

1. Abstract

This study investigated retrofit measures for improving the seismic performance of cruciform-shaped columns in the Aurora Avenue Bridge located in Seattle, Washington. Tests on column specimens representing as-built conditions resulted in shear failures at modest displacement levels, accompanied by severe strength and stiffness degradation. Tests on column specimens retrofitted with FRP jacketing resulted in improved performance compared to that obtained for the as-built column specimens. It was found that the FRP jacket needs to be anchored in the reentrant corners of the cruciform-shaped columns to be effective. In addition, the FRP jacket does not provide adequate confinement to prevent flexural hinge degradation. The final retrofit design incorporating reentrant corner anchorage and grout-filled steel collars at the plastic hinge regions produced a ductile flexural response.



Figure 1. Aurora Avenue Bridge in Seattle.

2. Aurora Avenue Bridge

The George Washington Memorial Bridge (commonly referred to as the Aurora Avenue Bridge) is a cantilever truss bridge that carries Aurora Avenue North over the west end of Seattle's Lake Union (see Figure 1). It is owned and operated by the Washington State Department of Transportation (WSDOT). The bridge was constructed in 1932, thereby completing the final link of U.S. Highway 99 from Canada to Mexico. Currently the bridge has an estimated Average Daily Traffic (ADT) of over 100,000 vehicles. The bridge was added to the national register of historic places in 1982.

The approach structures feature cruciform-shaped concrete columns (Figure 2) that were determined to be deficient in shear. Retrofit using fiber reinforced polymer (FRP) wrapping retrofit was selected to maintain the historic character and overall aesthetic appeal of the bridge by keeping the original cruciform shape of the columns. The testing program reported here was performed to verify the effectiveness of FRP wrapping for improving shear performance in cruciform-shaped columns.



Figure 2. Cruciform-Shaped Bridge Column.

3. Test Specimens

The specimens were constructed to be representative of the cruciform-shaped columns present in the Aurora Avenue Bridge. The experimental tests were conducted on 1/3-scale specimens that modeled the dimensions, reinforcement, detailing, and material properties of the tapered columns in the bridge.

A summary of the details for the test specimens is given in Table 1. Two column specimens were tested without any retrofitting to reveal vulnerabilities present in the existing columns and to establish benchmarks for evaluating the effectiveness of the applied retrofit measures. All other columns were wrapped with carbon FRP fabric with primary fibers oriented in the horizontal direction. One retrofitted column was tested without reentrant corner anchorage to evaluate whether such anchorage was necessary to fully engage the FRP jacket. Reentrant corner anchorage was provided for the other two retrofitted columns using different anchorage methods.

The test setup for the column specimens consisted of a stiff loading frame connecting the column loading stub to a horizontal double-acting actuator aligned at the point of zero moment, inducing double bending in the column specimen. Horizontal loads were applied to the test specimens under displacement control based on a pattern of progressively increasing displacements.

Table 1. Specimen Test Parameters

| Specimen | Test Parameter |
|----------|---|
| Column 1 | As-built |
| Column 2 | FRP jacket without reentrant corner anchorage and no hinge confinement |
| Column 3 | FRP jacket with angle and steel inserts for corner anchorage and no hinge confinement |
| Column 4 | FRP jacket with FRP inserts for corner anchorage and confinement in top and bottom hinges |
| Column 5 | As-built - repeat of Column 1 |



Figure 3. Testing Setup.

4. Results for As-Built Column Specimens

Columns 1 and 5 were representative of the as-built conditions in the columns in the Aurora Avenue Bridge. The overall response of the two as-built column specimens was essentially the same, with early shear cracks forming followed by flexural cracks forming at the top and bottom of the column. Yielding of the transverse reinforcement occurred near the peak lateral force level followed by opening of large shear cracks (Figure 4). The final failure mode was a shear failure with modest ductility. Load-displacement hysteresis curves for Column 5 are given in Figure 5.



Figure 4. As-Built Column Shear Failure.

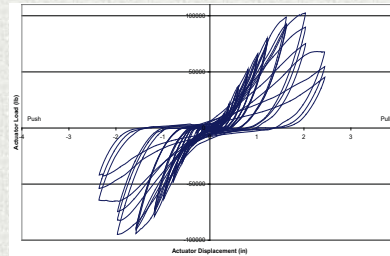


Figure 5. As-Built Load-Displacement Curves.

5. Results for Retrofit Column Specimens

Columns 2, 3 and 4 were identical to the as-built Columns 1 and 5 except that they were retrofitted with an FRP jacket. Column 2 was tested without reentrant corner anchorage to evaluate whether such anchorage was necessary to achieve the required strength from the FRP jacket. Reentrant corner anchorage was provided for Columns 3 and 4 using two different anchorage methods.

Column 2 exhibited slightly improved energy dissipation capacity and ductility as compared with those for the as-built columns (see Figure 6). Initially, no shear distress was observed in the column. After cycling several times near the peak load, the FRP jacket began to pull away from the reentrant corners at the top and bottom of the column, resulting in a significant decrease in the lateral load. Removal of the FRP jacket after testing revealed that the final failure mode for the column was in shear.

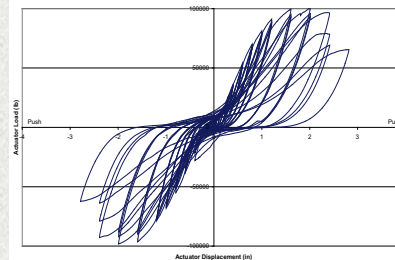


Figure 6. Column 2 Load-Displacement Curves.

Column 3 was identical to Column 2 except that the FRP jacket was anchored in the reentrant corners of the column with bent steel plates anchored to the column using epoxy anchors. Column 3 showed improvement in the overall cyclic response with significant enhancement of energy dissipation and displacement capacity (Figure 7). Failure in Column 3 was caused by bulging of the FRP jacket in the plastic hinge regions, leading to flexural hinge degradation and reentrant corner anchorage failure (Figure 8).

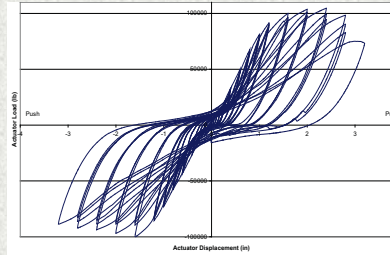


Figure 7. Column 3 Load-Displacement Curves.

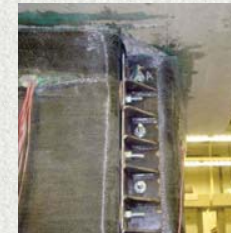


Figure 8. Bulging of FRP Jacket in Column 3.

Column 4 was identical to Column 2 except that the FRP jacket was anchored in the reentrant corners of the column with FRP anchors over the full-height of the column (Figure 9). The column also incorporated steel collars at the top and bottom of the column to restrain bulging from plastic hinging.



Figure 9. Column 4 During Testing.

Column 4 retrofitted with a FRP jacket with reentrant corner anchorages consisting of FRP anchors along with steel collars in the hinging regions provided the best cyclic response (Figure 10). Good energy dissipation along with a ductile response was achieved. Failure in Column 4 occurred due to extensive flexural hinging leading to low-cycle fatigue fracture of several of the longitudinal reinforcing bars.

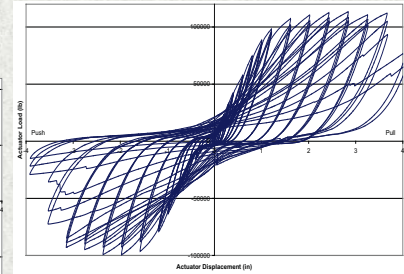


Figure 10. Column 4 Load-Displacement Curves.

6. Summary of Test Results

A summary of various characteristics for the column specimens is presented in Table 2. Listed characteristics include the effective secant stiffness and shear force corresponding to the first yield of the longitudinal reinforcement, the maximum observed column shear strength, the maximum displacement ductility and drift ratio attained at the maximum response, and the total amount of energy dissipated throughout testing.

Table 2. Summary of Column Results

| Column | V_y | Δ_y | K_y | V_{exp} | Δ_{max} | μ_{Δ} | % Drift | E_{total} |
|--------|-------|------------|-------|-----------|----------------|----------------|---------|-------------|
| 1 | 26.8 | 0.44 | 61 | 98 | 2.5 | 5.6 | 3.8 | 290 |
| 2 | 48.5 | 0.53 | 91 | 101 | 2.8 | 5.3 | 4.3 | 400 |
| 3 | 50.4 | 0.62 | 81 | 105 | 3.2 | 5.2 | 4.9 | 490 |
| 4 | 55.6 | 0.59 | 94 | 113 | 4.0 | 6.8 | 6.1 | 650 |
| 5 | 48.7 | 0.54 | 90 | 103 | 2.2 | 4.1 | 3.3 | 300 |

7. Conclusions

The results of this study show that FRP jacketing is effective at providing the required shear strength enhancement to prevent a brittle shear failure. The FRP jacket needs to be anchored into the reentrant corners of the column in order to be effective. In addition, due to the cruciform shape of the columns, the FRP jacket does not provide adequate confinement to develop ductile flexural hinging in the column. A steel collar filled with high-strength grout was effective at providing the required confinement. The final retrofit design incorporating both reentrant corner anchorage and steel collars produced a ductile flexural response. Both the steel bent plates with epoxy anchors and the FRP anchors were effective at anchoring the FRP jacket at the reentrant corners of the column. However, the FRP anchors did not significantly alter the appearance of the bridge columns and were significantly easier to install.

8. Acknowledgements

Funding for this project was provided by the Washington State Department of Transportation. The contributions and technical assistance provided by Brian Aldrich and Chyuan-Shen Lee of the WSDOT Bridge Office are appreciated.