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Fatigue behaviour of sea sand concrete beams reinforced with basalt fibre-reinforced polymer bars

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HIGHLIGHTS

- Fatigue tests were conducted on two sizes of basalt FRP (BFRP)-reinforced sea sand concrete beams.
- Interface damage between BFRP and concrete of the tested beam was evaluated.
- Fatigue life prediction based on the test results was performed, and a fatigue limit was proposed.

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ABSTRACT

As the most commonly used structural component in recent decades, the durability of reinforced concrete (RC) is always a concern owing to the corrosion of steel in harsh service environments. Using fibre-reinforced polymer (FRP) bars with sea sand concrete avoids the corrosion problem, solves the shortage of natural river sand, and is in line with the sustainable use of resources. In the present study, fatigue tests were conducted on two sizes of basalt FRP (BFRP)-reinforced sea sand concrete beams. The minimum load was set as zero, the maximum loads as 0.5, 0.6, and 0.7 of its ultimate capacity (F_u), and four-point bending with a frequency of 10 Hz was used. The experimental programme consists of two BFRP-reinforced concrete beams as control and four BFRP-reinforced concrete beams for the fatigue test, and a traditional RC beam was used for comparison. The load-deflection relationship showed a bilinear relationship for BFRP-reinforced concrete beams. The slope of the curves showed a rapid growth during the first stage and a relatively slow growth after concrete cracking as the cycles increased. This phenomenon can be attributed to the decreased stiffness of the concrete beam, and it was confirmed through the theoretical calculation of the interface damage. Fatigue life prediction was performed on the BFRP-reinforced sea sand concrete beam, and a fatigue limit 0.55F_u was proposed as a threshold for the applied load level.

1. Introduction

Reinforced concrete (RC) structural elements have been widely used in recent decades. These elements are likely to be subjected to harsh service environments in most civil engineering applications, and durability is a primary concern throughout the life cycle [1,2]. Durability issues are caused by various factors, e.g. aging of concrete and corrosion of steel reinforcements. In particular, chloride ions are a major cause of corrosion of steel in concrete members [3,4]. Fatigue load accelerates the degradation of steel, resulting in reduced resistance of structures and increased maintenance cost [5,6]. Some studies have been devoted to prevent steel corrosion, which include cathodic protection, protective coatings, and corrosion inhibitors [7,8]. However, these methods are usually expensive and cannot fundamentally solve the problem of steel corrosion [1,5].

In addition to the corrosion of steel reinforcements, the development of infrastructure and marine space has led to a huge demand for concrete, which is exacerbating the resource shortages of natural river sand and causing a serious impact on the ecological environment [9]. One of the solutions to this problem is the use of sea sand as substitute to natural river sand; however, sea sand contains a large amount of chloride ions, which accelerates the corrosion process of the steel reinforcement. Thus, the chloride ion content in fine aggregates is strictly limited [10]. Many previous studies have demonstrated that concrete using treated sea sand

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or concrete with partial substitution of natural river sand showed good mechanical properties and durability [11].

Besides studies to prevent premature corrosion of steel reinforcements, much effort has been devoted to developing new materials [12,13]. Among these new materials, fibre-reinforced polymer (FRP) composites can be considered as ideal alternative materials for steel replacement [3], particularly in sea sand concrete applications [14]. FRP has excellent resistance to chloride ions (seawater or deicing salt) [4,14] and strong alkaline solutions (simulating concrete pore water, pH = 12.6–13) [15]. Kang et al. [7] and Li et al. [9] demonstrated that FRP-reinforced natural sea sand concrete beams showed excellent bending and shear capacities.

The most common types of FRP bars are carbon FRP, glass FRP and aramid FRP [3]. In recent years, basalt FRP (BFRP) has attracted increasing research interest. Basalt fibres are manufactured from basalt rocks through a melting process at 1400 °C, without any other additives and with reduced costs [15]. Basalt fibres have greater failure strain than carbon fibres and better tensile strength than E-glass fibres [16]. Based on these advantages, the applicability of BFRPs as structural materials is highly expected [17]. Previous studies have demonstrated that FRP-reinforced concrete beams exhibited excellent static performance [9,18], and numerous studies have been performed to investigate their fatigue behaviour [5,19].

Younes et al. [5] studied the fatigue performance of prestressed concrete beams using BFRP bars, with the test frequency set as 5 Hz. The prestressed beams failed by concrete crushing at the top for both levels of prestressing, but the bars ruptured at lower load ranges. Non-prestressed beams reinforced with BFRP bars under fatigue load failed by bar rupture. Atutis et al. [19] also studied the behaviour of prestressed BFRP beams under cyclic loads. As found, BFRP bars shows sufficient fatigue resistance, and the applied stress range has a high influence on the fatigue life of BFRP bars, whereas a load frequency varying from 2 Hz to 4 Hz shows a slight impact on the results. If cracking occurs due to damage of the bonding interface between the FRP and concrete, it will lead to an increase in the temperature of the interface, changing the properties of the FRP. In this case, the fatigue life is affected by the frequency [5].

Regarding the fatigue behaviour of FRP bars in concrete members, Noël and Soudki [20] studied the fatigue behaviour of slabs with FRP reinforcement. The results showed that FRP can be used to effectively improve the serviceability, and the abrasion induced by bond slips between the FRP and concrete was adverse to fatigue [13]. Zhu et al. [21] studied the fatigue performance of concrete beams reinforced with hybrid GFRP and steel bars and concluded that the fatigue life was determined by the loading level and effective reinforcement ratio.

As mentioned previously, the studies on fatigue behaviour of FRP-reinforced concrete beams are still limited, particularly for sea sand concrete. As such, this study examined the fatigue behaviour of BFRP-reinforced sea sand concrete beams. The effects of specimen size on the fatigue behaviour was investigated, and a set of RC beams was tested for comparison. Finally, crack width calculation, damage of the interface and fatigue life were analysed.

2. Experimental programme

2.1. Raw materials

The cement used in this study was commercial ordinary Portland cement (P.O. 42.5), provided by Shijing Cement Co., Ltd (Guangzhou, China). The sea sand and coarse aggregate (granite) were sourced from a local supplier. The particle size of the coarse aggregate ranged from 5 mm to 30 mm. A polycarboxylate-based plasticizer (QL brand) was provided by Qiangli Building Material Co., Ltd, Jiangmen, China. In accordance with the guidelines [22–24], the mixture proportion by weight of the constituents was determined as: cement (1.0): water (0.35): coarse aggregate (2.8): fine aggregate (1.20): water-reducing agent (0.01). The average 28-day compressive strength of the sea sand concrete was 42.0 MPa obtained by 150 mm concrete cubes.

BFRP bars with a nominal diameter of 8 mm and 12 mm with ribbed surfaces, provided by Jiangsu Green Materials Valley New Material Co., T&D Ltd., Nanjing, China, were used. Both ends of the longitudinal bars were bent 90° to provide more efficient strengthening. The tensile strength, elastic modulus, and elongation at failure provided by the manufacturer for BFRP bars with diameters of 8 mm and 12 mm were 1100 MPa, 55 GPa, 2.6%, and 891 MPa, 55 GPa, 2.5%, respectively. BFRP stirrups with rectangle shapes were provided by the manufacturer. Q235 steel was purchased from local suppliers. The diameters were 8 mm and 12 mm, and the yield strength and elastic modulus of the steel bars were determined as 318.3 MPa, 202 GPa and 291.8 MPa, 200 GPa, respectively.

2.2. Design of sea sand concrete beam

According to ACI 440.1R-15 [25] and the Chinese guideline, 'Technical code for infrastructure application of FRP composites' [26], two sizes of concrete beams were designed, and the dimensions were 150 mm × 200 mm × 1500 mm and 180 mm × 300 mm × 2100 mm. Four longitudinal reinforcing bars were used. The spacings of the stirrups was set as 100 mm, and the reinforcement ratios for the two beam sizes were 0.67% and 0.60%, respectively. Details of the concrete beams are shown in Fig. 1. A summary of all specimens used in this study is presented in Table 1.

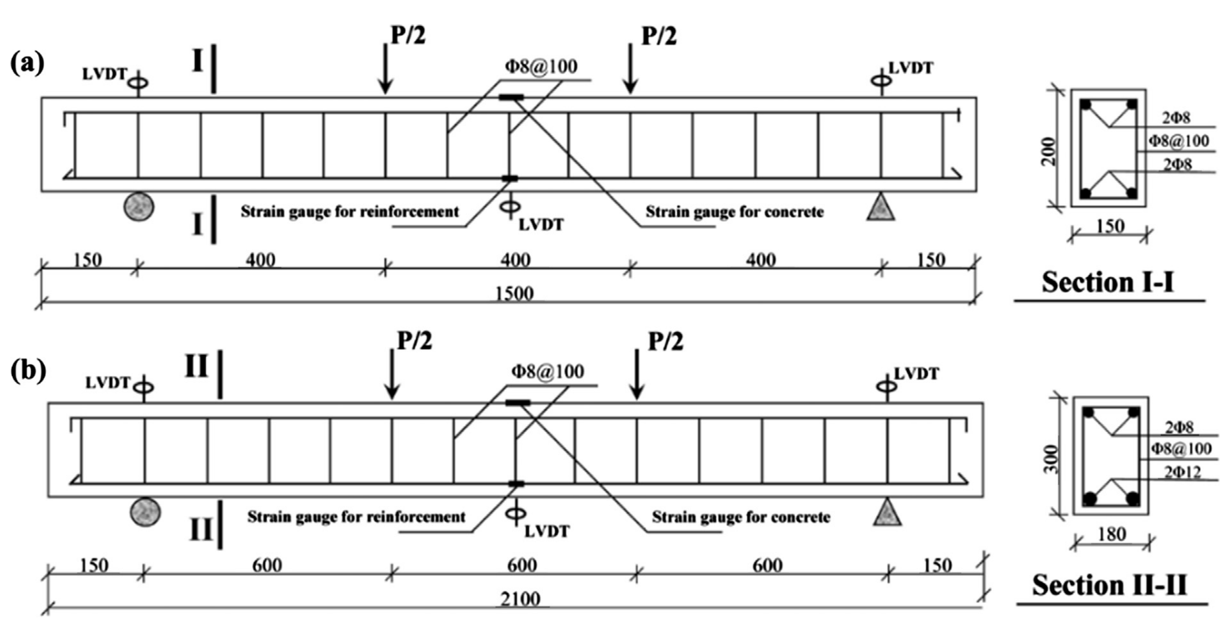

Fig. 1. Sketch of concrete beam: (a) 1500 mm in length; (b) 2100 mm in length.