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Experimental research on blast-resistance of one-way concrete slabs reinforced by BFRP bars under close-in explosion

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ABSTRACT

Avoiding steel-bar-like corrosion in concrete members, basalt fiber reinforced plastic (BFRP) bars behaving as reinforcement have advantages in coastal civil engineering. One-way concrete slabs reinforced by BFRP bars (SRBBs) were designed to investigate their mechanical responses under static loads and explosions. High strength but relatively low stiffness of BFRP bars make SRBBs have different responses to slabs reinforced by steel bars (SRSBs). BFRP bars work in the elastic stage while steel bars result into plastic deformation after limited elastic deformation. SRBBs have larger deflections but higher ultimate loads compared with SRSBs in static bending tests. Explosive experiments reveal the damage patterns of SRBBs under various scaled distances, from 0.474 m/kg$^{1/3}$ to 0.684 m/kg$^{1/3}$. Crack, spall and breach are three typical damage modes for blast-loaded slabs. Compared with SRSB, the SRBB of the same reinforcement ratio and under the same scaled distance has larger deflections, but smaller damage level and greater residual loads. It is indicated that although the SRBB is not stiffer than the SRSB, it has greater anti-blast ability in current research.

1. Introduction

In construction, steel-bar reinforced concrete is the most widely used structural material. Under certain environments corrosion of the steel bars can lead to the deterioration or even the collapse of structural elements. Many attempts have been made in recent years to solve the corrosion problem, including using fiber reinforced polymer (FRP) bars as an alternative to the steel bars [1,2]. Recently, basalt FRP (BFRP) has gathered attention as a replacement for other FRPs for its cost-effectiveness, easy-manufacture, freeze-thaw performance, good resistance to corrosion, acids, and vibration and impact loading [3–8]. Due to these outstanding features, there is an increasing application of BFRP bars in civil engineering.

BFRP bar consists of basalt fibers and resin matrix. Basalt fiber is the reinforced material supplying axial stiffness and strength, while resin matrix, including polyester, epoxy resin, vinyl ester, polyester resin and polyamide resin, etc., acts as bonding and shearing force transferring. Many efforts have been made to investigate the mechanical behavior of BRFP/steel bar reinforced concrete structural members, including beams, columns and slabs. Mahroug et al. [9] published the test results and code predictions of four continuously and two simply supported concrete slabs reinforced by BFRP bars. They found that ACI 440.1R-06 overestimates the failure moment in most continuous BFRP reinforced concrete slabs owing to the combined shear-deflection failure. Mohamed Hassan et al. [10] studied the bond durability of BFRP bars embedded in concrete in aggressive environments. Through a series of experiment about BFRP-reinforced pullout specimens that were fully immersed in an alkaline solution and subjected to elevated temperatures, they investigated the effects of alkaline environment, exposure periods, and elevated temperatures on bond strength as well as the degradation mechanism and failure mode of BFRP reinforced specimens. Corrosion resistance of concrete members reinforced with BFRP bars has been investigated by other researchers [11–19].

However, these studies of BFRP reinforced concrete structures are localized on quasi-static loads. Anti-blast ability of concrete members is also important for protective structures or civil structures in anti-terrorism. In this research, blast responses of BFRP reinforced concrete slabs were studied through experiments.

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2. BFRP reinforced slabs

2.1. Slabs

The dimension of all these slabs is 1100 mm in length, 1000 mm in width and 40 mm in depth. There is only one layer of reinforcing-bar mesh near the bottom face of the slab, as shown in Fig. 1. Spacing of the BFRP bars in the SRBBs are 50 mm, 75 mm and 100 mm, respectively. Spacing of the steel bars in the SRSBs is just 75 mm, as a control slab to the SRBBs of the same reinforcement ratio. The thickness of the concrete cover was 5 mm for all slabs. The diameter of both steel bars and BFRP bars is 6 mm. The effective depth of the slab is 32 mm. The reinforcement ratio of the SRBBs is 1.8%, 1.2%, and 0.9%, respectively. The reinforcement ratio of the SRSBs is 1.2%. It must be state that the effective depth and the reinforcement ratio given correspond to the direction of spanning. If one defines the slab as a two-way span element, the effective depth of the slab would be 29 mm and the reinforcement ratio of the SRBBs would be 2.0%, 1.3% and 1.0%, respectively. The design of each slab is listed in Table 1.

2.2. Tensile property of BFRP bars

BFRP bars have different tensile behaviors to steel bars, as revealed by the extension experiments. As shown in Fig. 2, the BFRP bar was stretched by the universal testing machine and the extensometer was fixed at the central of the bar to measure the displacement of the calibration distance, which could be used to calculate the strain. BFRP bar has brittle failure. No post-yield deformation was observed, as shown in Fig. 2. The tensile strength is over 1.53 GPa and the modulus is 57.68 GPa, in average. The fracture strain is below 5%.

The typical stress-strain curves of both BFRP bar and steel bar of the same diameter are compared in Fig. 2. Cold-drawn HPB 235 steel bars have long plastic deformation. The tensile strength is 653.4 MPa and the modulus is 210 GPa, in average. From the comparison, HPB235 bar is stiffer but BFRP bar is stronger. Elastic deformation of the BFRP bar is quite long, endowing SRBBs different behaviors in bending and explosion.

2.3. Concrete

All the beams were cast from the same batch of commercial concrete whose strength grade is C40. Seven 150 mm cubes were casted and tested. The average strength of concrete cubes cured for 28 days is only 34.3 MPa. The average strength of concrete cubes cured for 150 days is 46.9 MPa.

3. Quasi-static behavior

3.1. Three-point bending experiments

In order to investigate the static mechanical behavior of the SRBB and the SRSB, static experiments in three-point bending were conducted. The curing time of the slabs is about 28 days.

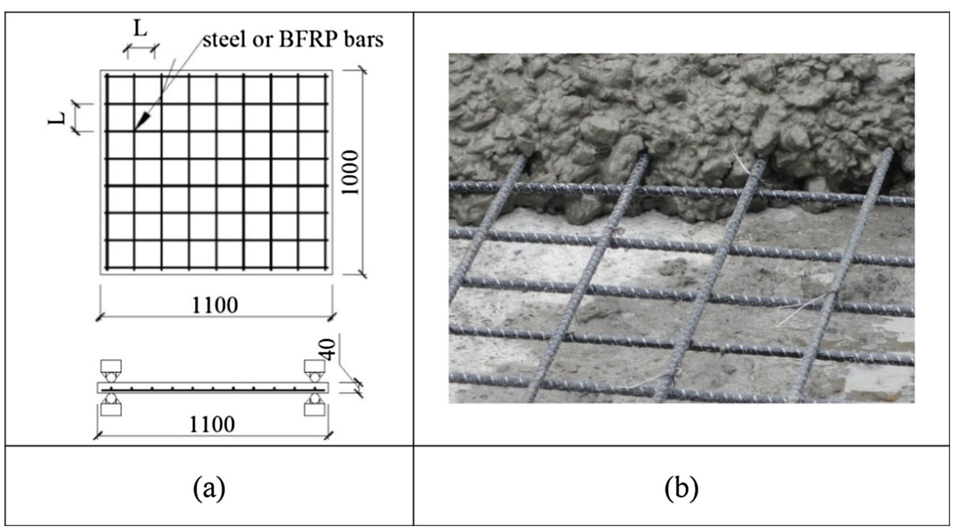

Fig. 1. (a) Geometry of the slab reinforced by steel or BFRP bars and (b) casting BFRP reinforced concrete slab.

Table 1
Type of slabs. "S" represents SRSB; "B" represents SRBB. The first number represents the reinforcement ration; "1" represents ρ = 1.8%; "2" represents ρ = 1.2%; "3" represents ρ = 0.9%. The latter number represents the scaled distance; "1" represents R = 0.684 m/kg$^{1/3}$; "2" represents R = 0.543 m/kg$^{1/3}$; "3" represents R = 0.474 m/kg$^{1/3}$.

Specimen	Reinforcement type	Reinforcing space (mm)	Reinforcement ratio (%)	Explosive mass (kg)	Scaled distance (m/kg$^{1/3}$)
B1-1	BFRP	50	1.8	0.2	0.684
B1-2				0.4	0.543
B1-3				0.6	0.474
B2-1		75	1.2	0.2	0.684
B2-2				0.4	0.543
B2-3				0.6	0.474
B3-1		100	0.9	0.2	0.684
B3-2				0.4	0.543
B3-3				0.6	0.474
S2-1	Steel bar	75	1.2	0.2	0.684
S2-2				0.4	0.543
S2-3				0.6	0.474