SEISMIC BEHAVIOR AND DAMAGE EVALUATION OF SELF-SENSING CONCRETE-FILLED FRP/FRP-STEEL COMPOSITE TUBULAR COLUMNS FOR BRIDGE PIERS

X. Yan[1], H. Li[2] and J.P. Ou[2,3]

[1] *PhD Candidate, School of Civil Engineering, Harbin Institute of Technology, Harbin. China*
[2] *Professor, School of Civil Engineering, Harbin Institute of Technology, Harbin. China*
[3] *Professor, School of Civil & Hydraulic Engineering, Dalian University of Technology, Dalian, China*
Email: yanxin66hrb@hit.edu.cn

ABSTRACT:
Two concrete-filled fiber reinforced polymer (FRP) tubular (CFFT) columns and two concrete-filled FRP-steel composite tubular (CFST) columns, as well as a control reinforced concrete column, were prepared to investigate the seismic behavior of them as bridge piers. The columns were subjected to a constant axial load and a pseudo-static lateral load. To monitor the axial deformations of the inner concrete under the cyclic loading, two optic fiber Bragg grating (FBG) strain sensors were pre-embedded in the top of every CFFT and CFST columns. They were arranged parallel to the longitudinal axis of the column and at the two ends of the horizontal axis along the direction of the lateral load. Moreover, each column also included two FBG strain sensors and two electric resistance (ER) strain gauges embedded in the inter-ply of FRP for CFFT or the interface between FRP and steel for CFST, to monitor the hoop deformations of the tube. The embedded sensors made the column have the ability of self-sensing, and the deformations of the column under the combined axial and lateral loads were recorded in real time. The results showed that the lateral loading resistances for the CFFT and CFST columns were much higher than the RC column. Moreover, the composite columns both behaved excellent earthquake resistance ductility and the CFST columns achieved better energy dissipation. Based on the monitoring data, the deteriorations of the composite column at different stages were detected and a seismic damage evaluation method was presented.

KEYWORDS:
Composite column, Fiber reinforced polymer, Seismic, Pseudo-static, Self-sensing, Damage evaluation

1. INTRODUCTION

As a natural disaster, earthquake is a great threat to human lives and infrastructures. In the 1994 Northridge earthquake (USA) and the 1995 Kobe earthquake (Japan), many reinforced concrete bridge piers were damaged severely [1-2]. In the recent great Wenchuan earthquake (China), the direct economic loses in infrastructures (highway, bridge and tunnel) reached about RMB67 billion Yuan. Bridges suffered the most severe damages, and about 6140 bridges were damaged. The damages of bridges not only led to large economic loses, but also blocked the advances of the succors and vehicles to the rural disaster area. Therefore, increasing the earthquake resistance of bridges becomes an essential and important work that insures the safe of lifeline construction.
Fiber reinforced polymer is composed of high strength fibers with corrosion resistant resin matrix. For its advantages of high stiffness to weight ratio, enhanced fatigue life, corrosion resistance, controllable thermal properties, part integration, tailored properties, non-magnetic properties and lower life-cycle costs, FRP has successfully been used in civil infrastructure in the past ten-odd years [3-4]. The concept of concrete-filled FRP tubular column for new construction was firstly presented by Mirmiran and Shahawy. The composite system includes a filament-wound FRP tubular shell and a concrete core. Uniaxial compression test indicated that the FRP tube significantly increases the strength and ductility of concrete [5]. However, the structure behaves brittle failure with the sudden rupture of the FRP tube at its limit hoop tensile strength. Therefore, the concrete-filled FRP-steel composite tubular column was developed in this study. It consists of a concrete core reinforced with

an exterior FRP-steel composite tube. The composite tube can be prefabricated at the factory through winding continuous fibers on the exterior surface of a thin-wall steel tube in the form of hoop. In this system, the FRP-steel composite tube can provide sufficient axial stiffness as permanent construction formwork. Uniaxial compression test showed that the structure behaved a ductile failure.
The purpose of this paper is to study the earthquake resistance of the new concrete-filled FRP-steel composite tubular structures as bridge piers. At the same time, it is intended to find a way to evaluate the seismic damages of the FRP composite columns based on the self-sensing data from the structures.

2. EXPERIMENTS

2.1. Specimens Details

The test specimens include two concrete-filled GFRP tubes (CFFT), two concrete-filled GFRP-steel composite tubes (CFST) and one reinforced concrete column as comparison. The size of the GFRP tube is 1580mm height and 150mm inner diameter. It was filament-wound with E-glass fibers/epoxy resin in the hoop direction with 5 plies (0.385mm per ply). The E-glass fibers used are RO99 2200 P122 manufactured by Beijing Saint-Gobain Vetrotex Glass Fiber Co. Ltd. And the matrix is normally-used diphenol propane epoxy resin solidified by the diethylene triamine. The volume percentages of the fibers and epoxy are 45% and 55%, respectively. The GFRP-steel composite tube has the same size with the GFRP tube. It was filament-wound with E-glass fibers/epoxy resin in the hoop direction on the exterior surface of a thin-wall steel tube. The steel tube is commercially available with a wall thickness of 1.8mm and yield strength of 181MPa. And the confinement effectiveness of it is approximately equal to that of 2-ply GFRP tube. So the GFRP tube filament-wound on the steel tube is 3 plies with 0.385mm per ply, to achieve the same confinement effectiveness of the GFRP-steel composite tube with the GFRP tube.
After the fabrication, each tube was assembled with two reinforced concrete column heads at its two ends, to form a test column. The column has a total height of 1600mm and a clear height of 550mm as shown in Figure 1. The composite tubes were fully embedded into the reinforced concrete column heads with only 10mm left from the top and bottom surfaces of the column head. The longitudinal bars of the column head cross the tubes to insure the perfect rotate restraint to the composite column.

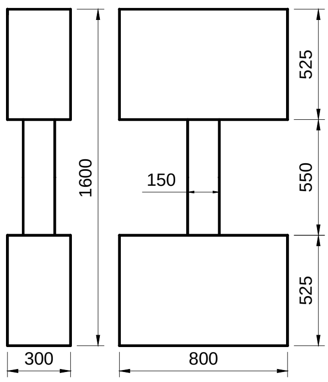


Figure 1 Size of test column

After the column assembly, concrete with 28-day cylinder strength of 63.7MPa was filled into the composite columns. As comparison, one reinforced concrete column with the same size was fabricated at the same time. The column has 4 longitudinal bars with a diameter of 12mm, and hoop reinforcements at intervals of 60mm. The longitudinal ratio of reinforcement of the column is 2.56%. The details of the test specimens are shown in Table 2.1.
To achieve the self-sensing ability, two optic fiber Bragg grating (FBG) strain sensors were pre-embedded in the interlaminations of the 2nd ply and the 3rd ply of the GFRP tube and the interphase between the GFRP tube and

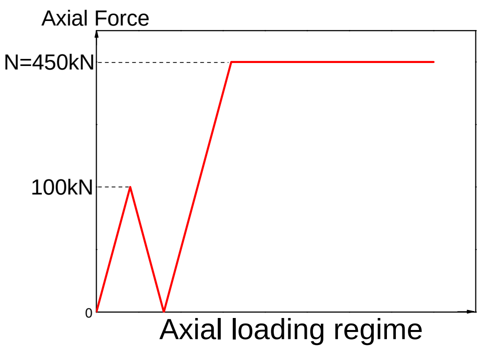
the steel tube in the hoop direction. The sensors lie on one side center of the column and up and down 10mm from the column head, to monitor the hoop strain changes of the column ends. In the corresponding side of the column, two electric resistance (ER) strain gauges were also embedded. Moreover, to monitor the axial strain changes of the concrete core, two FBG strain sensors for each composite column were pre-embedded on both sides of 10mm to the top interface between the column and the column head along the horizontal force direction.

Table 2.1 Outline of details of the test specimens

Specimen	Type	Number	Steel tube	GFRP tube
CFFTn4	concrete-filled GFRP tube	1	N/A	1.925mm/5 plies/0.385mm per ply
CFFTn6		1	N/A	1.925mm/5 plies/0.385mm per ply
CFSTn4	concrete-filled GFRP-steel tube	1	1.8mm	1.155mm/3 plies/0.385mm per ply
CFSTn6		1	1.8mm	1.155mm/3 plies/0.385mm per ply
RCn4	reinforced concrete	1	N/A	N/A
Specimen	Winding mode	Compression ratio	Shear span ratio	Confinement coefficient
CFFTn4	$[90]_5$	0.4	1.83	0.341
CFFTn6	$[90]_5$	0.6	1.83	0.341
CFSTn4	$[90]_3$	0.4	1.83	0.344
CFSTn6	$[90]_3$	0.6	1.83	0.344
RCn4	N/A	0.4	1.83	N/A

2.2. Test Setup and Loading Regime

The specimens were tested on the four bar linkage mechanism. They were first applied a sustained axial load. In this study, two axial compression ratios were selected, that is 0.4 $f_{co}^{'}$ and 0.6 $f_{co}^{'}$ as shown in Table 2.1. The axial loads are 450kN and 675kN, respectively, corresponding to the cylinder compressive strength of the concrete core of 63.7MPa. Then the specimens were applied reciprocating horizontal lateral loads with the loading method of force-displacement double-control. Before the yielding of the specimen, the horizontal loads were controlled by force. Once the specimen suffered yielding, the horizontal loads were then controlled by displacement until the damage of the specimen. The loading regimes are shown in Figure 2.



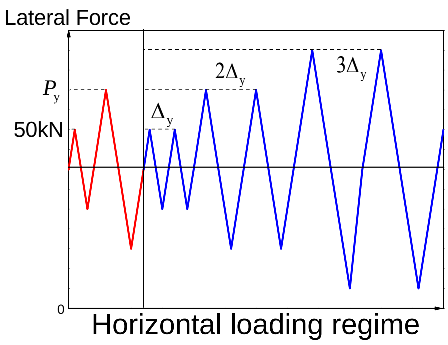


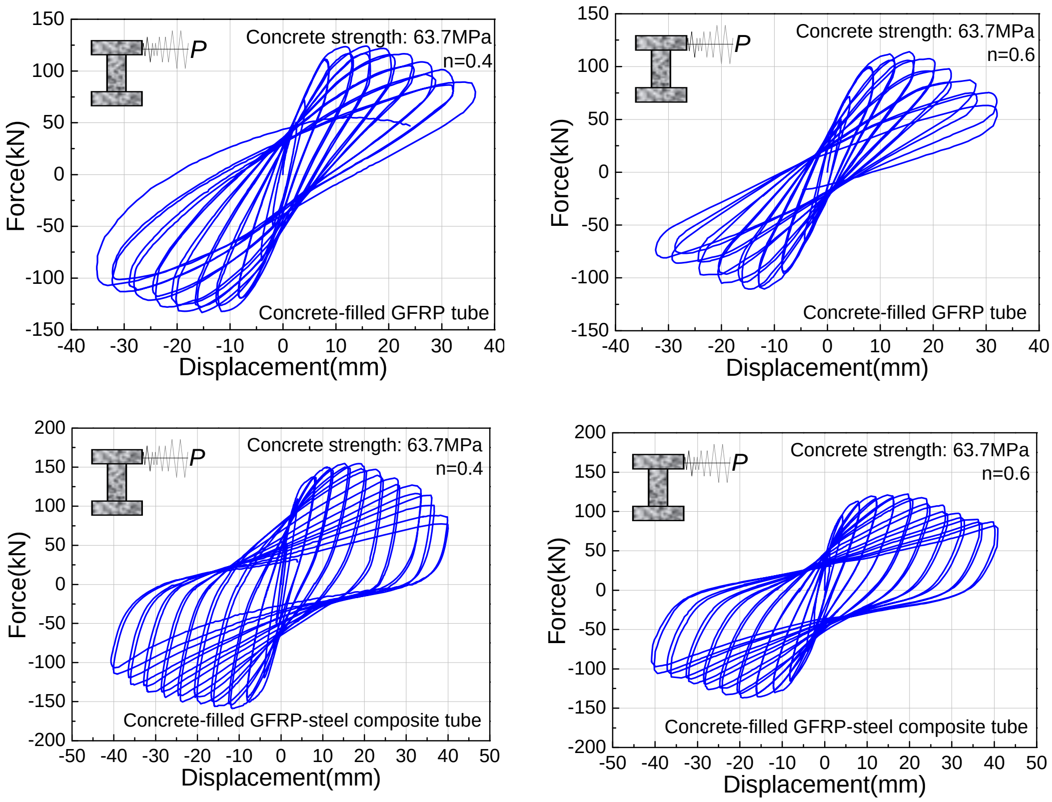
Figure 2 Loading regimes

3. RESULTS AND DISCUSSION

3.1. Damage Modes

Under the combined actions of the sustained axial load and the reciprocating lateral load, all the specimens behaved shear failure, distinctly for the reinforced concrete column. With the increasing in the lateral loads, axial diagonal cracks occurred continuously at the two ends of the RC column and developed to the column center. At failure of the column, the concrete at the two ends of the column behaved shear spalling and formed different shear spalling surface, as shown in Figure 3(a). However, there was no obvious phenomenon indicating the shear failures of the concrete-filled GFRP tubular columns and the concrete-filled GFRP-steel composite tubular columns. With the increasing in the lateral loads, both types of the composite columns appeared fracture of the GFRP tubes from the two ends of the column to its center. Even when the column lost its lateral loading bearing, it only appeared GFRP tube fracture at its ends and especially for the CFST specimens that the buckling of the steel tube at the ends of the column, as shown in Figure 3(b, c). Post loading, the composite columns were removed the composite shell. Axial diagonal cracks were found formed in the concrete core, and appeared a distinct shear failure, as shown in Figure 3(d).

Figure 3 Damage modes



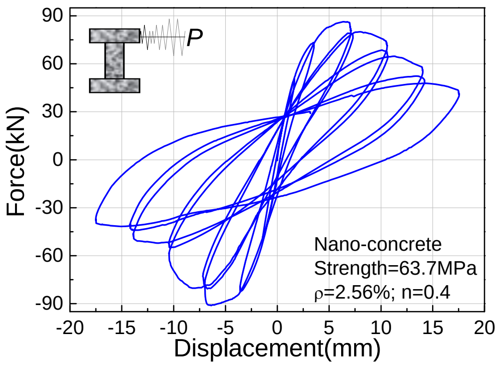


Figure 4 Hysteretic curves

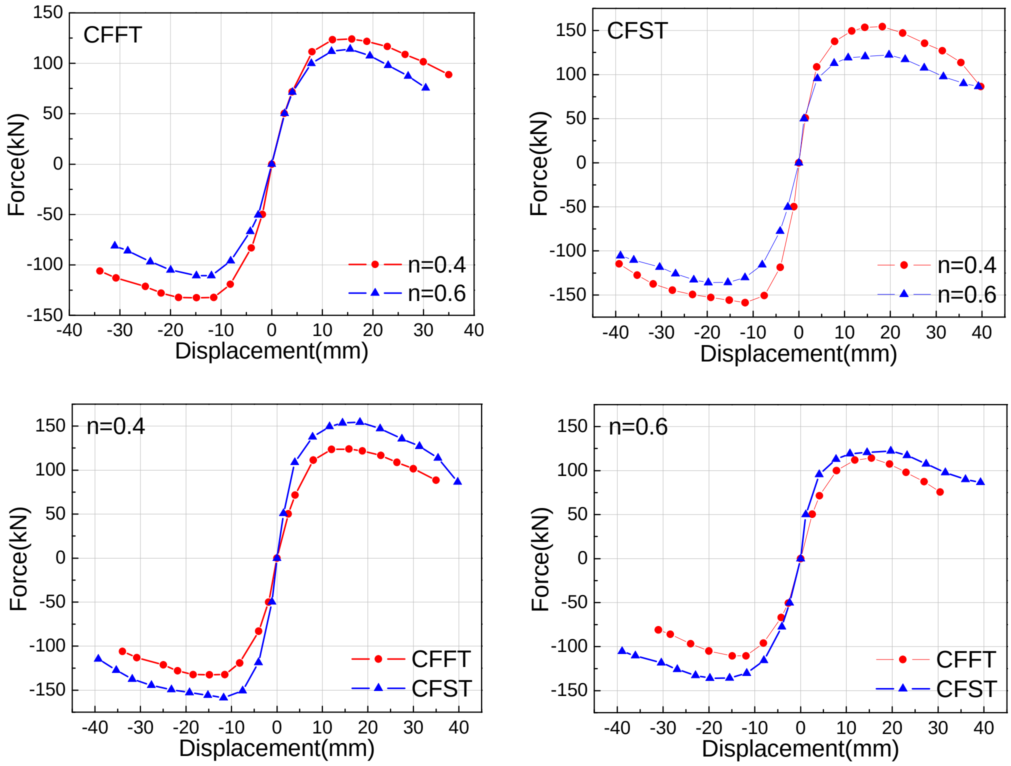


Figure 5 Skeleton curves

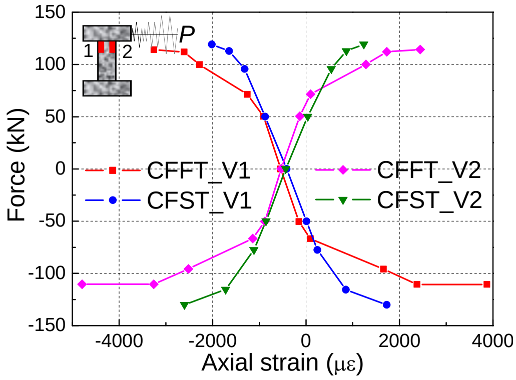


Figure 6 Axial strain changes of concrete core monitored by FBG sensors

3.2. Hysteretic Curves

Figure 4 shows the test force-displacement curves for all the specimens, and the composite columns behaved much better load bearing, ductility and energy dissipation than the reinforced concrete column. Under the same axial compressive ratio, the CFST specimens achieved better energy dissipation than the CFFT specimen. For the same type of composite columns, the ability of energy dissipation of the structure decreased with the increase in the axial compressive ratio.

3.3. Skeleton Curves

Figure 5 shows the comparisons of the skeleton curves for the composite columns. The CFFT specimen behaved obvious decrease in lateral load bearing and ductility with the increase in the axial compressive ratio. The CFST specimen behaved the similar trend in the lateral load bearing ability, but its ductility suffered few changes. As compared with the CFFT specimen, the CFST specimen had higher lateral load bearing and ductility at any axial compression level.

3.4. Self-sensing of Axial Strains

The embedded FBG strain sensors made the composite columns have the ability of self-sensing. Figure 6 shows the axial strain changes of the concrete core for CFFT and CFST specimens monitored by the embedded FBG strain sensors. Under the pure axial loading, the CFFT and CFST suffered axial strains of -537με and -425με. It indicated that the CFST specimen has a higher axial modulus. With the increase in lateral loading, the concrete core of CFFT specimen behaved higher increase in axial strain, which indicated that the deeper decrease in axial stiffness of the specimen.

4. DAMAGE EVALUATION BASED ON SELF-SENSING

During a moderate earthquake, bridge piers will be damaged severely. Even though they are not collapse, the piers will be in danger. Damage evaluation needs to be conducted on the deteriorated piers and repair should be carried based on the damage evaluation results. In this study, a damage evaluation method on the composite structures was presented based on the self-sensing data from the structures. Herein, a frame for the method will be introduced below, and the detail of the method is in proceeding.

For a newly constructed composite pier, its initial status will be recorded by the embedded FBG strain sensors when it is applied sustained axial service load. Not only in the daily use but also during the earthquake, the hoop strain changes in the composite tubes and the axial strain changes in the concrete core can both be recorded in timing or real-time. Based on these strain data, the changes in mechanical properties of the composite tubes and the concrete core can be evaluated and the damage status of the structures can then be assessed. At present, a finite program is being established for the damage evaluation.

5. CONCLUSIONS

In this paper, the seismic behavior of concrete-filled GFRP/GFRP-steel composite tubular columns was investigated. The composite columns behaved excellent lateral load bearing, ductility and energy dissipation as compared with reinforced concrete column. The composite structures also obeyed the rule that the lateral load bearing, ductility and energy dissipation decrease with the increasing of axial compression ratio. As a newly developed structure, the CFST specimen behaved better lateral load bearing, ductility and energy dissipation than the CFFT specimen. Self-sensing strain data indicated that with the increase in lateral loading, the CFST specimen behaved a lower decrease in axial stiffness.

Based on the self-sensing hoop and axial strain data, a method was presented to evaluate the damage of the composite structures under earthquake. Further work will be focused on the detail of the damage evaluation method and the corresponding finite program is being constructed.

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REFERENCES

1. Lee, D.H., Choi, E. and Zi, G. (2005). Evaluation of Earthquake Deformation and Performance for RC Bridge Piers. *Engineering Structures* **27**: 1451-1464.
2. Kawashima, K. (2000). Seismic Performance of RC Bridge Piers in Japan: an Evaluation after the 1995 Hyogo-ken Nanbu Earthquake. *Progress in Structural Engineering Materials* **2**: 82-91.
3. Karbhari, V.M. and Zhao, L. (2000). Use of Composites for 21st Century Civil Infrastructure. *Computer methods in applied mechanics and engineering* **185**: 433-454.
4. Hollaway, L.C. (2003). The Evolution of and the Way Forward for Advanced Polymer Composites in the Civil Infrastructure. *Construction and Building Materials* **17**: 365-378.
5. Mirmiran, A. and Shahawy, M. (1997). Behavior of Concrete Columns Confined by Fiber Composites. *Journal of Structural Engineering* **123(5)**: 583-590.