COMPARATIVE STUDY ON SEISMIC PERFORMANCE OF CIRCULAR CONCRETE COLUMNS STRENGTHENED WITH BFRP AND CFRP COMPOSITES

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ABSTRACT

Basalt fiber is expected to be widely applied in civil engineering for its fine mechanic performance, good stability and comparatively low price. However, there is still little research on the aspect concerning with the application of basalt fiber in civil engineering. Comparative test on the seismic performance of circular concrete columns strengthened with basalt fiber reinforced polymer (BFRP) and carbon fiber reinforced polymer (CFRP) was conducted. The influence of fiber type and fiber amount on the strengthening effect was discussed. Test results show that BFRP and CFRP can both obviously improve the seismic performance of circular concrete columns, and more, BFRP has higher ratio of performance to price.

KEYWORDS

circular concrete columns, continuous basalt fiber, seismic retrofitting, ductility

INTRODUCTION

The use of fiber reinforced polymers (FRP) represents an innovative and effective technology for strengthening, retrofitting and upgrading of existing concrete structures due to their much more beneficial characteristic such as high strength and stiffness to weight ratio, high corrosion resistance, electromagnetic neutrality, inherent tailor ability and ease of application in the field (Seible 1997). The popular FRP composites used in structural engineering is CFRP, GFRP and AFRP. Among them CFRP is most used, but the price of CFRP is still very high now. Although the price of GFRP and AFRP is low, their mechanics property are not good. The durability of GFRP and AFRP used in some stern environment is not satisfied.

Continuous basalt fiber (CBF) is a kind of high-tech fibers developed in the former Soviet Union about 30 years ago, using natural lava as raw materials. The lava is broken and then melt in furnace with the temperature of 1450 ~ 1500 °C, after drawing platinum and rhodium alloy plate made of leakage continuous fiber. Basalt fiber reinforced polymer (BFRP) has a lot of advantages comparing with CFRP, AFRP and other FRPs, such as excellent mechanical properties, high temperature compatibility and large working temperature scope between -269 to 700 °C, acid alkali - resistant, anti-UV properties, low hygroscopicity, better environment adaptability. So it has great development prospects, especially in the last few years. Now China has the batch quantity production ability and begin to promote the use of the CBF (Hu 2005; Wu 2007).

COMPARISON BETWEEN CFRP AND BFRP

The mechanical properties of CFRP and BFRP were determined by testing. The average tensile strength of CFRP sheets is about 3500MPa, the average elastic modulus is about 235GPa, and average the ultimate strain is 1.50%. BFRP-1 is a kind of early stage production, which is used in this experiment. The average tensile strength of v sheets is about 1835MPa, the average elastic modulus is about 92GPa, and average the ultimate strain is 1.99%. BFRP-2 is the new production developed recently, the tensile strength is 2332MPa, average elastic modulus is about 106GPa, and average the ultimate strain is 2.40%.
The elastic modulus of CFRP is higher than that of BFRP, which is an advantage in flexural retrofitting RC beams. But the ultimate strain of BFRP is higher than that of CFRP, this advantage can be regarded in RC columns retrofitting to enhance the seismic performance. This paper is focused on investigating the effectiveness and efficiency of improving the seismic performance of RC columns strengthened with BFRP and CFRP composites.

EXPERIMENTAL PROGRAM

Four large-scale reinforced concrete columns were constructed and tested to investigate the retrofit effectiveness of the FRP jacketing systems. As shown in Fig.1, the 1000mm-tall and 360mm-diameter model columns were reinforced with 12 deformed No.25(nominal diameter=25mm, yield stress is 382MPa obtained from tensile coupon tests) bars that constituted a longitudinal steel ratio of 5.8% of the gross area of column section. Round No.6(diameter=6.5mm, yield stress is 320MPa obtained from tensile coupon tests) hoops spaced at 150 mm were used as transverse reinforcement. The average strength of concrete was 34.9MPa by the test of cylinders made at the same time with columns. The axial load was 1200kN. The region of 100mm from the stub face was strengthened with additional eight D25mm bars, and the D10mm ties were placed at a spacing of 30 mm within this region to minimize the chances of failure at the section of the stub face(Gu 2006). All the specimens were tested under constant axial load and cyclic lateral excursions simulating seismic loading conditions, as shown in Fig.2.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>FRP treatment</th>
<th>Thickness of FRP (mm)</th>
<th>Axial load (kN)</th>
<th>Axial load ratio</th>
<th>Aspect ratio</th>
<th>Character value of FRP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL0</td>
<td>As built</td>
<td>—</td>
<td>1200</td>
<td>0.39</td>
<td>1.94</td>
<td>0</td>
</tr>
<tr>
<td>CL1</td>
<td>1.0 CFRP</td>
<td>0.167</td>
<td>1200</td>
<td>0.39</td>
<td>1.94</td>
<td>0.217</td>
</tr>
<tr>
<td>CL2</td>
<td>4.5 CFRP</td>
<td>0.752</td>
<td>1200</td>
<td>0.39</td>
<td>1.94</td>
<td>0.977</td>
</tr>
<tr>
<td>CL3</td>
<td>BFRP</td>
<td>2.0</td>
<td>1200</td>
<td>0.39</td>
<td>1.94</td>
<td>1.212</td>
</tr>
</tbody>
</table>

One of these four specimens was used as control column. Two columns was wrapped with CFRP, One was wrapped with 1 layer of CFRP composite straps, and the other was wrapped with 4.5 layer of CFRP composite straps. The forth specimen was wrapped with 12 layers of CBF fiber composite. The total thickness of CBF is 2mm. The thickness of CBF is determined according to the same confined stiffness (Wu 2006) with the 4.5 layer of CFRP. As the strap was wrapped around the column, epoxy was applied to the surface and the multiple layers of the strap were adhered together to form a single composite wrap with the desired thickness. The main object of this experiment is to study the seismic performance of RC circular columns retrofitted with different FRPs.

A hydraulic jack with a capacity of 3000kN was used to apply the axial load that was measured by a load cell. The cyclic lateral load was applied by an actuator with a 1000kN load capacity and a 200 mm stroke capacity. The load cycles were divided into two phases: load control and displacement control. Load control phase was used up to yielding of the longitudinal bars, beyond that point, a displacement control load sequence was used. The lateral load sequence consisted of three cycles each to \( \Delta_y \), \( 2\Delta_y \), \( 3\Delta_y \), and so on, until the specimen was unable to maintain the applied lateral load. Deflection \( \Delta_y \) was defined according to the method advised by Xiao, 1999. The displacement ductility \( \mu \) is defined as the ratio of displacement to the yield displacement \( \Delta_y \).
RESULTS AND DISCUSSION

Load-versus-displacement Response

The test results are shown in Table 2. The ultimate displacement is the displacement when the columns failed or the displacement corresponding to the lateral load which dropped 85% to the maximum load. The drift ratio is the ratio of ultimate displacement to the column height. The result listed in the table is the average value in the push and pull loading cycles. Plots of the lateral load-versus-displacement for the specimens are shown in Fig.3.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Maximum load (kN)</th>
<th>Improvement</th>
<th>Ultimate displacement (mm)</th>
<th>Drift ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL-0</td>
<td>425</td>
<td>—</td>
<td>7.0</td>
<td>0.010</td>
</tr>
<tr>
<td>CL1-1.0C</td>
<td>568</td>
<td>33.2%</td>
<td>18.0</td>
<td>0.022</td>
</tr>
<tr>
<td>CL2-4.5C</td>
<td>680</td>
<td>59.9%</td>
<td>56.9</td>
<td>0.071</td>
</tr>
<tr>
<td>CL3- BF</td>
<td>669</td>
<td>57.3%</td>
<td>57.4</td>
<td>0.072</td>
</tr>
</tbody>
</table>

Fig.3(a) shows hysteresis loops for CL0 exhibiting a brittle shear failure mode. As is apparent from hysteresis loops, strength and stiffness degradation is particularly severe. Fig.3(b) shows hysteresis loops for CL1 exhibiting a shear failure mode with limited ductility. It can be found that in the Fig.3(c) (d) that stable flexural hysteresis loops with peak lateral loads exceeds the shear force corresponding to the ideal flexural strength of the retrofitted section. In further loading, suddenly degradation in strength and stiffness occurred. Diagonal cracks at the sides of the units caused loss of aggregate interlock capacity of concrete. The reduction in the strength of the concrete shear resisting mechanisms caused a demand for further contribution from CFRP, which could not be provided because the amount of CFRP used is not enough. Coupled with this, the CFRP ruptured at the sides of the unit, and then the specimen suffered shear failure. Inverse to CL1, CL2 and CL3 produced a fully ductile response. The enough FRP used in these two specimens can provide the shear strength loss in concrete. Local FRP ruptured within the plastic hinge region was noted in the experiment. At the last, FRP can not provide enough confinement to the concrete in the hinge region, and subsequently the specimens failed. Comparison of hysteresis loops of CL2 and CL3 shows that CFRP and BFRP both can improve the seismic performance of RC circular columns efficiently.

Jacket Strain Response

Strain gauges were mounted on the composite along its circumferential direction during testing. In the four directions, from 150 mm above the base, four strain gauges were mounted every one 50mm.

Fig. 4 shows the strain distributions of CL2 along the column height on the face parallel to the loading direction corresponding to the push displacement at peak. As shown in the Fig.4, jacket strains increase significantly corresponding to the increased ductility levels. This indicates the increased engagement of shear resistance from the composite jacket following the decrease of shear resistance contributions of the original RC mechanisms. The larger strains near the column ends also implied the confinement effect of the jacket on concrete. Fig. 5 shows the strain at the middle height on specimen CL3 according to the displacement. When the displacement comes to zero, the residual strain increases significantly corresponding to the increased displacement. Fig. 6 shows the strain distributions of CL1 and CL2 along the column height on the face parallel to the loading direction corresponding to the push displacement equals 18mm. As can be seen in the Fig.6, the column which suffered ductile shear failure, such as CL1, the strain at the middle portion is significantly large than the strain at the lower portion of the column, and the FRP firstly ruptured at the middle portion.
Fig. 3 shows the relationship of the average strain of the three gauges at the middle portion of the column on the face parallel to the loading direction at peak displacement in push. When the FRP used is not enough, such as CL1, FRP cannot provide enough shear strength to compensate the reduction in the strength in the concrete shear resisting mechanisms. So the strain increased significantly corresponding to the increased displacement. To avoid this type of failure, more FRP is needed. The added FRP can bear the shear force directly, and also it can provide efficient confinement to concrete to prevent the loss of aggregate interlock capacity of concrete. As can be seen in the Fig. 7, when the FRP is added, the strain increases slowly with the increased displacement. This relationship of specimen CL3 which is retrofitted with BFRP is very similar to the specimen CL2 retrofitted with 4.5 lays of CFRP.
Energy Dissipation Ability

Plots of the lateral load-versus-displacement for the specimens are shown in Fig.3. It can be seen that the as built Specimen CL0 exhibits a brittle shear failure mode with very limited displacement ductility and energy dissipation ability. Specimen CL1 retrofitted with one layer of CFRP, improved displacement ductility and stable hysteresis loops indicate that CFRP can improve the seismic performance of RC circular columns. But this specimen is still controlled by shear failure mode because the FRP used is not enough. In contrast, in specimens CL2 and CL3, the shear failure was completely prevented. Excellent performance, such as significantly increase of ductility and energy dissipation ability shows the efficiently improvement of seismic performance with composite jackets for the retrofitted columns. The energy dissipated by the columns can be evaluated by the area of covered by the horizontal force-displacement envelopes curve. Here the area of every displacement cycle is calculated to study the energy dissipation ability of CL2 and CL3. As shown in Fig.8, the area of per cycle of CL2 and CL3 is almost identical before the displacement comes to 48mm where the load-carrying capacity both drops for the two specimens. The strength degradation of CL3 is a little slowly than CL2, which shows that BFRP can also have the same energy dissipation ability with CFRP under the same lateral confinement stiffness.

Fig.9 shows the equivalent viscous damping $\beta$ of CL2 and CL3. It is also can be seen that the equivalent viscous damping $\beta$ of CL3 is slightly more than CL2 beyond the displacement ductility $\mu = 4.0$, which shows the good energy dissipation ability of CL3.

Comparison of the Economical Efficiency

According to the experiment result, CL3 have the same seismic performance with CL2. We can calculate the price of the FRP used to compare the economical efficiency of these two types of FRP. The total area of 4.5layer of CFRP used in CL2 is 2.46m$^2$. The price of per m$^2$ of CFRP is about 220 yuan/¥/m$^2$, so the total price of CFRP is about 542 yuan. The total weight of CBF used in CL3 is about 1.70kg. The price of CBF is about 60000 yuan/T now, so the total price of CFRP is about 102 yuan. The economical efficiency of CBF is higher than CFRP in seismic retrofitted of circular columns.

CONCLUSIONS

According to this experiment, BFRP can be used efficiently to improve the RC circular seismic performance.
The retrofitted columns can have the same or even better performance than the columns retrofitted with CFRP. Considering the low price of basalt fiber, it is believed that continuous basalt fiber can have a good prospect in seismic retrofitting of RC columns.

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