Construction and Building Materials 136 (2017) 217–229

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Experimental investigations on reinforced concrete shear walls strengthened with basalt fiber-reinforced polymers under cyclic load

Dejian Shen [a,b,c,*], Qun Yang [a,b], Yang Jiao [a,b], Zhenghua Cui [a,b], Jinyang Zhang [d]

[a] College of Civil and Transportation Engineering, Hohai Univ., No. 1, Xikang Rd., Nanjing 210098, China
[b] Jiangsu Engineering Research Center of Crack Control in Concrete, No. 1, Xikang Rd., Nanjing 210098
[c] China State Key Laboratory for Disaster Reduction in Civil Engineering, Tongji Univ., No. 1239, Siping Rd., Shanghai 200092, China
[d] Anhui and Huai River Water Resources Research Institute, No. 771, Zhihuai Rd., Bengbu 233000, China

HIGHLIGHTS

- The seismic performance of RC shear walls strengthened with BFRP was investigated.
- The final secant stiffness increased for strengthening with BFRP strips.
- The energy dissipation capacities increased for strengthening with BFRP strips.
- The shear strength of strengthened walls was obtained based on Strut-and-Tie model.

ARTICLE INFO

Article history:
Received 23 July 2016
Received in revised form 24 October 2016
Accepted 21 December 2016
Available online 19 January 2017

Keywords:
Reinforced concrete shear walls
Basalt fiber-reinforced polymer
Strengthening
Cyclic load
Hysteretic loop
Stiffness characteristic
Strut-and-Tie model
Load carrying capacity

ABSTRACT

Reinforced concrete (RC) shear walls are common lateral load resisting systems used in many RC structures. In the seismic region, the effectiveness of fiber-reinforced polymer (FRP) externally bonded reinforcement is today widely recognized with respect to enhancing the behavior of RC shear walls, particularly of those not satisfying the requirements of modern seismic codes. Although a number of studies have been concentrated on the RC shear walls strengthened with FRP, the investigations on the RC shear walls strengthened with basalt FRP (BFRP) are relatively limited compared with RC shear walls strengthened with carbon FRP or glass FRP. Six RC shear wall specimens with an aspect ratio of 1.6, characterized as medium-rise, were subjected to cyclic load to investigate failure modes, displacement ductility ratio, stiffness characteristic, energy dissipation capacity, and load carrying capacity. One of them was tested without any strengthening as a reference specimen and the other five specimens were strengthened using BFRP strips with different configurations. The theoretical load carrying capacity was also calculated and compared with the test results. The test and theoretical results show that: (1) use of BFRP strips significantly improved the seismic performance of RC shear wall under cyclic load; (2) the final secant stiffness of specimens SHW1-SHW5 increased by 55.2%, 10.3%, 13.8%, 17.2%, and 37.9% compared with that of reference specimen SHW0; (3) the final cumulative dissipated energies of specimens SHW1-SHW5 increased by 37.5%, 175.3%, 134.2%, 153.7%, and 95.2% compared with that of reference specimen SHW0; (4) the calculated load carrying capacity of the RC shear walls based on the Li's method showed a good agreement with the test results.

1. Introduction

Reinforced concrete (RC) shear walls are commonly used in high-rise buildings to resist lateral loads such as winds and earthquakes [1]. Their benefits such as high load carrying capacity and high energy dissipation make them an attractive alternative in the construction of high-rise buildings particularly in areas of seismic activity. However, one of the main problems limiting their practical application is stiffness degradation during an earthquake event. As results, strengthening approaches for RC shear walls including the use of thin steel sheet or fiber-reinforced polymer (FRP) [2–7], and the use of steel/FRP hybrid system [8] have increasingly developed. It has been proved that bonding of FRP sheets on RC shear walls is the most cost effective alternative in

* Corresponding author at: College of Civil and Transportation Engineering, Hohai Univ., No. 1, Xikang Rd., Nanjing 210098, China.

E-mail addresses: shendjn@163.com (D. Shen), yangqun19930209@163.com (Q. Yang), m15150683285@163.com (Y. Jiao), cocozhenghua@163.com (Z. Cui), jyjy60085@vip.sina.com (J. Zhang).

http://dx.doi.org/10.1016/j.conbuildmat.2016.12.102
0950-0618/

strengthening buildings in a very short time [9]. The use of thin steel sheets indeed improves the bending and vibration characteristics of walls, however, FRP materials improve even more as a result of better flexibility [2]. More recently, the use of FRP for strengthening existing buildings has been drawn attention, due to the low weight-strength ratio, short installation periods, corrosion resistance, and low intervention on the structures [10,11]. The load carrying capacity and durability of structures can also be improved effectively.

Investigations on the behavior of RC members with externally bonded FRP jackets have mainly concentrated on either carbon FRP (CFRP) or glass FRP (GFRP) last decades. Two key issues have a considerable influence on seismic performance of strengthened walls, involving the configuration of FRP strips and anchor system between FRP strips and concrete surface. X-shaped, U-shaped, lateral and parallel or combination of them are widely adopted in [12–16]. Results reported in [16] show that the best performance for the improvement of lateral displacement capacity and load carrying capacity of RC shear walls has been obtained from the strengthening with lateral strips. At present, epoxy is used to bond FRP materials to the exterior surface of concrete, however, it is commonly reported that the FRP strips debond from the surface prior to fracture under cyclic load. Despite of FRPs' high ultimate strength, structures strengthened with FRPs can fail in a brittle manner potentially below its mechanical capacity due to a bonding problem at the FRP material-concrete surface. In this case, the FRP materials do not play the most important role in strengthening RC structures and it is a waste of material to some extent. To enhance the bond behavior between FRP materials and concrete effectively, anchor systems including steel plate anchor [13], U-shaped FRP and bonded metal anchor [14,15], fan type anchor [16], and improved hybrid bond FRP anchor [17] are widely used. Experimental results show that as results of prevention of debonding of FRP strips totally by the anchors, the tensile forces of the strips provide the load carrying capacity to continue till reaching considerable lateral displacement [16]. The flexibility of FRP materials has been fully used.

Although CFRP and GFRP are typical representations in FRP family, several shortcomings cannot be ignored. The CFRP, the most expensive in the family, shows the highest tensile strength and elastic modulus, as well as moderate physical properties, whereas the common failure observed is debonding rather than rupture, resulting in the CFRP seldom reaches its ultimate tensile strength. While the GFRP shows poor performance in thermal stability, heat resistance, and alkali resistance [18,19]. The BFRP is a new inorganic continuous fiber, which is not only much cheaper than the CFRP but also has excellent physical and mechanical properties, such as light weight [20,21], high tensile stress [22], and easy application [20,23]. Furthermore, BFRP provides an advantage over CFRP in terms of ductility, of which ultimate strain is less than that of BFRP [20]. This is beneficial for RC members to maintain ductility during earthquake events. As a new fiber reinforced plastic, BFRP has a good prospect in the area of seismic strengthening for its low cost and comprehensive mechanical properties [18]. Additionally, BFRP exhibits better performance on bond behavior than CFRP [24–27] and better performance in acidic environments than GFRP [28].

Although investigations on BFRP in strengthening and/or repairing RC beams, columns, beam-column joints, and frames have been conducted [18,29–32], experimental studies on seismic performance of RC shear walls strengthened with BFRP are still limited. The present paper conducted an experimental study on seismic performance of RC shear walls strengthened with BFRP strips. Six RC shear wall specimens with an aspect ratio of 1.6 were designed, which generally exhibited an essentially flexure-dominated response. The specimens were subjected to cyclic lateral load tests, simulating a moderate earthquake, in order to investigate the effect of strengthening using BFRP with different configurations on the seismic performance of RC shear walls. A key issue in present study was the fan type anchor for the BFRP strips used to enhance bond behavior. The effect of BFRP strips configurations on seismic performance of RC shear wall was studied, and issues that are critical with respect to the seismic performance, i.e. failure mode, ductility, stiffness characteristic, energy dissipation capacity and load carrying capacity were presented and discussed.

2. Experimental program

2.1. Material properties

Commercial concrete was used to cast the specimens. Its mix proportions are shown in Table 1. The 28 day mechanical properties of concrete were determined according to Chinese Standard [33]. The concrete cubic compressive strength was f_{cu} = 39.3 MPa; concrete axial compressive strength was f_c = 31.0 MPa; concrete axial tensile strength was f_t = 2.33 MPa; compressive elastic modulus was $E_c = 3.24 \times 10^4$ MPa; and tensile elastic modulus was $E_t = 3.29 \times 10^4$ MPa.

The BFRP strips with 15.0 mm width and 0.121 mm thickness were used to test mechanical properties [34]. BFRP tensile elastic modulus was obtained through tensile flat coupon tests, with the average value of $E_f = 1.05 \times 10^5$ MPa; ultimate average strain of ε_u = 2.2%; and ultimate tensile strength average value of $f_{ft} = 2.30 \times 10^3$ MPa. The tested elastic modulus, ultimate strain, and ultimate tensile strength value of the epoxy resin were 2.60×10^3 MPa, 3.5%, and 45.8 MPa, respectively.

2.2. Description of specimens

Six RC shear wall specimens designated as SHW0-SHW5 were prepared in accordance with the test method recommended by Chinese Standard [35], which represented the part of a shear wall of an existing building. Geometric dimensions and reinforcement details of all specimens were identical, as shown in Fig. 1(a). All specimens were cantilever walls. Each specimen consisted of three subassemblies as follows: (1) the head beam, (2) the wall panel, and (3) the foundation beam. The length, height, and thickness of wall were l = 1000 mm, h = 1600 mm, and t = 120 mm, respectively. The aspect ratio of the wall was 1.6, which guaranteed a flexural type of failure generally occurred. The web reinforcement consisted of a double orthogonal grid of 8 mm diameter bars vertically and laterally with spacing 110 mm, and 150 mm, respectively. The 225 mm × 120 mm boundary elements were reinforced with six bars of 10 mm diameter. Confinement in the boundary element was provided by 8 mm diameter closed stirrups spaced at 150 mm [see Fig. 1(a)]. Average values of measured yield

Table 1
Mix proportions of concrete (kg/m^3).

Cement	Sand	Water	Coarse aggregates	Fly ash	Ground granulated blast furnace slag	Superplasticizer
212	721	168	1123	70	70	4.22