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This study introduces developed post-tensioned (PT) hollow bridge columns with triangular confinement modules. The proposed triangular reinforcement details with post-tensioning ducts 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 (1/8 in.) required for segmental precast columns, which has been often troublesome for regular precast columns. The special-purpose design program of CalPM-SCH II for hollow bridge columns with triangular reinforcement details is developed with the embedded triangular modules, and verified using existing commercial programs for PT columns with which the triangular confinement modules are not easily modeled. Applicability and economic feasibility of the developed PT hollow bridge column are studied using existing design cases. During this process, productivity of the special-purpose design program has been improved for more accurate and quick design. One of the most important features of the developed system is that triangular confinement modules with PT ducts can be pre-manufactured prior to the actual final design of PT hollow columns and pre-installed with minimal tolerance in a precast formwork, followed by the installation of additional longitudinal reinforcing bars. Overall, such advantages enhance the constructability and efficiency even with better structural rationality.

INTRODUCTION

Current trends in bridge construction indicate the increasing use of long-span bridges. To improve economy and performance of long-span bridges, reduction of dead load and reduced possibility of column overturning are important. Therefore, the application of hollow section columns is increasing. Hollow section columns also provide the advantage of a reduction in excessive design seismic force generated by the increased self-weight of bridges and hydration heat. The use of hollow cross sections is preferable to maximize the structural efficiency of the strength/mass and stiffness/mass ratios and to reduce the mass contribution of the column to seismic response (Zahn et al. 1990; Yeh et al. 2002; Kim et al. 2012; Kim et al. 2013; Kim and Kang 2012).

Further, post-tensioning strands instead of longitudinal reinforcing bar are being applied to hollow section columns to reduce quantity of reinforcing bar with the same performance. The columns with post-tensioning strands are easy to apply using the precast method. Precast columns have the advantages of a shortened construction period, quality assurance, and minimization of environment risks (Billington et al. 2001; Chou and Chen 2006; Cheng 2008; Wang et al. 2008).

In the authors' previous studies, triangular reinforcing bar details formed as triangles by cross tie were developed to solve the difficulty of works and interference due to complicated arrangements of reinforcing bar (Kim et al. 2013, 2014a,b). The proposed triangular confinement modules showed ductile behavior and satisfactory hysteretic energy dissipation capacity. In advance, this study aims to expand the application of triangular confinement modules with post-tensioning duct and strands that would have the same or better performance instead of vertical main reinforcing bars.

The purpose of the development is to maximize constructability, structural integrity, and economic feasibility by extending triangular confinement modules with post-tensioning strands for proposed hollow cast-in-place concrete and precast concrete bridge columns and to develop a special-purpose design program related to it. The special-purpose design program improves produc-

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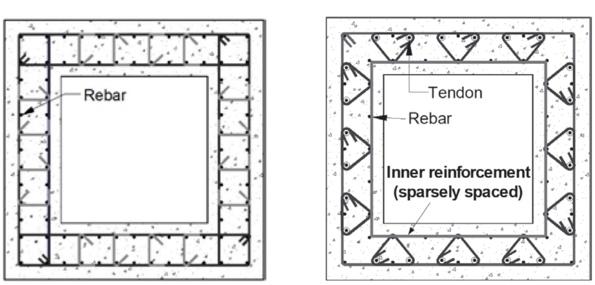
tivity by allowing quick and accurate review. Overall, this study attempts to discuss such advantages and assess the economic feasibility among key advantages.

RESEARCH SIGNIFICANCE

The current study presents a new concept of triangular confinement modules with post-tensioning ducts and strands that offer several advantages. Here, the post-tensioned hollow bridge columns with triangular confinement modules are developed, as well as the relevant special-purpose design program. The developed prefabricated triangular confinement modules have many structural and constructional advantages, such as superior concrete confinement, seismic performance, increased moment capacity with outer PT strands, reduced construction time, stability of steel cage modules; minimized tolerance (particularly for precast segmental columns), reduced steel congestion, and material efficiency. The authors found from the prior experimental studies of reinforced concrete columns that a series of triangular modules are exceptionally efficient even without inner transverse reinforcing bars, maximizing three-axis confinement effects and leading to acquire seismic ductility superior to that with conventional confinement reinforcement. Among the aforementioned advantages, efficient constructability is a key benefit. Each prefabricated triangular module can stand alone prior to fabricating a whole bridge column cage. The tolerance is less than 3 mm for precast segmental construction using prefabricated triangular modules, which is one of the most important aspects for very long bridge columns (for example, 100 m long columns in the valley of mountainous terrain).

POST-TENSIONED HOLLOW COLUMNS WITH TRIANGULAR CONFINEMENT MODULES

As shown in Fig. 1(a), in existing hollow sections for bridge columns, a number of layers of longitudinal and transverse reinforcing bars are placed near both the outside



(a) Existing details *(b) Proposed details*

Fig. 1—Existing and proposed details in hollow column section.

and inside faces and are tied through the wall thickness with cross-ties. The cross-ties must have a standard 135-degree hook at one end and a standard 90-degree hook at the other end. These hollow column sections have increased construction complexity and hence, increased labor costs.

To solve these problems of existing reinforcing bar details and to satisfy both structural efficiency and economic feasibility, as shown Fig. 1(b) and Fig. 2(a), triangular confinement modules were previously proposed by the authors (Kim et al. 2013, 2014a,b). Because the triangular modules can have a three-axis confinement effect on the concrete by a stable triangular structure, it is possible to resist the brittle fracture effectively and has the advantage of eliminating or reducing the inner transverse reinforcing bars, which have little effect on the plastic behavior. A single layer of reinforcement is placed closer to the outer face of the hollow column and the core inside the outer hoop is mostly subjected to radial confining pressure. 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 section (Hoshikuma and Priestley 2000; Zahn et al. 1990). In the aspect of constructability, advantages for the use of triangular confinement modules exist. Each pre-fabricated triangular module can stand alone prior to the fabrication of a whole bridge column cage, and this is particularly advantageous in cast-in-place construction. For precast segmental construction, it is very important to minimize the tolerance for continuous strands. The use of triangular confinement modules is an effective way to achieve it because of its stable triangular shape, keeping the tolerance within only 3 mm (1/8 in.).

Additionally, cross-section verifications and parameter studies were previously performed by the authors (Kim et al. 2015) to expand the application of the triangular confinement modules to hollow bridge columns with a hollow ratio (inner/outer diameter ratio) to 0.8. The current study extends the application of post-tensioning strands of concrete columns along with the triangular confinement modules. With the use of the triangular modules with post-tensioning strands, it is expected to optimize the quantity of reinforcing bars and concrete. A large quantity of the outermost longitudinal reinforcing bars is replaced by bonded or unbonded strands, which are inserted in the sheath located near the outer surface of columns (refer to Fig. 2(b)), maximizing the efficiency of post-tensioning strands in resisting column moments. In the following sections, only the bonded systems are dealt with.

REVISION OF SPECIAL-PURPOSE DESIGN PROGRAM, CalPM-SHC II

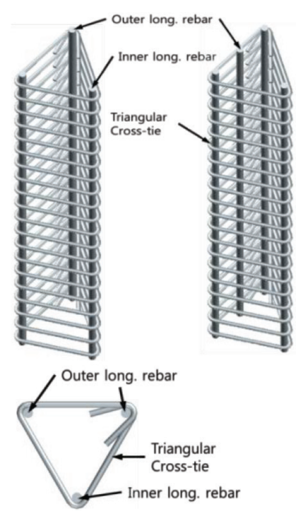
Overview

The main design considerations of hollow bridge columns include structural safety in terms of axial force and bending moment and their interaction (P-M curve) and efficiency regarding total quantity of transverse reinforcing bars. As part of the current study, the features for generating P-M curves for prestressed concrete columns are developed and implemented in a special-purpose design program, which was previously developed by the authors (Kim et al. 2014b). The purpose of the special-purpose design program is to improve productivity during the design process for hollow bridge columns by allowing for accurate and quick review of the design progress.

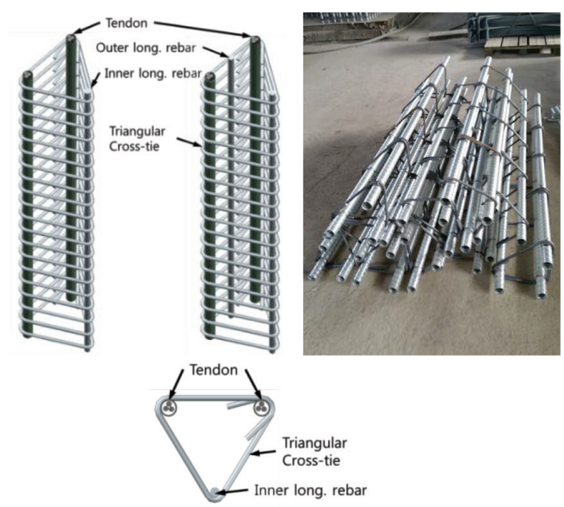
The special-purpose design program revised in this study uses spreadsheets of EXCEL and VBA (Visual Basic for Application) to analyze the results of various input and variables. The EXCEL and VBA, which are used universally for general purpose, have various functions such as graphic function and have advantages of being able to be programmed by GUI (graphical user interface) for convenient analysis and design.

As such, the special-purpose design program CalPM-SHC II is revised to check structural stability of hollow bridge columns having the triangular confinement modules with post-tensioning strands. The Korean Highway Bridge Design Code (Ministry of Land, Infrastructure and Transport 2015), AASHTO-LRFD (2014), and Eurocode 2 (2004) are applied to use for various projects. In addition, the concept of prestressed concrete is applied considering combined flexural and compression behavior caused by strands. Most of all, the preexisting option of triangular confinement modules is available with CalPM-SHC II.

CalPM-SHC II, as shown in Fig. 3, is equipped with automated design features for various hollow or solid rectangular, circular, track-shaped, and hexagonal sections. In the case of hollow concrete columns, most of the design cases are long slender columns. The effective length of a column, slenderness ratio, and end boundary conditions of a column are considered in order to incorporate the second order effects of slender columns of the compression members. All

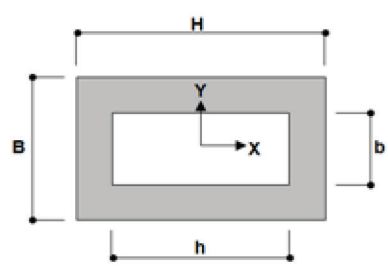


(a) Triangular confinement module with reinforcing bars

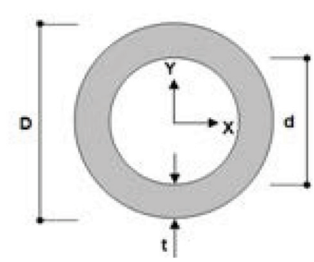


(b) Triangular confinement module with post-tensioning strands

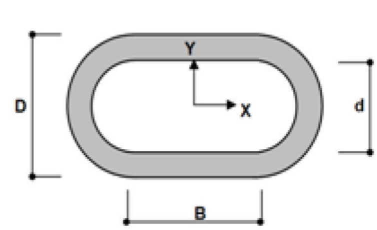
Fig. 2—Triangular confinement module.



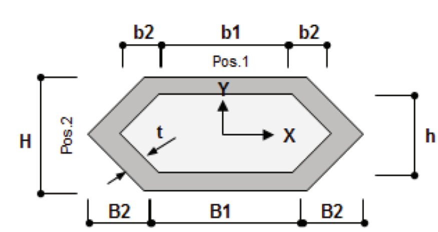
(a) Rectangular



(b) Circular



(c) Track



(d) Hexagonal

Fig. 3—Cross section in column.

these features are implemented for the purpose of convenient design of bonded post-tensioned bridge columns, and not completely available in existing commercial programs. The developed program will be shared when requested for actual projects.

To confirm the reliability of the developed special-purpose design program, it is verified with the analytical values based on the existing commercial program.

Program modules

The special-purpose design program of section analysis for hollow column consists of five sheets as user manual, input and output sheets. Modules of the program consist of five main modules and 12 sub-modules, as shown in Fig. 4. Main modules are configured for P-M analysis for each design code. Sub-modules are configured for cross-sectional information, reinforcing bar and strand coordinates, yield strain, and more for section analysis.

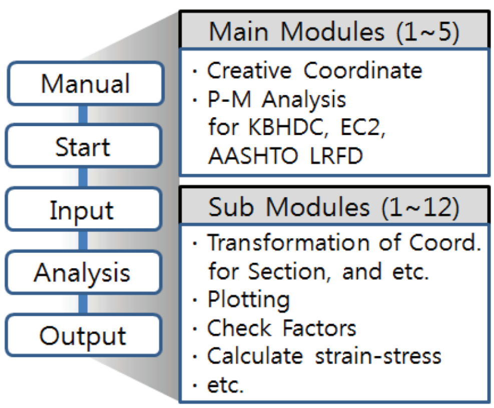


Fig. 4—Summary of sheets and modules.

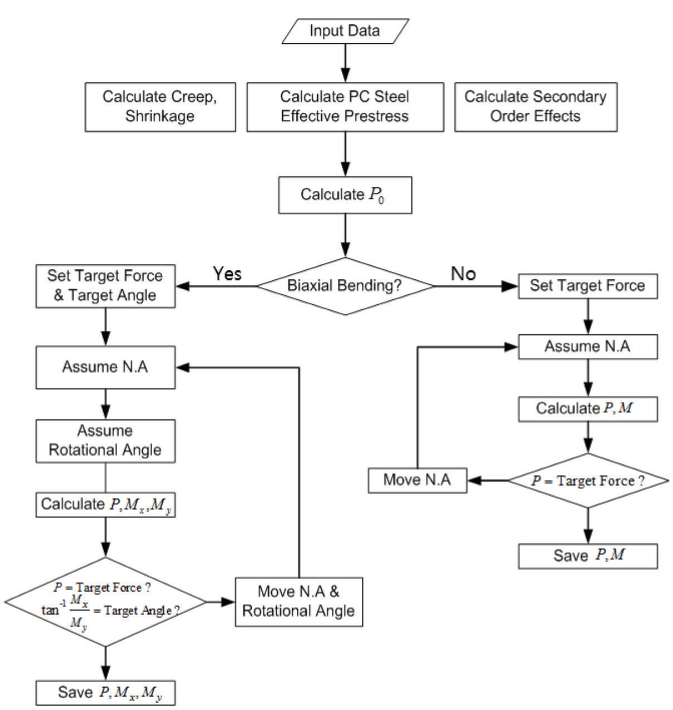


Fig. 5—Program procedure.

Program procedure

The program procedure of CalPM-SHC II is shown in Fig. 5. The input data of CalPM-SHC II includes sectional properties, material properties, information of strands and reinforcing bar, and applied loads. When the input is completed, it is known whether or not the biaxial bending occurs based on the calculation of axial force, eccentricity of the applied loads, or another factor. In the case of column members subjected to biaxial bending, the angle of the neutral axis as well as depth of the neutral axis is initially unknown. Because the angle of the neutral axis changes with the axis load, an iterative calculation process is applied to determine the position and angle of the neutral axis (refer to Fig. 6).

Note the following: for the stress-strain of each material according to the design code of the developed program, the compressive stress distribution of the concrete is applied to the P-R curve (parabolic-straight line) in the Korean Highway Bridge Design standard (2015) and Eurocode 2 (2004), and is applied to the rectangular block in AASHTO-LRFD 5.7.2.2 (2014). In addition, the stress-strain curves of the reinforcing bar are assumed to be a horizontal straight line after a yield stress; that is, an elastic-perfectly plastic stress-strain curve is applied. Moreover, the stress-strain curve of the strand is also adopted as bi-linear with a slope after yielding in the Korean Highway Bridge Design standard (Limit

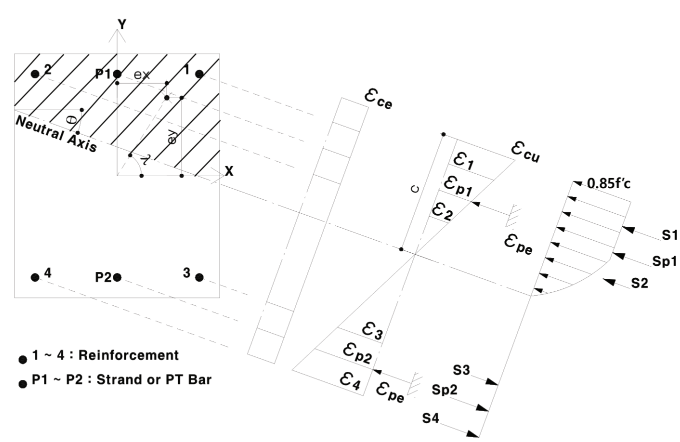


Fig. 6—Bi-axial behavior with reinforcing bar and strands.

State Design, 2015) and Eurocode 2 (2004), and in AASHTO-LRFD 5.7.3 (2014), a mathematically proven formula (Namman 2012) is applied to calculate the stress.

VERIFICATION FOR SPECIAL-PURPOSE DESIGN PROGRAM

Overview

The developed special-purpose design program of CalPM-SCH II is verified and compared with existing commercial programs to confirm the reliability of analytical values. Hollow bridge columns with triangular confinement modules and bonded PT strands need to be modeled manually in the existing programs. In this study, the cross-sectional analysis program Oasys-AdSec (2014) is used. The Oasys-AdSec program is a program for nonlinear sectional analysis of concrete. It is available for analyzing the prestressed concrete with bonded post-tensioning strands as well as providing a cross-sectional analysis in accordance with various design codes (Oasys-AdSec 2014). It is verified with circular, square, track-shaped, octagonal, and hexagonal sections and both hollow and solid cross sections. The reliability of the developed program is confirmed by considering the loads in the two principle axes. The comparative verifications are performed on 30 cases. The cases consist of three cases of only reinforcing bars in section, 11 cases of only strands in section, and 16 cases of both reinforcing bars and strands.

The concrete strengths used in the verification are applied such that the design standard strength f_c' of concrete is 30 MPa (4400 psi) for sections with only reinforcing bars or strands, and 35 MPa (5100 psi) for sections with both reinforcing bars and strands. The yield strength f_y of the reinforcing bar is 400 MPa (58 ksi), and the tensile strength f_{pu} of the strand is 1860 MPa (270 ksi). The jacking stress is 1440 MPa (209 ksi).

As shown in Table 1, the pure compression (P0), pure moment (M0), balanced eccentricity, and applied eccentricity are verified in the P-M curve for each case. The reliability of the program for the neutral axis at the failure is confirmed by comparing the values of the developed program and the commercial program. The applied eccentricity for the calculation of the neutral axis of the cross section is defined as the point where the connecting line from the origin to the applied load is extended to meet with the P-M curve. The neutral axis position at the failure is shown as the section rotated by the rotation angle λ and the neutral axis distance (C) from the compression edge to the neutral axis.

In the P-M curve of AASHTO-LRFD 5.7 (2014), the nominal strengths M_n and P_n are compared. The design strength is shown by applying the strength reduction factor of a column. In addition, in the P-M curve of Eurocode 2 (2004) and the Korean Highway Bridge Design Code (Limit State Design 2015), the design strengths M_d and P_d are shown by applying the material resistance factors of concrete and reinforcing bars.

Among the 30 cases that are compared and verified, Cases 12, 23, and 28 are shown in Fig. 7 and Table 2. In Case 12, Eurocode 2 (2004) is verified using a track section, and strands are externally and internally tensioned without reinforcing bars.

In Case 23, AASHTO-LRFD (2014) is verified using a hexagonal section, and only one row of strands is tensioned without reinforcing

Table 1—Verification items (1 kN = 225 lb. and 1 m = 3.3 ft).

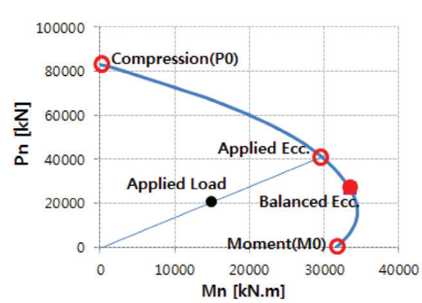
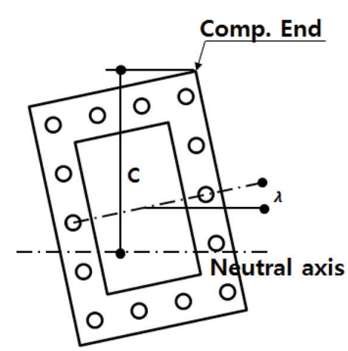
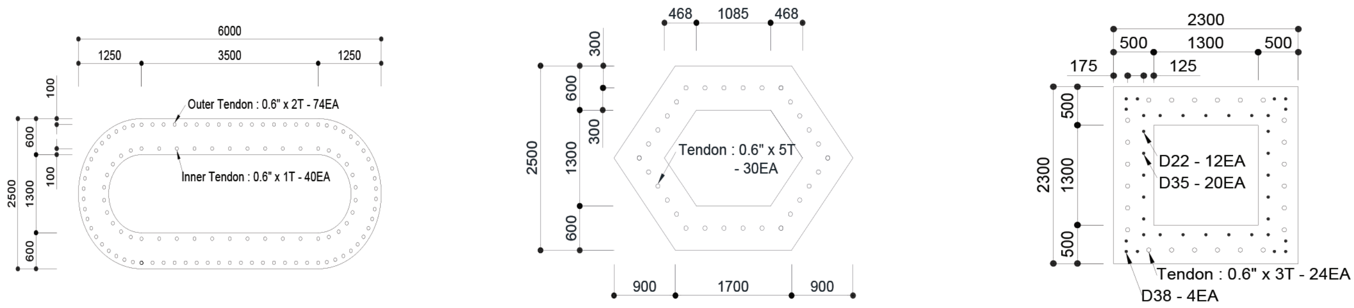
P-M curve	Neutral axis at failure
	

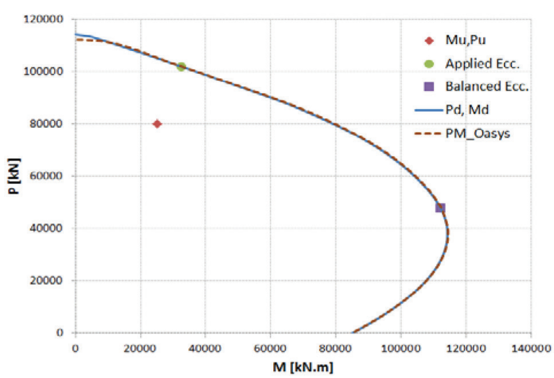
Table 2—Applied loads.

Items	Case 12	Case 23	Case 28
f_{se}, MPa	1048	1144	1000
P_u, kN	80,000	6000	28,736
M_x, kN·m	3100	7500	14,274
M_y, kN·m	24,800	10,000	32,263

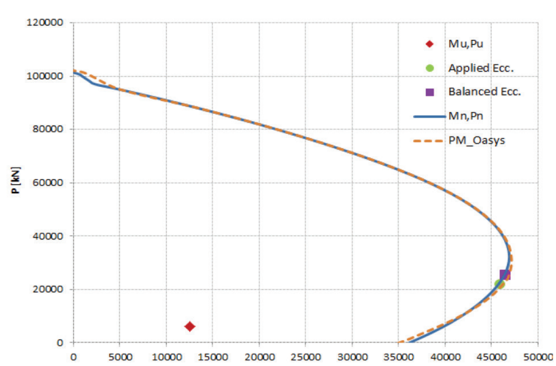


(a) Case 12 *(b) Case 23* *(b) Case 23*

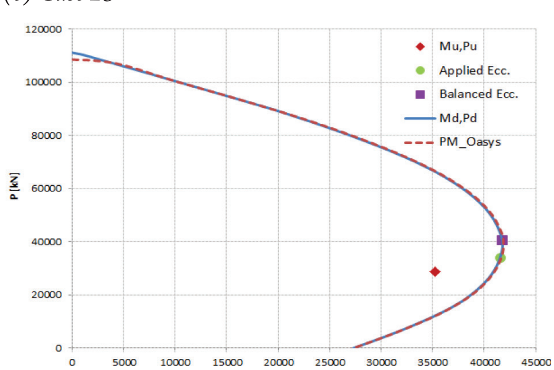
Fig. 7—Verification cases: Case 12, 23, and 28 (Note: 1 m = 39.4 in.).



(a) Case 12



(b) Case 23



(c) Case 28

Fig. 8—Verification of P-M curves.

bars. In Case 28, the Korean Highway Bridge Design Code (Limit State Design, 2015) is verified using a rectangular section, and the reinforcing bars and strands are simultaneously applied. The material properties—yield strength of reinforcing bar and tensile strength of strands—are as described earlier. The concrete design strength f_c' is applied at 30 MPa (4400 psi) in Cases 12 and 23 where only strands are applied, and 35 MPa (5100 psi) in Case 28 where reinforcing bars and strands are simultaneously applied.

As a result of comparing the pure compression (P0), pure moment (M0), balanced eccentricity, and applied eccentricity for 30 cases, most of the differences are within approximately 1% and have almost the same values, which a maximum of 3.1% in some cases. It is considered due to the difference in the degree of convergence according to the repeated analysis in each program. Therefore, CalPM-SHC II, which is a special-purpose design program developed for bonded post-tensioned hollow bridge columns with standardized sections and triangular confinement modules, can be applied in accordance with design codes in actual design (refer to Table 3 and Fig. 8).

Second-order effect with axial load

In the special-purpose design program of CalPM-SCH II, magnification factored moment accounting for the second-order effect along with axial load of each design code is verified with the numerical calculation. In this study, comparative validation of the Korean Highway Bridge Design Code (2015) is shown. The cross section used for the verification of second-order effect shown in Fig. 9. The column length Lc is 30 m (98 ft), the design strength of concrete f_c' is 35 MPa (5100 psi), the yield strength of reinforcing bars f_y is 400 MPa (58 ksi), and the tensile strength of strands f_{pu} is 1860 MPa (270 ksi). The jacking stress is 1440 MPa (209 ksi).

Table 3—Verification of programs.

Case	Program	P0, MN	M0, MN·m	Balanced eccentricity		Applied eccentricity		Neutral axis	
				P, MN	M, MN·m	P, MN	M, MN·m	Depth, mm	Angle, deg
Case 12	Oasys	111.7	84.9	47.3	112.7	102.3	32.8	7093.0	62.5
	CalPM-SCH II	114.5	85.0	47.3	112.5	102.3	32.5	7070.6	62.3
	Difference (%)	2.5	0.1	0.0	0.2	0.0	0.7	0.3	0.4
Case 23	Oasys	102.2	35.1	25.1	46.9	21.7	46.3	1405.0	43.5
	CalPM-SCH II	101.8	36.2	25.8	46.6	21.7	45.8	1382.6	43.4
	Difference (%)	0.4	3.1	2.7	0.6	0.0	1.0	1.6	0.2
Case 28	Oasys	107.7	27.3	41.6	41.9	34.1	41.5	1615.0	62.2
	CalPM-SCH II	111.1	27.3	40.7	41.7	34.1	41.5	1603.3	62.3
	Difference (%)	3.1	0.0	2.0	0.3	0.0	0.0	0.7	0.2

Table 4—Load conditions.

Items	Top of column		Bottom of column	
	x-axis	y-axis	x-axis	y-axis
Axial force, MN	Pu = 30			
Nonsway moment, MN·m	0.8	0.6	2.8	6.6
Sway moment, MN·m	3.2	2.4	11.2	26.4
Factored moment, MN·m	4.0	3.0	14.0	26.4

Table 5—Magnification factors of moments.

Items	x-axis	y-axis
Cm	0.714	0.636
δ_{ns}	1.021	1.000
δ_s	1.430	1.141

The load conditions are shown in Table 4. The effective length k is assumed to be 2, and $\beta d = 0.6$ which is ratio of maximum factored permanent load moment to maximum factored total load moment. It is confirmed that the slenderness ratio is calculated to be 61 and 39 for each of the x- and y-axis direction, respectively, having the critical slenderness ratio of 22 or more. The magnification factor moments are calculated based on Eq. (4) used in the Korean Highway Bridge Design Code (2015) and compared with the numerical calculation as shown in Tables 5 and 6. From the comparison of the results, it is estimated to be almost the same as the difference of 0.01% and 0.04% in each direction, respectively. Therefore, it is found that the magnification factor moments of the developed program are appropriately calculated, considering the second-order effect with axial load.

Table 6—Comparison of results of magnification factored moments (unit: kN·m).

Items	M_{cx}	M_{cy}	M_{cu}
Hand calculation	18875	36749	41313
CalPM-SCH II	18873	36734	41299
Difference, %	0.01	0.04	0.03

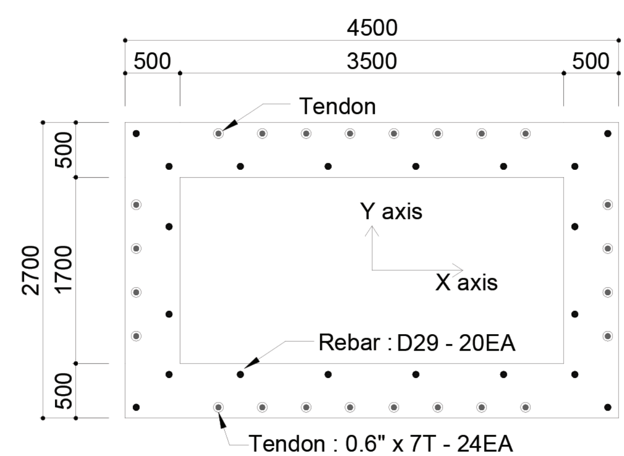


Fig. 9—Verification of second-order effect with axial load (Note: Units are in mm).

$$Mc = \delta_{ns} M_{ns} + \delta_s M_s \quad (1)$$

where Mc is magnification moment; M_{ns} and δ_{ns} are moment of compressive member and magnification factor of moment for design load with no sway, respectively; and M_s and δ_s are moment of compressive member and magnification factor of moment for design load with sway, respectively.

Table 7—Pier and section of target bridge (Unit: mm).

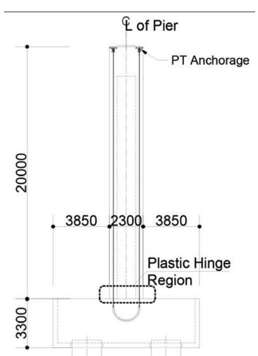
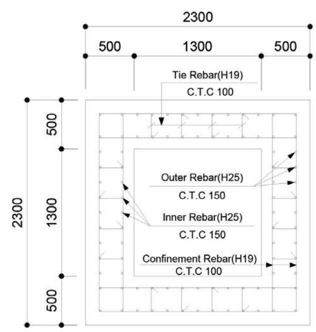
P9 Column	Existing section	
		
	$f_c' = 35$ MPa	$f_y = 400$ MPa

Table 8—Applied loads of earthquake case.

P, kN	V_x, kN	V_y, kN	M_x, kN·m	M_y, kN·m
28,736	3423	1569	14,274	32,263

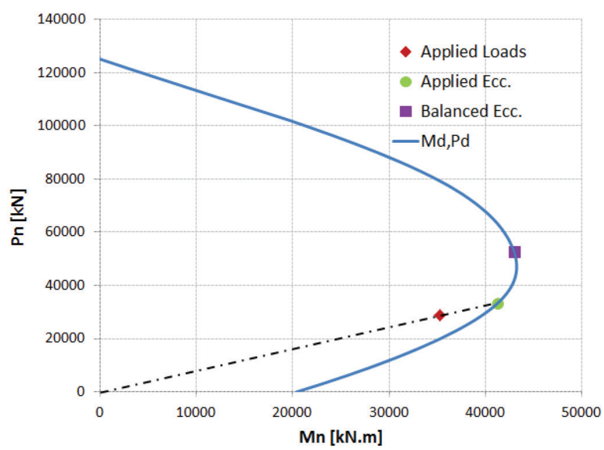


Fig. 10—P-M curve of existing section.

COMPARATIVE STUDY

Overview

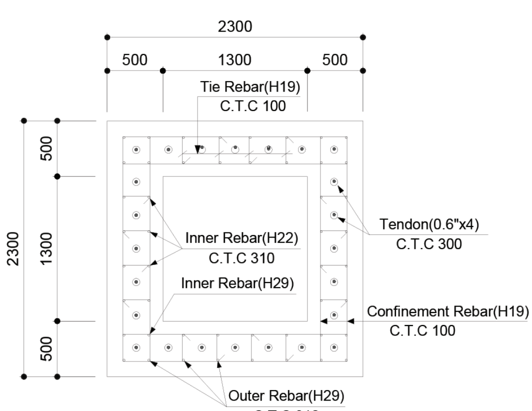
This study presents a cross section of a hollow concrete column with post-tensioning strands applying triangular confinement modules. Based on the comparison between the proposed section and the existing section, it is confirmed the performance and the economic effect with existing section.

Target bridge and sections

In Korea, it is difficult to find a case of a hollow column using post-tensioning strands yet. First, a bridge with hollow reinforced concrete (RC) columns is selected. Second, the cross section is changed to the one in which the post-tensioning strands are used. In the modified case, post-tensioning strands and reinforcing bars are arranged to be similar to the performance of existing conventional RC sections (with a similar safety factor on the P-M curve). A sufficient quantity of conventional transverse reinforcement (confinement steel) is arranged in accordance with the design code.

The P9 column shown in Table 7, which was previously designed and constructed in Korea, is selected as the target. The location of review section is set to the column base where the plastic hinge is formed. The design strength of concrete is 35 MPa (5100 psi) and the yield strength of the reinforcing bars is 400 MPa (58 ksi). Table 8 shows applied internal loads or moments due to earthquake. As shown in Fig. 10, it is noted that the safety factor is 1.17 in terms of the P-M curve for the existing RC section.

The section modified to apply the strands to the existing section is called "equivalent" section, and the section with the details of the triangular confinement modules along with post-tensioning strands is called "proposed" section. Both equivalent and proposed sections have a similar



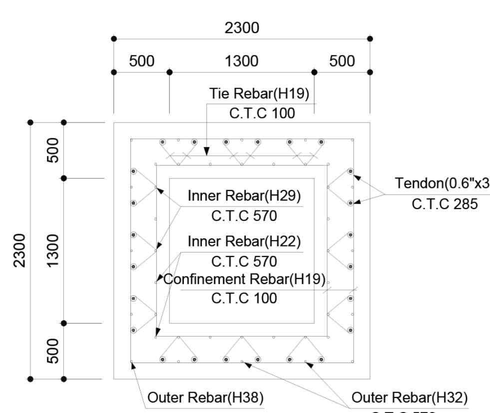


Fig. 11—Equivalent section with strand and proposed section (Note: Units in mm).

safety factor to that of the RC section in terms of the P-M curve. The Korean Highway Bridge Design Code (2015) is applied for the comparison of structural performance of the strength.

While the equivalent and proposed sections have the same shape as the existing RC section, the quantity and arrangement of reinforcing bars and strands are different. Only the safety factors on the P-M curve are similar for the same earthquake load. Figure 11 shows the equivalent section and the proposed section. As shown in Fig. 12, in the P-M curves of the equivalent and proposed section, it is confirmed that the safety factors are 1.18 and 1.17, respectively, which are similar to the existing section.

Material quantity reduction evaluation

Material quantity evaluation is conducted in this study. The material quantities for the equivalent cross section and the proposed cross section are compared in Table 9. The quantity per unit length (m) is calculated. When compared to the equivalent cross section of hollow columns in the target bridges, the proposed section presents reduction percentages of 2% for reinforcing bars and 25.5% for strands. If total steel is accounted for, 5% reduction is achieved.

This appears to be possible because the triangular configuration provides greater stability, uses a smaller amount of outside transverse reinforcement and cross-ties, and allows for the optimized arrangement of strands that are closer to the outer faces.

CONCLUSIONS

In this study, the post-tensioned hollow bridge columns with triangular confinement modules and the special-purpose design program are developed. A wide variety of advantages of the developed system are

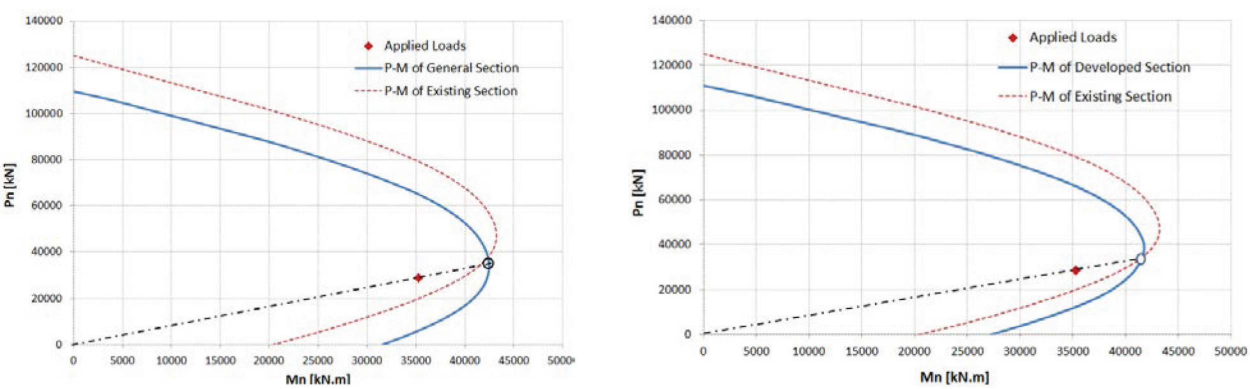


Fig. 12—P-M curve.

Table 9—Quantity comparison of reinforcing bar and strand.

Items		Equivalent section	Proposed section
Cross section area		3.6 m^2	3.6 m^2
Ratio of hollow		0.565	0.565
Reinforcing bar quantity per unit length (m)	Longitudinal reinforcing bar	0.222 tonf	0.208 tonf
	Confinement reinforcing bar	0.414 tonf	0.322 tonf
	Cross-tie bar	0.180 tonf	0.270 tonf
Total quantity of reinforcing bar		0.816 tonf	0.800 tonf
Quantity of strand per unit length, m		0.106 tonf	0.079 tonf
Reinforcing bar + strands		0.922 tonf	0.879 tonf
Ratio of reinforcing bar, %		100	98.0
Ratio of strands, %		100	74.5
Ratio of (reinforcing bar + strands), %		100	95.3

discussed in detail. Then, the developed system with post-tensioning strands is assessed in terms of material quantity reduction. The conclusions from the current study are drawn as follows:

- In-depth discussion revealed that the prefabricated triangular confinement modules for post-tensioned bridge hollow columns would offer many structural and constructional advantages, such as better concrete confinement, seismic performance, increased moment capacity with outer PT strands, reduced construction time, stability of steel cage modules, minimized tolerance (particularly important for precast segmental PT bridges), reduced steel congestion, and material efficiency. Most of all, constructability of the developed system was emphasized: each prefabricated triangular module can stand alone prior to fabricating a whole bridge column cage and tolerances for segmental bridges can be less than 3 mm.
- The applicability of the proposed triangular confinement modules with post-tensioning strands is confirmed. The structural efficiency is proven to be greater than comparable conventional systems, as the material quantity reduction is not insignificant. By applying the proposed pre-fabricated module details, enhance the efficiency in terms of both construction and economical design section.
- The developed program of CalPM-SHC II can be applied to the design with the triangular confinement modules in accordance with the Korean highway bridge (2015), AASHTO-LRFD (2014), and Eurocode 2 (2004). It would be convenient to apply the rectangular, circular, track-shaped, and hexagonal sections that are mainly used. The second-order effect with axial load is also accounted for in the developed program. The triangular modules with confined concrete models are implemented in the program and readily available for users.
- The developed triangular confinement modules and the special-purpose design program can be applied to hollow and solid bridge columns subjected to various flexure and compression in accordance with each code, and are demonstrated to have beneficial effects on structural performance, efficiency, and constructability. Additional research such as experimental verification is needed as a further study.

REFERENCES

AASHTO, 2014, "AASHTO LRFD Bridge Design Specifications", seventh edition, American Association of State Highway and Transportation Officials, Washington, DC .

Billington, S. L.; Barnes, R. W.; and Breen, J. E., 2001, "Alternative Substructure Systems for Standard Highway Bridges," *Journal of Bridge Engineering*, ASCE, V. 6, No. 2, pp. 87-94.

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

Cheng, C.-T., 2008, "Shaking Table Tests a Self-Centering Designed Bridge Substructure," *Engineering Structures*, V. 30, No. 12, pp. 3426-3433.

Chou, C.-C., and Chen, Y-C., 2006, "Cyclic Tests of Post-Tensioned Precast CFT Segmental Bridge Columns with Unbonded Strands," *Earthquake Engineering & Structural Dynamics*, V. 35, pp. 159-175.

Hoshikuma J., and Priestley, M. J. N., 2000, "Flexural Behavior of Circular Hollow Columns with a Single Layer of Reinforcement under Seismic Loading," University of California, San Diego, La Jolla, CA, Report SSRP-2000/13.

Kim, I.-H.; Sun, C.-H.; and Shin, M.-S., 2012, "Concrete Contribution to Initial Shear Strength of RC Hollow Bridge Columns," *Structural Engineering and Mechanics*, V. 41, No. 1, pp. 43-65.

Kim, T.-H.; Choi, J.-H.; Lee, J.-H.; and Shin, H. M., 2013, "Performance Assessment of Hollow RC Bridge Column Sections with Reinforcement Details for Material Quantity Reduction," Magazine of Concrete Research, V. 65, No. 21, pp.1277-1292.

Kim, T.-H., and Kang, H.-T., 2012, "Seismic Performance Assessment of Hollow Circular Reinforced Concrete Bridge Columns with Confinement Steel," *Journal of the Earthquake Engineering Society of Korea*, V. 16, No. 1, pp. 13-25.

Kim, T.-H.; Kim, H.-Y.; Lee, S.-H.; Lee, J.-H.; and Shin, H. M., "Performance Assessment of Advanced Hollow RC Bridge Column Sections," *Computers & Concrete*, V. 16, No. 5, 2015, pp. 703-722.

Kim, T.-H.; Lee, J.-H.; and Shin, H. M., 2014a, "Performance Assessment of Hollow Reinforced Concrete Bridge Columns with Triangular Reinforcement Details," *Magazine of Concrete Research*, V. 66, No. 16, pp. 809-824.

Kim, T.-H.; Son, J.-K.; Yang, N.-S.; and Lee, S.-H., 2014b, "Design Program and Economic Evaluation for Hollow RC Bridge Columns with Reinforcement Details for Material Quantity Reduction," *Journal of the*

Computational Structural Engineering Institute of Korea, V. 27, No. 5, pp. 403-412.

Ministry of Land, Infrastructure and Transport, 2015, "Korean Highway Bridge Design Code (Limit State Design)," Sejong, Republic of Korea.

Naaman, A. E., 2012, *Concrete Analysis and Design: Fundamentals*, TECHNO PRESS 3000, Sarasota, FL, pp. 853-938.

Oasys Adsec, 2014, Oasys Software, London, UK, www.oasys-software.com/products/engineering/adsec.html . (last accessed Sept. 25, 2018)

Wang, J. C.; Ou, Y. C.; Chang, K. C.; and Lee, G. C., 2008, "Large-Scale Seismic Tests of Tall Concrete Bridge Columns with Precast Segmental Construction," *Earthquake Engineering & Structural Dynamics*, V. 37, pp. 1449-1465.

Yeh, Y. K.; Mo, Y. L.; and Yang, Y., 2002, "Seismic Performance of Rectangular Hollow Bridge Columns," *Journal of Structural Engineering*, ASCE, V. 128, No. 1, pp. 60-68.

Zahn, F. A.; Park, R.; and Priestely, M. J. N., 1990, "Flexural Strength and Ductility of Circular Hollow Reinforced Concrete Columns without Confinement on Inside Face," *ACI Structural Journal*, V. 87, No. 2, Mar.-Apr., pp. 156-166.

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