

Seismic Performance and Retrofit of Hollow Bridge Columns

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ABSTRACT

The seismic performance of hollow bridge columns has been studied by tests and analytical models, including flexural and shear strengths as well as ductility capacity. The period of this integrated research project is four years. This is the third year of this integrated research project. There are five sub-projects. All model tests and theoretical analysis were performed at the university of the principal investigator of each sub-project. The full-scale tests were held at the structural laboratory of the national center for research on earthquake engineering. Theoretically the flexural strength and ductility capacity were derived from the moment-curvature analysis, and the shear strength was analyzed by using the truss model. The good design of confining reinforcement for such columns was confirmed by tests. When this project is completed, the seismic performance of hollow bridge columns will be well understood, and the seismic retrofit can be applied to such columns.

INTRODUCTION

The high-speed rail project to improve Taiwan's transportation systems is an effort by the Taiwanese government to further the island's economic development. The planned route is 345km long, and the viaducts and bridges are approximately 207km long. Hence, there are many bridge columns in the project. To maximize structural efficiency in terms of the strength/mass and stiffness/mass ratios and to reduce

the mass contribution of the column to seismic response, it is desirable to use a hollow section with high-strength concrete for the columns. To consider both the ductility and workability, the configuration of lateral steel in the hollow columns used in the high-speed rail project of Taiwan (Fig. 1) is quite different from those studied in the past [1~7].

During the past three decades, various studies on the confinement effects of lateral steel in columns have

been conducted, and the analytical models for both normal strength concrete [8~18] and high strength concrete [19~22] have been proposed. It is not known that if any of the stress-strain models of confined concrete proposed in the past is appropriate for the hollow sections used in the high-speed rail project of Taiwan. Therefore, such hollow sections need to be studied by both tests and analysis.

In this integrated project, the title of each sub-project is shown below.

Sub-project 1: Flexural, shear, and retrofit tests of small-scale hollow circular reinforced concrete bridge columns [23].

Sub-project 2: Flexural, shear, and retrofit tests of small-scale hollow rectangular reinforced concrete bridge columns [24].

Sub-project 3: Analytical models of ductility capacity, and shear and retrofit strengths of hollow reinforced concrete bridge columns [25].

Sub-project 4: Flexural, shear, and retrofit tests of full-scale hollow reinforced concrete bridge columns [26].

Sub-project 5: Repair tests of hollow reinforced concrete bridge columns [27].

OBJECTIVES OF RESEARCH

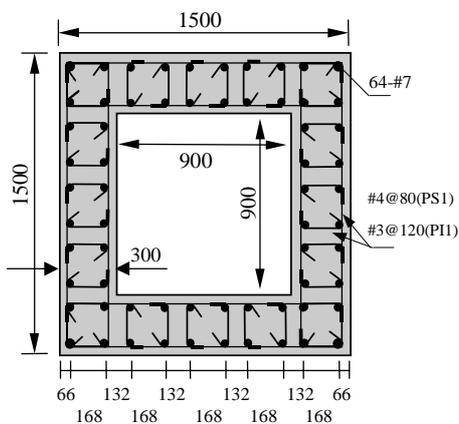
The purpose of this integrated project is eight-fold: (1) to study experimentally the flexural, shear, and retrofit performances of hollow rectangular and circular reinforced concrete bridge columns, (2) to investigate the constitutive models of confined concrete as affected by the configuration, spacing

and steel ratio of confinement reinforcement, as well as the compression/shear ratio, (3) to extend the applicability of the truss model for shear element to include such columns, (4) to evaluate the reduction of shear strength with increasing ductility factor, (5) to find a good method for seismic repair of such columns, (6) to develop a set of guidelines for seismic design, retrofit, and repair of such columns, (7) to develop a computer program that can predict the shear stress-shear strain relationship of hollow bridge columns with confined reinforcement, and (8) to develop a computer program that can perform seismic design, retrofit, and repair of such columns.

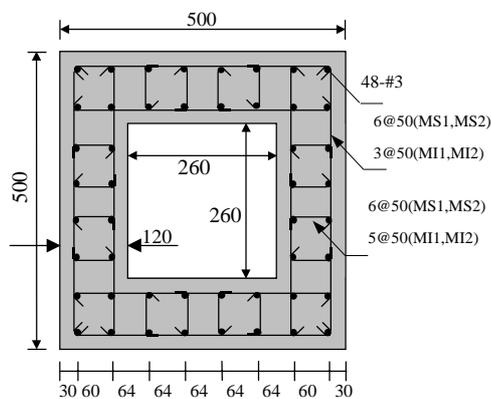
This wide range of goals can be achieved by using the structural research laboratory at the university of the principal investigator of each sub-project, as described above. First, hollow reinforced concrete bridge columns have been tested by the cyclic reversal loading system to determine the constitutive models of these columns. Second, after the constitutive laws of confined concrete is found, both the analytical models and a computer program for column analysis can be extended to include the descending portion of the force-displacement relationship, and the computer predictions and the design guidelines will be validated by both the full-scale and model tests.

EXPERIMENTAL PROGRAM

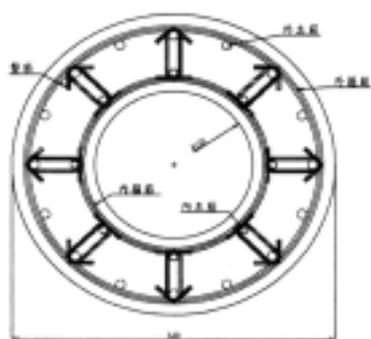
The cross-sections used in this integrated research project are shown in Fig. 1. Figure 1(a) indicates a full-scale rectangular section in sub-project 4, while Fig. 1(b) indicating a model



(a) Prototype — rectangular section



(b) Model — rectangular section



(c) Model — circular section

Fig. 1 Configurations of lateral reinforcement in hollow columns

rectangular section in sub-project 2. In contrast, Fig. 1(c) shows a model circular section in sub-project 1. It should be noted that both sections in Figs. 1(a) and 1(b) were used in sub-project 5, and that both rectangular and circular sections were employed in sub-project 3. Figure 2 shows the test setup of full-scale columns. The test setup of both rectangular and circular model columns was similar to Fig. 2. It can be seen from Fig. 2 that the column was subjected to a constant axial load at the top of the column and cyclically reversed horizontal loads at the free end of the column.

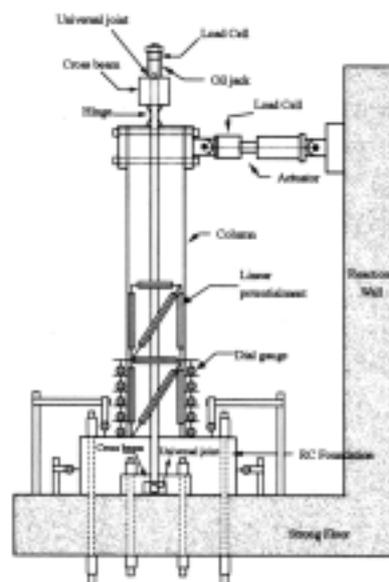


Fig. 2 Test setup of full scale columns

RESEARCH FINDINGS

The research findings from each sub-project in the third-year period are described below.

Sub-project 1:

- (1) When damaged columns were repaired by CFRP sheets, their

ductilities could be developed, as shown in Figs. 3 to 5. In addition, shear failure and rebar buckling were not taken place.

- (2) The ultimate displacements and flexural capacities of FRP-repaired columns were about 50% to 60% and 10% to 20%, respectively, greater than those of original columns.
- (3) The stiffness of repaired columns was less than that of original columns because columns cracked before repair, and were subjected to cyclic reversal loads.
- (4) The dissipated energy of repaired columns was about 50% to 100% greater than that of original columns. Hence, FRP-repaired columns could provide much better seismic performance.
- (5) The ultimate displacement of FRP-repaired columns was about 8 to 9 times of the yield displacement of original columns. Hence, the ductility of FRP-repaired columns could reach 8 to 9 if columns were wrapped by FRP sheets before damage.

Sub-project 2:

- (1) An analytical model was developed to predict the moment curvature curve of cross sections and the lateral load displacement relationship of hollow rectangular columns that were FRP-retrofitted.
- (2) When the FRP-retrofitted columns were satisfied with the lateral reinforcement requirements of the 1995 ACI code, the developed analytical model could be applied to find the behavior of such columns with acceptable accuracy.

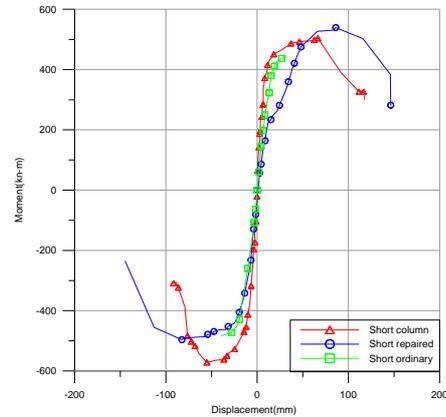


Fig. 3 Enveloped moment-displacement curves of short columns

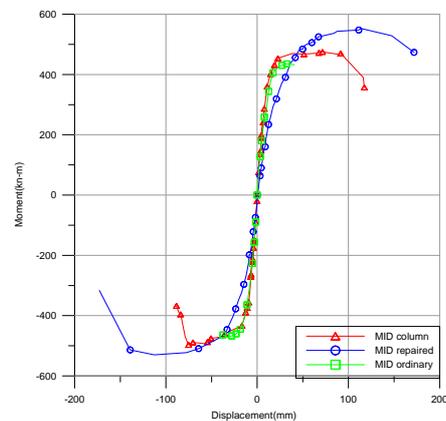


Fig. 4 Enveloped moment-displacement curves of middle height columns

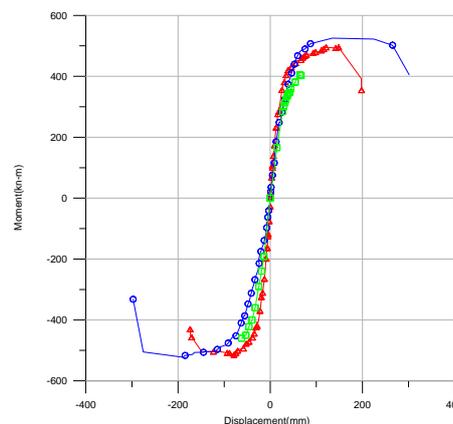


Fig. 5 Enveloped moment-displacement curves of long columns

- (3) The enveloped moment-curvature curve of each of all specimens is shown in Figs. 6 and 7. When compared to the analytical results, it was found that Modified Kent and Park Model for confined concrete generally provided better results.
- (4) When a specimen with insufficient shear reinforcement was FRP-retrofitted, the failure mode of the specimen could change from brittle shear failure to ductile flexural failure.
- (5) When a specimen without lateral reinforcement was FRP-retrofitted, the FRP sheet of the specimen subjected to both a constant axial load and horizontally reversed cyclic loads could be outward, resulting in falling of the spalled concrete in the plastic hinge region of the specimen.

Sub-project 3:

- (1) In the column analyses there were three cases, namely, Case 1 with code-required confinement reinforcement, Case 2 with 50% of code-required confinement reinforcement, and Case 3 with 50% of code-required confinement reinforcement and the remaining 50% replaced by steel plate. Using these three cases a parametric study was performed. The primary parameters include thickness of steel plate, axial force, and opening size of section, etc.
- (2) With flexural failure the ductility of columns could be determined by using moment curvature method, and the corresponding shear capacity at different ductility factor was found by the softened truss model.
- (3) In Case 1, the ductility capacity was very good, and increased with increasing confinement reinforcement. The shear strength was less than that calculated by Priestley's formula. Shear failure could be taken place in some columns.
- (4) In Case 2, both the ductility capacity and the shear strength were reduced dramatically. In addition, all columns had shear failure.
- (5) In Case 3, both the ductility capacity and the shear strength were not less than those for Case 1. However, the retrofitted hollow circular columns were exception because the confining effect from steel plate was valid only

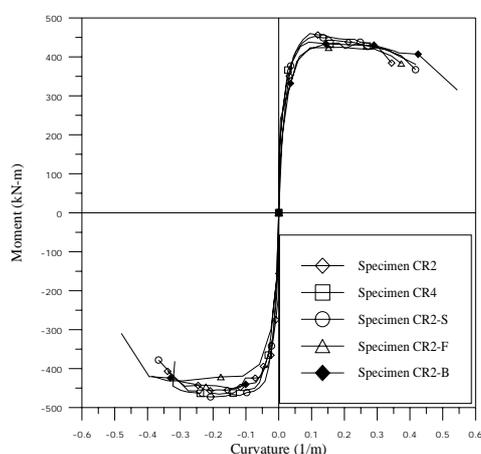


Fig. 6 Moment-curvature curves of FRP-retrofitted columns

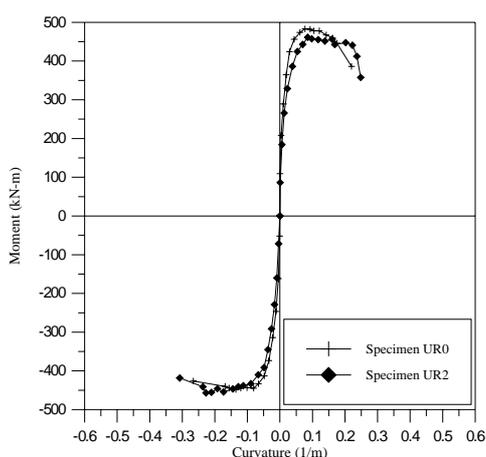


Fig. 7 Moment-curvature curves of non-retrofitted columns

in the tangential direction, and was invalid in the radial direction.

Sub-project 4:

- (1) The specimen, used in the high-speed rail of Taiwan and designed according to the 1995 ACI code, has acceptable seismic performance because its displacement ductility factor can reach 9.9, and its failure mode is flexure.
- (2) The specimen, with both insufficient lateral reinforcement and lap splice at the plastic hinge region, should not be used in design because it has much lower ductility due to premature bond failure.
- (3) The specimen, with insufficient lateral reinforcement, has flexure and shear failures. Its ductility is less than that of specimen failed by flexure because its plastic hinge could not be fully developed.
- (4) The horizontal load-displacement relationship of each of all three full-scale specimens is shown in Fig. 8. The proposed analytical model can well predict the load-displacement relationship of hollow circular bridge piers with flexure failure. The prediction accuracy for

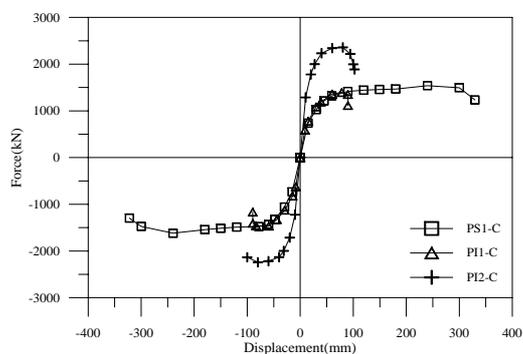


Fig. 8 Horizontal load-displacement curves of full scale columns

the specimen with bond failure or flexure and shear failures needs to be improved.

Sub-project 5:

- (1) A repair method was developed by using the following techniques. (a) Original broken rebars were replaced with new rebars. (b) Damaged columns was wrapped by steel plate to provide confining stress. (c) Spalled concrete was replaced with strength-developed early and non-shrinkage concrete. The damaged columns could be repaired within a week. The horizontal load-drift curve of each of the repaired columns is compared to that of the original columns, as shown in Fig. 9.
- (2) The flexural strengths of the repaired columns reached at least 90 percent of the original strength. The ultimate displacements of the repaired columns became greater. However, the ductility factor was not increased because the yield displacement also became greater.
- (3) To keep the concept of strong beam and weak column, the flexural capacity of the repaired column should not be greater than that of the original column.

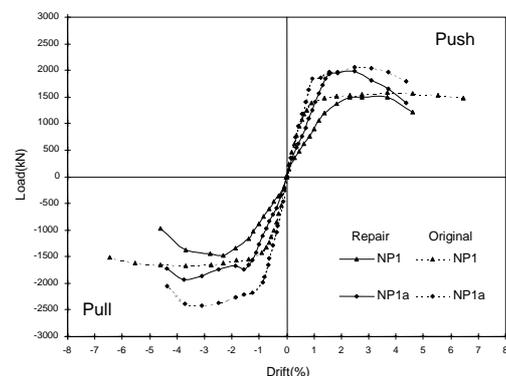


Fig. 9 Horizontal load-drift curves of original and repaired columns

- (4) When a column was only slightly damaged, such as slightly buckling of rebars and spalling of concrete cover, the repaired column could maintain the original flexural capacity. However, its ductility reduced significantly.

CONCLUSIONS

75% of this integrated research project has been finished. Both rectangular and circular hollow columns have been tested and analyzed during the past three years. The flexural, shear, and retrofit behaviors of such columns have been investigated. Detailed research results can be found from the research report of each sub-project [23~27]. Guidelines for flexural, shear, and retrofit designs of rectangular and circular hollow columns to resist earthquake forces are being developed, and will be completed in a year.

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