damage for interlocking columns IC-1 and IC-3.

Draft

List of Figures

Fig. 1. Construction of cracked concrete model.

Fig. 2. Equivalent stress-equivalent strain relationship for concrete.

Fig. 3. Model for reinforcing bar in concrete.

Fig. 4. Analytical seismic performance assessment using a novel damage index.

Fig. 5. Interlocking column specimens (Unit: mm): (a) IC-1, (b) IC-2, and (c) IC-3.

Fig. 6. Details of load frame and test setup: (a) Schematic of test setup; (b) Photograph of test setup.

Fig. 7. Finite element model for interlocking column specimens: (a) Finite element mesh for specimen IC-1 and IC-2 and (b) Finite element mesh for specimen IC3.

Fig. 8. Comparison of results from the experimental results: (a) IC-1, (b) IC-2, and (c) IC-3.

Fig. 9. Assessment of performance level for specimens: (a) IC-1 and IC-2 and (b) IC-1 and IC-3.

Fig. 10. Development of damage during test for specimen IC-1: (a) First cracking (Drift 0.25%), (b) Open cracks (Drift 1.5%), (c) Spalling (Drift 4.0%), (d) Buckling (Drift 7.0%), and (e) Fracture (Drift 8.0%).

Table 1. Specimen properties.

Specimen		IC-1	IC-2	IC-3
Cross section (mm)		450 × 650	450 × 650	650 × 450
Cylinder concrete strength (MPa)			22.4	
Longitudinal reinforcement (D19)	f_{yl} (MPa)		351.4	
	ρ_l (%)		1.37	
	f_{yt} (MPa)		392.3	
Transverse reinforcement (D13)	Space (mm)	70	180	70
	$\frac{\rho_s}{\rho_{s,req}}$ (%)	100	40	100
Axial force	$\frac{P}{f_{ck}A_g}$		0.1	

Table 2. Experiment and analysis results.

Specimen	Experiment		Analysis		Ratio of experimental and analytical results	
	$V_{\max}$ (kN)	μ_{Δ}	$V_{\max}$ (kN)	μ_{Δ}	$V_{\max}$	μ_{Δ}
IC-1	163.6	8.5	146.6	8.6	1.12	0.99
IC-2	156.8	4.0	141.4	4.4	1.11	0.91
IC-3	206.7	9.5	222.4	9.9	0.93	0.96
		Mean			1.05	0.95
		COV			0.10	0.04

Table 3. Comparative evaluation of progressive damage for interlocking columns IC-1 and IC-2.

Drift (%)	IC-1			IC-2		
	Experiment	Analysis		Experiment	Analysis	
	Notes	Damage index	Performance level	Notes	Damage index	Performance level
0.25	First cracking	0.03	Fully operational	First cracking	0.07	Fully operational
0.5		0.06			0.11	
1.0		0.12		Open cracks	0.24	Delayed operational
1.5	Open cracks	0.19	Delayed operational		0.37	
2.0		0.24		Spalling	0.42	Stability
2.5		0.27			0.58	
3.0		0.29		Buckling	0.63	Stability
4.0	Spalling	0.33	Delayed operational	Fracture	1.00	-
5.0		0.37			1.00	-
6.0		0.44				
7.0	Buckling	0.52	Stability			
8.0	Fracture	0.79	-			

Table 4. Comparative evaluation of progressive damage for interlocking columns IC-1 and IC-3.

IC-1				IC-3		
Drift (%)	Experiment	Analysis		Experiment	Analysis	
	Notes	Damage index	Performance level	Notes	Damage index	Performance level
0.25	First cracking	0.03	Fully operational	First cracking	0.06	Fully operational
0.5		0.06			0.10	
1.0		0.12		Open cracks	0.23	Delayed operational
1.5	Open cracks	0.19	Delayed operational		0.28	
2.0		0.24			0.31	
2.5		0.27		Spalling	0.33	Delayed operational
3.0		0.29		Buckling	0.73	Stability
4.0	Spalling	0.33	Delayed operational		0.73	
5.0		0.37		Fracture	0.93	-
6.0		0.44			1.00	-
7.0	Buckling	0.52	Stability		1.00	-
8.0	Fracture	0.79	-			

Fig. 1. Construction of cracked concrete model.

Fig. 2. Equivalent stress-equivalent strain relationship for concrete.

Fig. 3. Model for reinforcing bar in concrete.

Fig. 4. Analytical seismic performance assessment using a novel damage index.

(a)

(c)

Fig. 6. Details of load frame and test setup: (a) Schematic of test setup; (b) Photograph of test setup.

Fig. 7. Finite element model for interlocking column specimens: (a) Finite element mesh for specimen IC-1 and IC-2 and (b) Finite element mesh for specimen IC-3.

(a)

(b)

Fig 8. Comparison of results from the experimental results: (a) IC-1, (b) IC-2, and (c) IC-3.

Fig. 9. Assessment of performance level for specimens: (a) IC-1 and IC-2 and (b) IC-1 and IC-3.

Fig. 10. Development of damage during test for specimen IC-1: (a) First cracking (Drift 0.25%), (b) Open cracks (Drift 1.5%), (c) Spalling (Drift 4.0%), (d) Buckling (Drift 7.0%), and (e) Fracture (Drift 8.0%).

(e)