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SEISMIC PERFORMANCE OF AN INNOVATIVE STEEL AND REINFORCED CONCRETE COMPOSITE BRIDGE PIER

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ABSTRACT

Reinforced concrete is widely used for bridge piers in Taiwan. Due to the requirements of strength and ductility for seismic design of RC bridge pier, a large number of reinforcement is usually required. This tight arrangement of reinforcement not only complicates the construction works, it also increases the risk of construction during the erection of the large number of reinforcements. In order to reduce the construction risk due to the collapse of the large reinforcement cage, an innovative steel and reinforced concrete composite bridge pier, which replaces partial vertical reinforcement of the conventional RC pier by the H-shaped sectional steel, was proposed. For the newly developed composite pier, the sectional steel can not only provide the support for the stirrup cage and hold the longitudinal bars during construction, it can also enhance the confinement effect of the inner core concrete. Consequently, not only the construction safety can be improved, seismic performance of the proposed pier is also better than a conventional RC design. In this paper, the design of a 0.6 scaled model and the construction practice of the composite bridge column are described. In addition, experimental studies for the proposed system as well as a conventional RC column were conducted and tested at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan. By comparing the experimental results of the developed system with those of the conventionally detailed one, the high seismic resistance of the proposed pier in effect of ductile steel and good confinement provided by the stirrup cage and the steel section was confirmed.

Keywords: Composite bridge pier, cycling loading test, seismic performance, construction safety.

1. INTRODUCTION

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 bridge pier, a large number of reinforcement is usually required, especially for a railway bridge pier which has to support a heavy superstructure. With the increase in the size of the rebar cage, the risk of rebar cage collapse when it is lifted from the horizontal to the vertical position and before the concrete is cast increases too. The

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collapse of the pretied reinforcing-bar cage not only results in added costs, project delays, it sometimes causes injuries or death. Thus, the safe handling of reinforcing-bar cages during the erection process for a cast-in-place concrete bridge pier has become a crucial issue. Recently, to ease the worsening urban traffic and to integrate the metropolitan area transportation systems, the Taichung Metropolitan Area Elevated Railway Project has been planned and implemented by Railway Reconstruction Bureau in Taiwan. This project includes the construction of viaducts and bridges along the current railway lines. To reduce the construction risk during the erection of a large rebar cage and avoid jeopardizing the nearby railway line that is still running, an innovative steel and reinforced concrete composite bridge pier, which replaces partial vertical reinforcement of the conventional RC pier by the H-shaped sectional steel, was proposed. The flanges and the webs of two neighboring sectional steels can provide the support for the stirrup cage between them and to hold the longitudinal bars in position. In addition, the sectional steel can also reduce the bulging of rectilinear hoops which is often observed in the conventional rectilinear hoops and stirrups and thus enhance the confinement of the concrete core. In order to verify the constructability of the proposed method and to investigate the seismic performance of the proposed systems, large scale specimens for this system as well as a conventionally detailed system were constructed at the National Center for Research on Earthquake Engineering (NCREE) in Taiwan, followed by a cyclic loading test. 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.

2. SPECIMEN DESIGN

The prototype bridge is a railway bridge and located beside the railway line which is still running. In order to reduce the construction risk during the assembling and setup of the reinforcement cage, an innovative steel and reinforced concrete composite column was designed. The dimension of the prototype bridge pier is $3\text{m} \times 2\text{m}$ and reinforced with 208-D32 rebars and six A572 RH250 $\times$ 250 $\times$ 9 $\times$ 4 sectional steel. By such an arrangement, the steel ratio of the composite pier is 0.92 % for the rebar and 3.5 % for the sectional steel. The total steel ratio with respect to the rebar is 4.26 %. The composite pier was transversely reinforced with D19 perimeter hoops and internal stirrups spaced 15 cm (volumetric confinement ratio = 2.08 %).

Because this type of bridge pier has not been adopted in any practical application, a scaled model test was conducted at NCREE before the prototype bridge was constructed. 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 specimen column which was designed to have the same capacity of the composite test specimen was also constructed. Thus, a total of two 0.6 scaled specimens were designed and constructed at NCREE. One is a RC column with the conventional design details, and the other is the proposed steel and reinforced concrete composite column. The scaled specimens are 9 m in clear height with a cross section of 1.8m $\times$ 1.2m, as shown in Fig. 1(a). The design details of both specimens are also schematically shown in Fig. 1 (b) and (c), respectively.

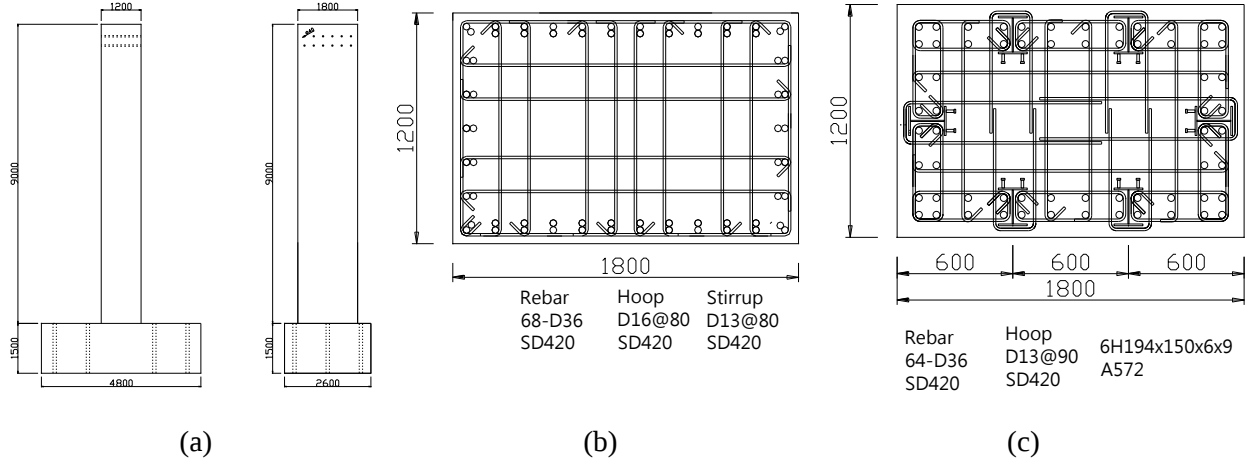


Figure 1: Design details of specimen (a) side view of the specimens (b) design details of the conventional column (c) design details of the proposed composite column

As can be observed in Fig. 1(b), the specimen with the conventional details was reinforced with 68-D36 SD420 rebars (steel ratio = 3.17%) and transversely reinforced with D16 perimeter hoops and D13 internal stirrups spaced 8 cm (volumetric confinement ratio = 2.06%). The steel and reinforced concrete composite column was reinforced with 64-D36 rebars and six A572 RH194×150×6×9 sectional steel. By such an arrangement, the steel ratio of the composite specimen is 2.98 % for the rebar and 1.06 % for the sectional steel. The total steel ratio with respect to the rebar is 3.86 %, which is larger than the conventionally detailed one. This is because the effective depth of the rebars and the steel section for the composite column is smaller than that of the benchmark conventional specimen. The composite column was transversely reinforced with D13 hoop and stirrup spaced 9 cm, as shown in Fig.1 (c), with a confinement ratio of 2.01%. The design of the transverse reinforcements for both specimens was based on current seismic design code for railway bridge in Taiwan (MOTC, 2007). For the composite column, to achieve a good bonding effect between the steel and the surrounding concrete two shear studs were also welded on the inner surface of each H sectional steel for every 20 cm in the potential plastic region and for every 1 m in the other region. In addition, in consideration of a larger concrete cover due to the existence of the H sectional steel, the north side of the pier was attached by a 4m high wire mesh. The nominated material properties for these specimens are as follows: concrete compressive strength is 350 kg/cm²; yield strength of both main reinforcement and transverse reinforcement is 4200 kg/cm²; the yield strength of the sectional steel is 3500 kg/cm².

3. CONSTRUCTION PROCESS

For the construction of the proposed composite column, the first step was the erection of the prefabricated segment of steel sections. The second step was the installation of the main bars and the erection of the hoop cage for the footing, followed by the binding of the foundation reinforcement. The third step was the setup of the formwork, and then the concrete was poured into the foundation. For the column above the foundation, the first step was the erection of scaffold,

followed by the installation of the pre-assembled hoop cage. Then after the installation of the U shape stirrups and the biding of the cross ties, the form work was setup and the concrete was poured. By repeating the process mentioned above for the column above the foundation for other two times, the construction was completed. In order to demonstrate the construction sequence of the proposed composite column, the construction photos are given in Fig. 2.



Figure 2: Construction photos

4. EXPERIMENTAL PROGRAM

In order to investigate the seismic performance of the proposed steel and reinforced concrete composite column, cyclic loading test were conducted on two specimens at NCREC. Fig. 3 illustrates the test setup. Twelve high tensile 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 top 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 $0.07A_g f_c'$. 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 8.5m up from the top of the footing. Displacement-controlled cyclic loading test was performed on these two specimens. Fig.4 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%, 5.0%, 8% and 9%. 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, due to the stroke limit of the actuators, the drift ratios 8% and 9% were only applied along the North (push) direction; while along the South (pull) direction, the applied drift ratios were only 1%. 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.5. Tiltmeters T1 to T7 were

mounted at distances of 10 cm, 50cm, 90cm, 130cm, 170cm, 150cm and 330cm above the foundation top. Displacement gauges L1~L12 were crossly mounted between the tiltmeters.

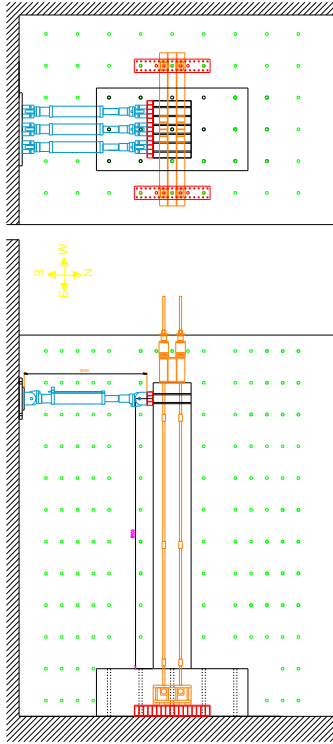


Figure 3: Schematics of experimental setups

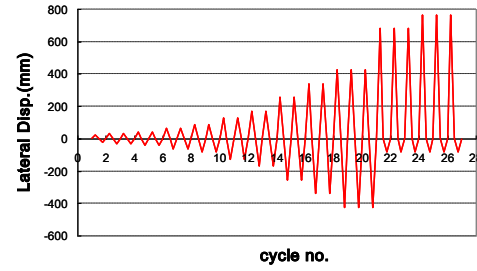


Figure 4: Loading protocol for the cyclic loading test

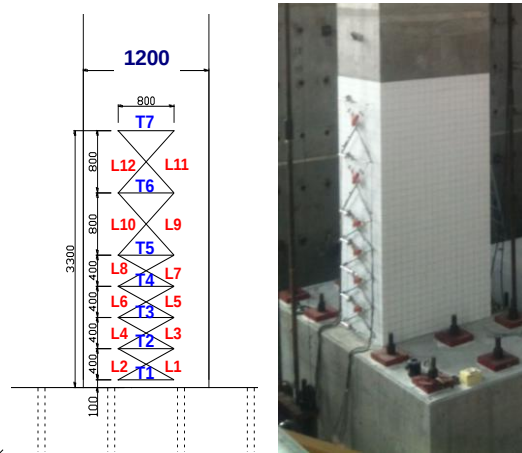


Figure 5: Arrangement of tiltmeters and LVDT displacement gauges

5. TEST RESULTS

Fig. 6 shows the hysteretic curves for the test columns under the excitation of the cyclic loading. As can be seen, the lateral strength of the conventional detailed column was a little bit lower than that of the composite column, but the difference is not much and both are around 2500 kN. The strength didn't degrade after the third cycle of the displacement corresponding to the drift ratio of 5% for both cases. Thus, a drift ratio of 8% and 9 % along the push direction and 1% along the pull direction were continuously conducted on the columns. After the third cycle of the displacement corresponding to the drift ratio of 8 % and 9%, the lateral strength of the column still did not degrade significantly. However, due to the limitation of stroke, the test ended after the third cycle of the displacement corresponding to the drift ratio of 9 %.

According to the strain values measured by the strain gauge as observed in Fig. 7, the vertical rebars of the proposed composite column started to yield at the drift ratio around 1.5 %. Thus, the corresponding displacement ductility for drift ratio of 9 % has reaches 6, a value higher than the assumed value in the design code.

Fig. 8 (a) and (b) show the vertical distribution of the curvature in the potential plastic hinge region

for each test column after the excitation of the second cycle and third cycle. 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 the curvature distributions for both columns were all similar and localized at the bottom of the column.

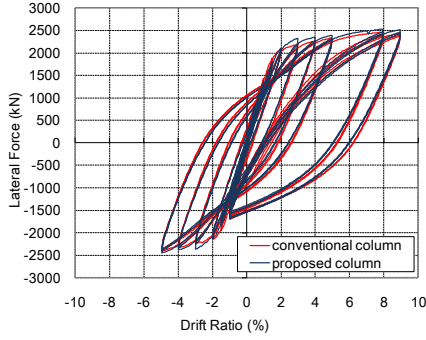


Figure 6: Experimental results

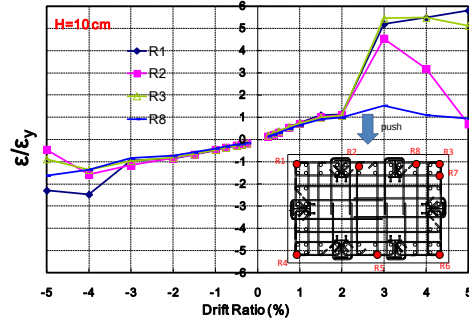
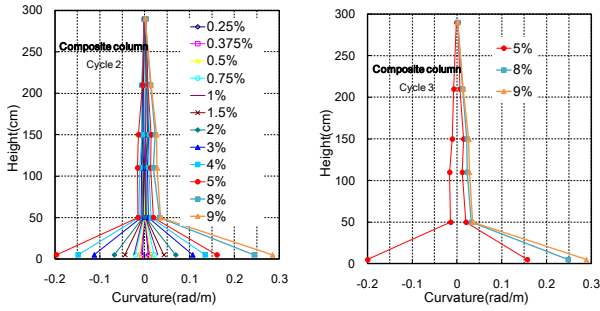
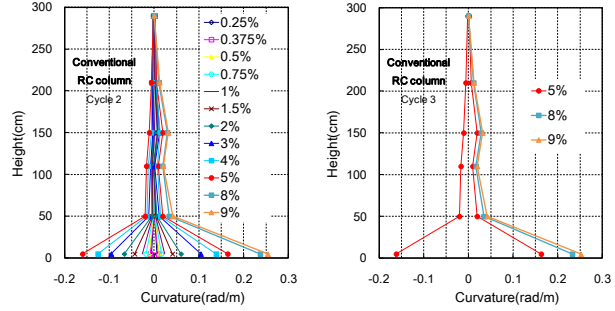


Figure 7: Strain ratio on the vertical reinforcement bar for the proposed column



(a) proposed column



(b) conventional column

Figure 8: Curvature distributions for different drift ratios

The failure photos for the specimens are given in Fig. 9, where (a) and (b) show the photos of the composite columns and the conventionally detailed column, respectively, after the excitation of drift ratio 9%. As can be seen, the transverse reinforcement on the south side of the composite column was partially exposed, but not that on the north side. On the north side, only the wire mesh was partially exposed. This observation suggests that the installation of the wire mesh for the composite column can mitigate the spalling of the thick concrete cover. Other observation can be found from these photos is that both the main reinforcing bars and the steel section for the composite column were not exposed at this stage, whereas for the conventional RC columns, both the transverse and vertical rebars were exposed. Moreover, the bulging of the rectilinear hoops caused by the large lateral dilation of the concrete was serious for the conventional RC column and resulted in the failure of cross ties at the 90 or 135-degree bends. Consequently, some of the hook of cross ties were open up and followed by buckling of the nearby longitudinal bars. Figure 10 shows the failure photos of the specimens after removing the surface fractured concrete. As can be seen, the sectional steel was slightly buckled, but the buckling was localized between the U shape stirrups for the composite column. This result indicates that the U shape stirrup had some contribution to provide

lateral support and mitigate the buckling of the steel section. In addition, most of the rectilinear hoop was still in its original position because of the confinement provided by the steel section. On the other hand, for the conventional RC column, both the rectilinear hoops on the south side and north side were bulged significantly. On the north side, the vertical rebars that were not hooked by the cross ties were buckled. On the south side, some of the cross ties were open up at the end and the nearby vertical rebars buckled seriously. Based on the observation from the failure photos shown in Fig. 10, it is highly likely that the 9 % drift ratio was the ultimate capacity of the conventional RC column, even though its lateral strength did not degrade significant at the end of the test at the drift ratio of 9 %.

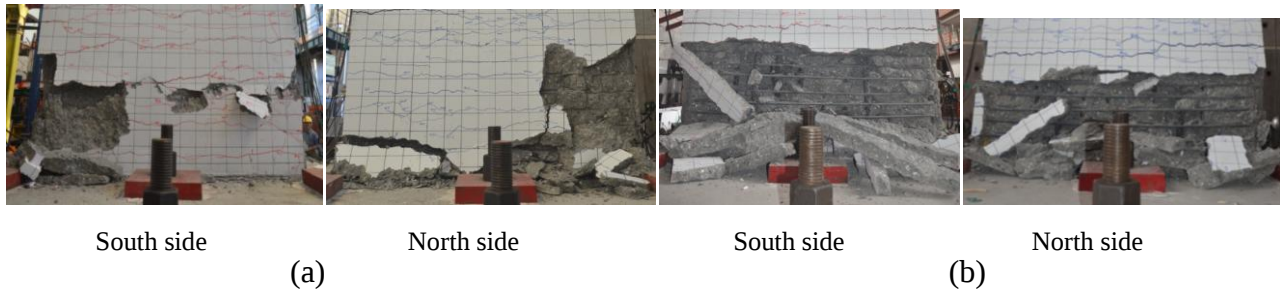


Figure 9: Comparison of failure mode (a) proposed pier (b) conventional pier



Figure 10: Comparison of failure mode (a) proposed pier (b) conventional pier

6. CONCLUSIONS

This paper proposes a steel and reinforced concrete composite bridge column. The proposed construction procedure was proved to be workable through a construction practice performed in this study. The instability of standing rebar cages can be mitigated because of the support provided by the steel section. In addition, from the cyclic loading test, it can be concluded that the seismic performance of the proposed composite column can not only reach the standard for the conventional RC column, it have a superior ductility under the cyclic excitation. The H-shaped steel section can provide effective confinement to prevent the bulging of the rectangular hoop that is often observed in conventional rectangular RC column. Thus, this method can be a good alternative to the conventional RC column to overcome the instability problem of the pretied reinforcing cage and to prevent piers collapse.

REFERENCES

MOTC. (2007), Seismic Design Code for Railway Bridges (in Chinese)