Large-scale Cyclic Loading Test on a Multi-Spiral Stirrup Bridge Pier Constructed by Automated Method

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SUMMARY:
Reinforced concrete is the most widely used construction material for bridge piers in Taiwan. Due to the requirements of strength and ductility for seismic design of RC structures, a large amount of reinforcements are usually required. This tight arrangement of reinforcements not only complicates the construction works but also deteriorates the quality of concrete casting. In order to solve this problem, a multi-spiral stirrup bridge pier system was proposed. Large scale experimental studies for the proposed system as well as the conventional system which was constructed based on the conventional construction technology were conducted. By comparing the experimental results and construction practices of the developed system with those of the conventional counterpart, the seismic performance and the constructability as well as construction cost of the proposed pier system was proved to be better than that of the conventional RC pier system.

Keywords: cyclic loading test   multi-spiral stirrup piers   automated methods in construction

1. INSTRUCTION

Reinforced concrete is the most widely used construction material for bridge piers in Taiwan. Once the bridge pier is high, due to the requirements of strength and ductility from seismic design of RC structures, a large amount of reinforcements, including longitudinal reinforcements, transverse reinforcements and internal cross ties, are usually required. The process for large amount of reinforcing binding is heavily relied on skilled labors, which is time-consuming and costly. In addition, this tight arrangement of reinforcements not only complicates the construction works but also deteriorates the quality of concrete casting. Thus, for such a conventional bridge pier system based on the conventional construction technology, the construction period is highly likely to be long and the seismic performance of the pier is also likely to be inferior to that was expected. In order to solve this problem and also to improve the construction safety based on a reasonable construction cost, the purpose of this study is to develop innovative bridge pier systems which are based on automated methods in construction and also have satisfactory seismic performance. Two bridge pier systems which possess these features were proposed. One is the multi-spiral stirrup bridge pier system and the other is the steel and reinforcement composite pier system. In order to verify the constructability of these proposed methods and to investigate the seismic performance of the proposed systems, large-scale specimens for both systems as well as a conventionally detailed system were all constructed at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan, followed by a lateral cyclic loading test performed on each specimen. During the construction practice, not only every construction steps were carefully recorded and photographed, the spending time and manpower used for each step were also narrowly documented. In this paper, focus is on the multi-spiral stirrup bridge pier system. By comparing the experimental results of the developed system with those of the conventionally detailed one, the seismic behavior of the proposed bridge pier was examined. Through the real construction practice performed at the laboratory, the efficiency of the proposed construction method was identified and the construction cost was discussed. The laboratory tests and the construction practice demonstrated that the proposed pier system with a multi-spiral confinement design can provide effective confinement with increased ductility, improved constructability and reduced cost.

2. SPECIMEN DESIGN

It has been recognized that rectilinear stirrups that are generally adopted for a rectangular column are less effective for concrete confinement because of the uneven distribution of the lateral confining stress. Furthermore, construction of conventional stirrups is more laborious that leads to highly expensive operation. Therefore, with an aim to improve the safety and efficiency of the bridge pier construction in Taiwan, a multi-spiral stirrup pier system with the usage of six interlocking spirals design was proposed in current study. The interlocking multi-spiral confinement design for rectangular RC columns was first developed by Yin et al. (2004). It has been proved that multi-spiral stirrups, especially 5-spirals, can provide good confining effect on core concrete of RC columns, with tangibly better toughness than RC columns with conventional rectilinear stirrup (Yin et al. 2012). The multi-spiral design also has been successfully used for several construction projects such as office, factory buildings and shopping malls, etc., in Taiwan. However, its application in bridge piers is still rare. In current study, a multi-spiral stirrup bridge pier was proposed with special emphasis on constructability improvement through automation in construction.

The proposed rectangular multi-spiral stirrup pier consists of two big interlocking spirals inside and four small spirals in the corner. These small spirals are also interlocked with the big spirals as shown in Fig. 1(b). By replacing the rectilinear hoop and cross ties of the conventional RC pier by the interlocking spirals, the total amount of lateral steel can be greatly reduced, and the usage of small spirals with small diameter in the corner of a rectangular pier can improve the confinement efficiency at the corner which is generally a problem for a rectangular pier. More importantly, the multi-spiral detail can be produced automatically and the multi-spiral stirrup cage can be pre-assembled in the prefabrication plants. Thus, the time-consuming bending and labour required for conventional stirrups can be greatly reduced, which can result in lower cost as well as shorter construction time.

In order to realize the seismic resistance of current proposed pier system as compared to the one with the conventional design details, a conventional RC column which was designed in accordance with current seismic design code in Taiwan (MOTC, 2008) was also constructed. Thus, a total of two 1/2 scaled specimens were designed and constructed at NCREE. One is a RC column with the conventional design details as the benchmark, and the other is the proposed multi-spiral stirrup column. The target pier for the test specimen is a rectangular bridge pier with a height of 18 m and a reinforcement ratio of 1.5%. Thus the scaled specimens are 9 m in clear height with a cross section of 1.8 m $\times$ 1.2m, as shown in Fig. 1(a). The design details of both specimens are also schematically shown in Fig. 1 (b) and (c). As can be observed in Fig. 1, the benchmark specimen with the conventional details was reinforced with 32-D36 rebars. To have the same design strength as the benchmark specimen, the multi-spiral stirrup column was also reinforced with 32-D36 vertical reinforcing bars with the same steel ratio of 1.5% as the conventionally detailed one. The reinforcements are T-headed reinforcements at one end and were anchored into the foundation with an anchorage length of 1375 mm. According to the design code, for the conventionally detailed column that is reinforced with rectangular hoops and cross ties, the calculated requirement for the volumetric confinement ratio is 1.04%, whereas for the multi-spiral stirrup column that is reinforced with spirals, the required volumetric confinement ratio is only 0.73%. For the final design of the specimens constructed in this study, the benchmark RC column was transversely reinforced with D13 perimeter hoops and internal cross-ties spaced 10 cm, corresponding to a volumetric confinement ratio of 1.19%. The proposed 6-spiral stirrup column was transversely reinforced with four small D10 spirals with a diameter of 360 mm and two bigger D16 spirals with a diameter of 1120 mm. All the spirals have a pitch of 90 mm. By such an arrangement, the calculated volumetric confinement ratio for this proposed column is 0.87%. Consequently, the use of the multi-spiral design reduced the lateral steel consumption by more than 25% as compared to the conventional counterpart.

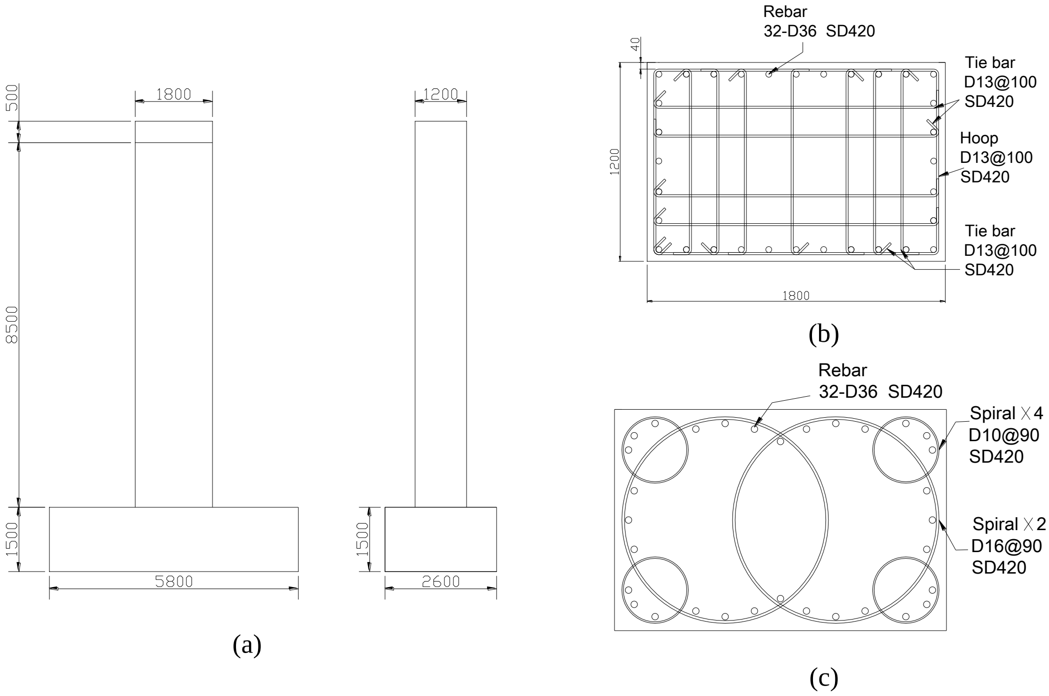
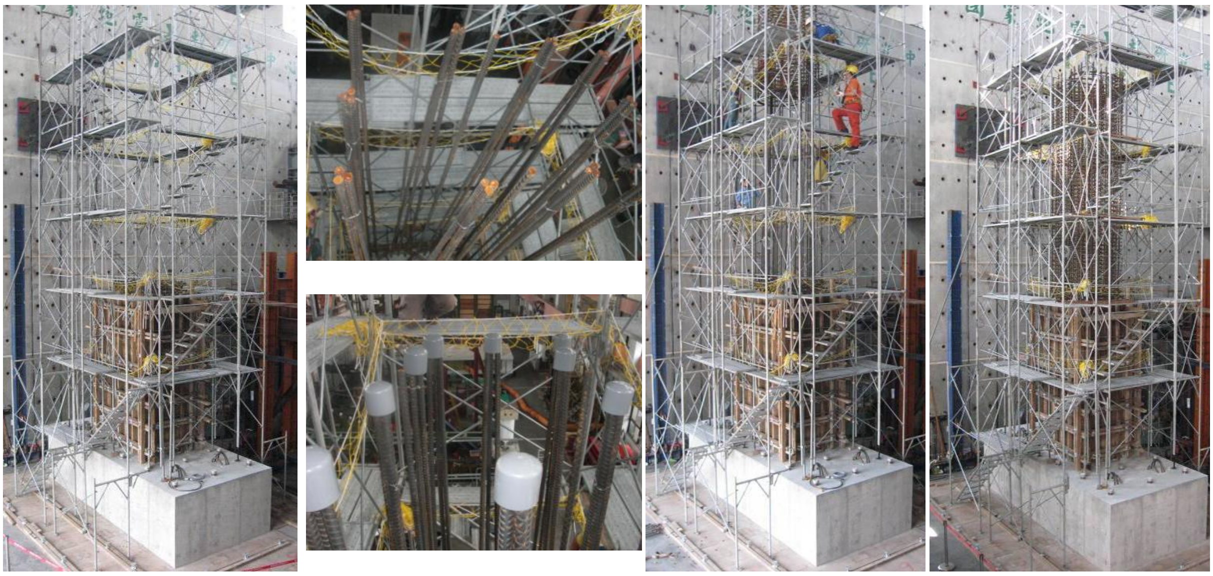


Figure 1. Design details of specimen (a) side view of the specimens (b) design details of the conventional column (c) design details of the proposed multi-spiral stirrup column

3. CONSTRUCTION PROCESS

For a real construction practice, due to the consideration of safety and the limit of transport, it cannot be avoided that the vertical reinforcing bars have to be separated into several parts. Thus, the quality control of the connection between the separated sections becomes a crucial issue for the seismic performance and a key factor for the construction efficiency of the column. In order to simulate the construction of the connections in our construction practice, all the vertical reinforcing bars, including that for the benchmark RC column and the proposed multi-spiral stirrup column, were separated into two sections with a connection at a height of around 4 m above the foundation, which is in a location outside the potential plastic hinge area. Standard thread couplers were adopted to join the re-bars. The adopted couplers meet the requirements for the necessary tests of SA grade of the locking couples. Therefore, all the rebars are connected in the same cross section. Standard couplers are designed to splice two bars by rotating one of them. Therefore, the vertical reinforcing bars and the spiral cage cannot be assembled together previously and have to be erected separately. For this study, the multi-spiral stirrup cages were produced and assembled automatically in the prefabrication plants in advance. The multi-spiral stirrup cages were separated into three segments. One with a length of 1120 mm was inside the foundation. The second with a length of 3840 mm was extended from 45 mm above the foundation to the location close to the reinforcement couplers. The third part was extended from 4 m above the foundation to 50 mm under the column top.

For the construction of the proposed multi-spiral stirrup column, the first step is the erection of the first segment of multi-spiral cage in the foundation. The second step is the binding of the foundation reinforcements and the installation the longitudinal reinforcing bars of the lower part. The third step is the setup of the scaffold, followed by the installation of the second multi-spiral cage. Then after the setup of the formwork, the concrete was poured into the lower part of the column. For the upper part of the column, the first step is the erection of scaffold, followed by the erection of the vertical reinforcing bar and the multi-spiral cage. The erection of the pre-fabricated multi-spiral cage is the key construction item for the construction efficiency. As a result, three types of procedure for the erection were practiced in current study. This practice was only performed for the upper part of the multi-spiral cage. These three procedures are as follows. Procedure I: to erect and connect the vertical reinforcing bars at first, followed by the erection of the multi-spiral cage. Procedure II: to erect and connect part of the vertical reinforcing bars at first except the eight corner rebars which are likely to interfere with the installation of the multi-spiral cage. The next step is to install the multi-spiral cage, followed by the erection of the remaining vertical rebars. Procedure III: to erect and couple the reinforcing bars at first. Every 3 neighboring bars were capped together with a cover at the top (Fig. 2b) to prevent their interruption over the installation of the multi-spiral cage. According to the construction practices, procedures II and III are most effective. After the positioning of the spiral cage and the coupling of the rebars were completed, followed by the setup of the form work and pouring of the concrete, the construction was completed.



(a) (b) (c) (d)

Figure 2. Construction photos for the proposed multi-spiral stirrup column (a) erection of scaffold (b) the capping of three vertical bars together with a cover; (c) installation of the pre-assembled multi-spiral stirrup cage; (d) fix position of the multi-spiral stirrup cage.

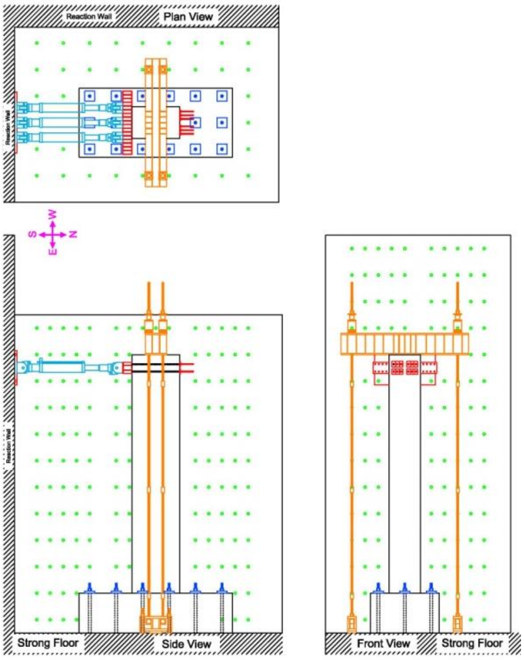
In order to demonstrate the construction sequence of the proposed column, the construction photos are given in Fig. 2. For brevity, only the construction photos for the upper section are listed. In Fig. 2, (a) shows the erection of the scaffold; (b) shows the capping of three vertical bars together with a cover to prevent their interruption over the installation of the spiral cage; (c) shows the installation of the pre-assembled spiral cage, and (d) shows the positioning of the spiral cage. By comparing these construction photos with those of the conventionally RC column as given in Fig. 3, no time-consuming on-site binding process of reinforcements is needed for the proposed composite column. So the quality and efficiency of the construction can be improved. In addition, the 6-spirals cages were manufactured with automatic machines in the factory, which substantially reduce manpower in fabricating conventional stirrups and shorten the construction period.

4. EXPERIMENTAL PROGRAM

In order to investigate the seismic performance of the proposed column, a lateral cyclic loading test was conducted. Fig. 4 illustrates the test setup. Sixteen high strength tie-down rods with a diameter of 69 mm were placed through the footing and anchored into the strong floor of the laboratory to simulate the fixed-base condition of the foundation. During the test, an axial load of 5186 kN was applied to the test column through a tap beam using two vertical high tensile strength rods. The vertical loading was kept constant throughout the test to simulate the tributary dead load of the deck, which is around $0.07A_gf_c'$. In which, A_g is the gross cross-sectional area of the column. In addition, three horizontal actuators were used to apply the lateral force to the column's top to simulate the seismic loading. The location of the application force was 8.5 m up from the top of the footing.

(a) (b) (c) (d)

Figure 3. Construction photos for the conventionally detailed column (a) erection of the lower main bars; (b) binding of the reinforcing bars for the lower part; (c) erection and connection of the upper main bars; (d) binding of the reinforcing bars for the upper part



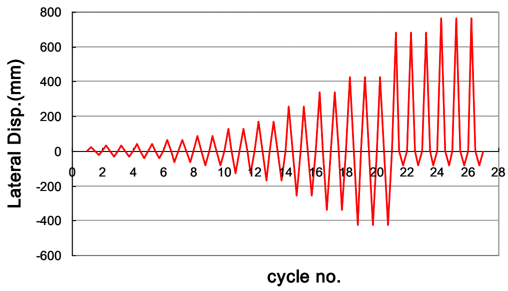


Figure 4. Schematics of experimental setups

Figure 5. Loading protocol for the cyclic loading test

Displacement-controlled cyclic loading test was performed on these two specimens. Fig.5 shows the displacement loading protocol for the test, where the excited drift ratios include 0.25%, 0.375%, 0.5%, 1.0%, 1.5%, 2.0%, 3.0%, 4.0% and 5.0%. The prescribed displacements were applied on the column two cycles for each drift ratio which is equal to or lower than 4%. For the drift ratio other than these values, the corresponding lateral displacement was applied on the column top for 3 cycles. In addition, considering that the proposed column may have a better ductility than the conventionally detailed one, drift ratios 8% was also applied. However, due to the stroke limit of the actuators, the drift ratio 8% was only applied along the North (push) direction; while along the South (pull) direction, the applied drift ratios were only 1%.

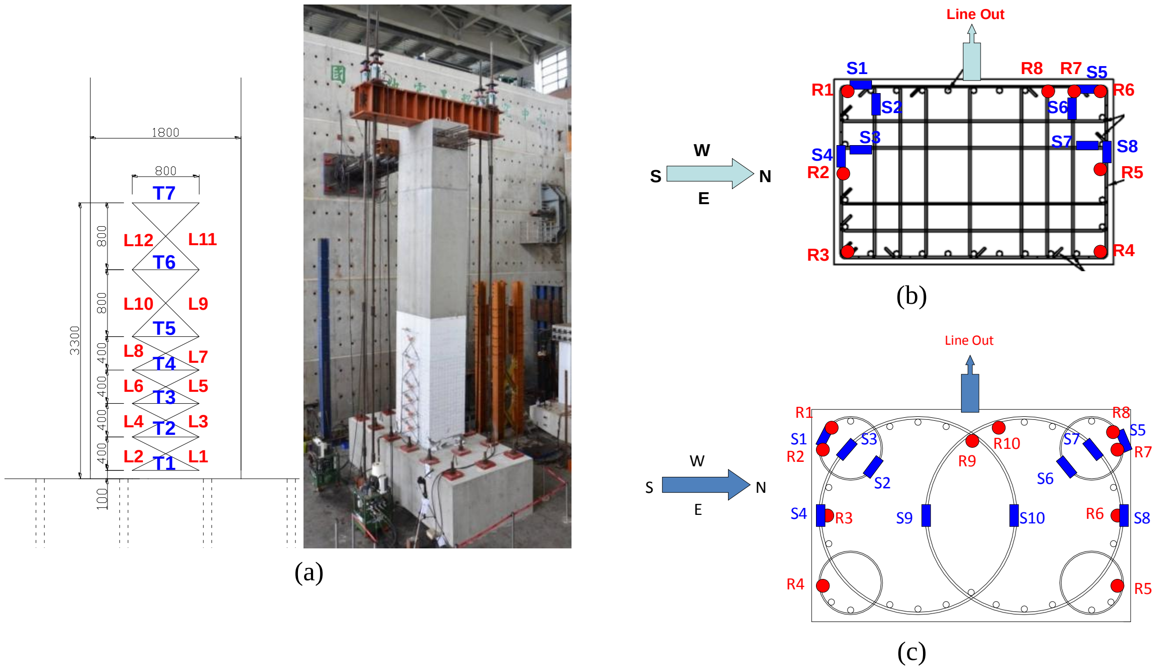
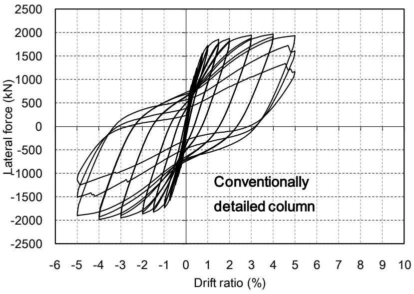


Figure 6. Instrumentation arrangement (a) tiltmeters and LVDT displacement gauges; (b) arrangement of strain gauge for the conventionally detailed columns; (c) arrangement of strain gaus for the proposed column

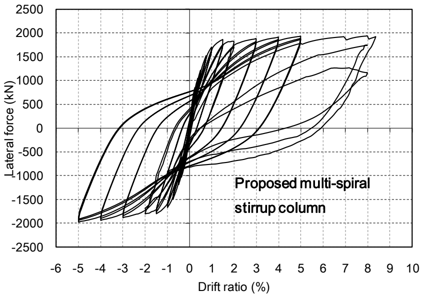
In order to measure the curvature and shear displacement of the test columns under the excitation of cyclic loadings, seven tiltmeters and twelve LVDT displacement gauges were mounted on the east side of the specimens as shown in Fig.6 (a). In which, tiltmeters T1 to T7 were mounted at distances of 10cm, 50cm, 90cm, 130cm, 170cm, 150cm and 330cm above the foundation top. Displacement gauges L1~L12 were crossly mounted between the tiltmeters. In order to measure strain of the rebars, several strain gauges were installed on the suitable location of both specimens. Fig. 6 (b) and (c) schematically show the layout of the strain gauges for the conventionally detailed specimen and the multi-spiral stirrup specimen, respectively. In which, symbol *R* represents the strain gauge on the main rebars and was installed at the cross section 10cm, 160cm and 318cm above the foundation. Symbol *S* represents the strain gauge on the transverse reinforcements and was installed at a location 15cm, 154 cm and 316 cm above the foundation.

5. TEST RESULTS

Fig. 7 shows the lateral load vs. drift ratio hysteretic loops of these two test columns under the excitation of the lateral cyclic loading. In which, figures (a) and (b) represent the results for the conventionally detailed specimen and the multi-spiral stirrup specimen, respectively. As can be seen, the lateral strength of the conventionally detailed one was around 2000 kN, and the strength degraded significantly at the second cycle of drift ratio 5%. Moreover, the strength continued to reduce to a low value of 1200 kN after the third cycle of 5% drift ratio. Thus the test ended at this moment. As for the multi-spiral stirrup specimen, the lateral strength of the specimen was also around 2000 kN as expected and there was no apparent strength degradation after the third cycle of drift ratio 5%. In consequence, a drift ratio of 8% along the push direction and 1% along the pull direction were sequentially conducted on this column. For the second cycle of drift ratio 8 %, the lateral strength of the column was degraded to a value around 1750 kN. For the third cycle, the lateral strength was degraded significantly to a value around 1200kN, which is lower than 80% of the specimen’s maximum strength. Therefore the test ended at this moment. This test result clearly verified that the column with interlocking multi-spiral confinement design exhibits higher ductility as compared to the column with conventional stirrup design, even though the spiral confinements took only 73% of the amount of confinement reinforcement for the conventional counterpart.



(a)



(b)

Figure 7. Experimental results (a) conventionally detailed column (b) proposed columns

The failure photos for the specimens are given in Fig. 8, where (a) and (b) respectively show the photos of the conventionally detailed column and the multi-spiral stirrup columns after the excitation of drift ratio 5%. Fig. 8(c) shows the failure photo of the multi-spiral stirrup column after the excitation of drift ratio 8%. By comparing Figs (a) and (b) at the same drift ratio 5%, the high ductility of the proposed column can be clearly observed. For the conventionally detailed column at the drift ratio of 5%, most of the longitudinal bars were buckled due to the failure of the hooks, whereas for the specimen with multi-spiral confinement design at the same drift ratio, even though the transverse reinforcement was exposed, but not the main reinforcing bars. Therefore, the proposed column shows a better ductility and its lateral strength did not degrade at this stage. After the excitation of drift ratio 8%, the fracture of some spiral reinforcements followed by buckling of the longitudinal bars can be seen in Fig. 8(c). The fracture of the spiral confinement was caused by the large lateral dilation of the concrete and the bearing of the buckled reinforcement against the spirals. Thus, the lateral strength declined to around 1200 kN at this moment. The superior confinement efficiency of the multi-spiral stirrup can further be clearly observed from the close-up photos given in Fig. 9. In which, figures (a) and (b) show the failure photos of the conventional column after the excitation of 5% drift ratio and proposed column after the excitation of 8% drift ratio, respectively. By comparing the photos for the north side, one can noted that for the traditional stirrup design, lateral dilation of concrete resulted in the failure of cross ties at the 90 or 135-degree bends of the stirrups and most of the hook of cross ties were open up. On the contrary, the 6-spirals and the core concrete in the spiral-confined column were found to be able to maintain in a satisfactory condition.

(a) (b) (c)

Figure 8. Failure photos for (a) the conventional column after drift ratio 5% (b) the proposed column after drift ratio 5% (c) the proposed column after drift ratio 8%

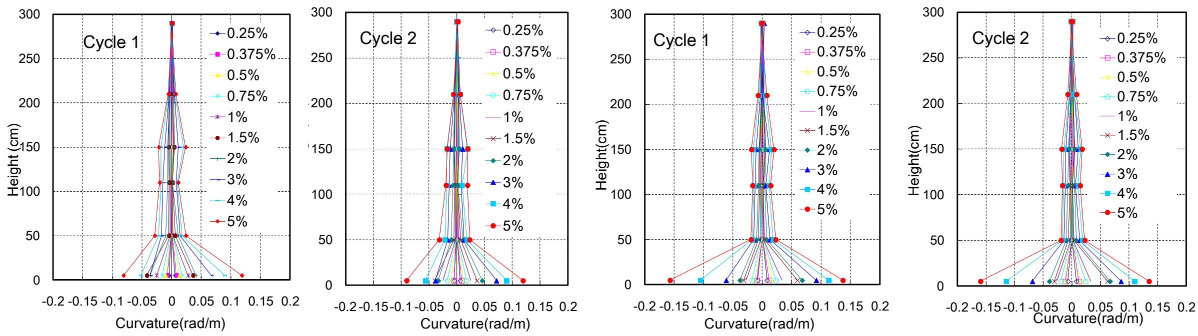
Fig. 10 (a) and (b) show the vertical distribution of the curvature in the potential plastic hinge region for each test column. The average curvature was obtained by taking the difference between the readings of two adjacent tiltmeters divided by the distance between them. It shows that failure was localized at the bottom of the column for both specimens. The curvature in the area outside the lower

30 cm region of the proposed column was smaller than that of the conventionally detailed column. This means that the damage occurred on the proposed column was less severe as compared to the conventional one. Fig. 11 shows the comparison of shear displacements between these two specimens. In which, the value of the vertical coordinates represents the percentage of the shear displacement with respect to the total displacement, and Figs. (a) and (b) represent the results for the loading applied along the south direction and north direction, respectively. As can be observed, the multi-spiral stirrup column has a little bit higher value of shear displacement than that of the conventional column. This is because the proposed column was reinforced with a lower amount of lateral reinforcing bars and thereby has a lower resistance to shear force. However, because the specimen is not a shear strength controlled column, this situation does not affect its overall performance under the cyclic loading. Fig. 12 (a) and (b) show the strain ratio of the transverse reinforcement for each specimen at the location 10 cm above the foundation. As can be seen, for the column confined by conventional hoops and cross ties, the cross ties along the loading direction were subjected to a higher value of strain. Thus, the hooks that were only have a 90 degree bends at the end of cross ties were likely to open up under the loading. On the other hand, for the column that was confined by multi-spirals, the highest strain occurred on the fringe of spirals. Because each spiral was bended from a continuous bar, it is not easy to open up during the excitation and therefore its confinement efficiency was better

South side North side South side North side

(a) (b)

Figure 9. Comparison of failure mode (a) conventional column for drift ratio 5% (b) proposed column for drift ratio 8%

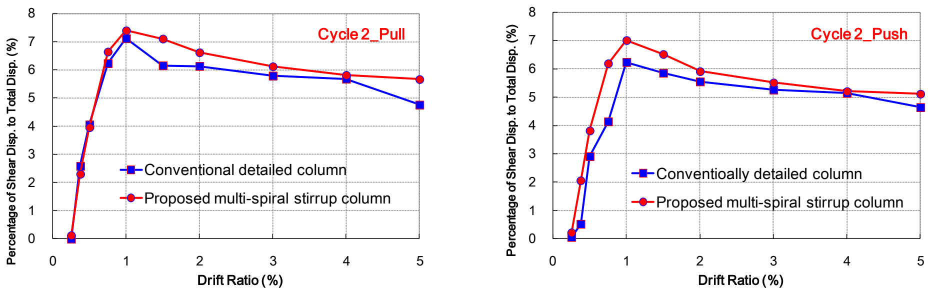


(a) (b)

Figure 10. Curvature distributions for different drift ratios (a) conventional column (b) proposed column

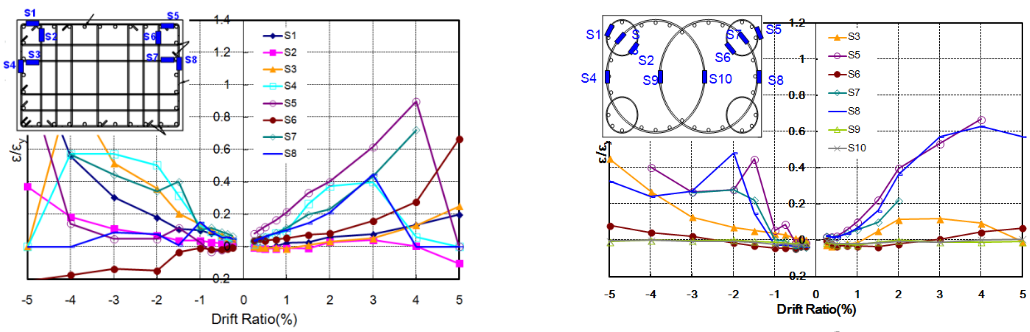
6. COMPARISON OF CONSTRUCTABILITY AND CONSTRUCTION COST

For the selection of a practical pier system, not only the seismic performance is an important issue, constructability as well as construction cost are also the decisive factors. Therefore, in this section, the constructability and the cost of the proposed columns were evaluated and discussed through the comparison with the conventionally detailed one. The construction work rate is the direct indicator for the efficiency of construction. As a result, the constructability of the proposed column with different procedures for the installation of spiral cage was compared with the conventionally detailed counterpart in the form of construction work rate and given in Table 6.1. Construction work rate, which is the product of the number of labour worker and the working time, represents the total amount of uninterrupted labor required to perform a task. As can be observed in Table 6.1, the construction work rate for the composite column is 358 man-hours for procedure (I), and 354 man-hours for procedure (II) and (III). These values are all lower than that of the conventionally detailed one, i.e., 407 man-hours. In other words, the construction work rate for the proposed column was around 87% of the conventional column. This information confirms that the construction efficiency of the proposed column is better than that of the conventional one. Table 6.2 shows the stirrup cost of specimens, where the cost includes material charges, processing charges and construction charges. As expected, the stirrup cost of the proposed column is only 54% of that of the conventional column. This is because the consumption of the lateral reinforcing bar for the column confined by the multi-spirals was much lower than that confined by cross ties and stirrup. Table 6.3 shows the total construction cost of specimens. It can be seen that cost of the total construction cost reduced by 6 % when the multi-spiral confinement was used instead of the conventional stirrups.



(a) (b)

Figure 11. Percentage of shear displacement to the total displacement for the second cycle of cyclic loading which was applied along: (a) the south direction (pull); (b) the north direction (push)



(a) (b)

Figure 12. Strain ratio on the lateral reinforcements at the location 10cm above the foundation: (a) conventional column (b) proposed column

It should be noted that the construction method for the specimen in current study was developed basically by combining existing technologies. This research adopted standard thread bar couplers to splice the reinforcing bars, for which the rotate of the adjoining bar is required. Therefore, the vertical reinforcing bars and the spiral cage have to be erected separately. In the future, if other types of coupler, for which the rotation of one bar is not necessary, are adopted, the vertical reinforcing bars and the multi-spiral stirrup cage can be pre-assembled together and erected together, thereby the construction efficiency can be further enhanced.

7. CONCLUSIONS

This paper proposes the multi-spiral stirrup bridge pier system. The most time-consuming and complicated work for the conventionally detailed bridge pier is the binding of the reinforcing bars.

Owing to the automation work of the pre-assembled multi-spiral cage which can be performed automatically in the prefabrication plants, the construction efficiency of the proposed system was proved to be better than that of the conventional one through a construction practice performed in this study. In addition, from the lateral cyclic loading test, it concluded that the seismic performance of the proposed column can not only reach the standard for the conventional RC column, its ductility can be even better than that of the conventional one. Moreover, because the usage of multi-spiral instead of rectilinear hoop and stirrups can greatly reduce the total amount of lateral reinforcements, the total cost of the proposed system is lower than that of the conventionally detailed one. Thus, in general, this study has demonstrated the advantages of the proposed multi-spiral stirrups pier system not only in ductility enhancement, but also in cost effectiveness and constructability improvement. This method with the interlocking multi-spiral confinement design offers an attractive and superior alternative to traditional stirrup confinement design of the conventional RC columns.

Table 6.1. Comparison of construction work rate (unit men-hour)

item	Conventional column	Multi-spiral stirrup column		
		Procedure I	Procedure II	Procedure III
Foundation	152.1	149.2	149.2	149.2
Lower part of the column	86	68.8	68.8	68.8
Middle part of the column	106.8	77.7	74	73.9
Upper part of the column	61.9	61.9	61.9	61.9
Total	406.8	358	354	354
%	100%	88.0%	87.0%	87.0%

Table 6.2. Comparison of the stirrup cost for the specimens (unit: NT dollar)

Items	Conventional column				Multi-spiral stirrup column			
	Processing charges	Construction charges	Material charges	Total	Processing charges	Construction charges	Material charges	Total
Foundation	583	2,422	7,284	10,288	546	1,042	4,905	6,493
Column	3,496	21,070	43,702	68,268	3,026	1,492	31,568	36,086
Total	4,079	23,492	50,985	78,556	3,573	2,534	36,473	42,579
Percentage				100%				54%

Note : based on procedure III

Table 6.3. Comparison of the construction cost for the specimens (unit: NT dollar)

Items	Conventional column				Multi-spiral stirrup column			
	Processing charges	Construction charges	Material charges	Total	Processing charges	Construction charges	Material charges	Total
Foundation	5,795	57,398	20,4021	267,214	5,795	57,398	204,021	267,214
Column	4,079	119,727	263,691	387,498	5,699	94,143	249,179	349,020
Total				654,711				616,234
Percentage				100%				94%

Note : based on procedure III

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