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Structural behaviour of RC beams externally strengthened with FRP sheets under fatigue and monotonic loading

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ABSTRACT

This paper presents experimental research on the fatigue and post-fatigue static behaviour of reinforced concrete beams strengthened with glass or carbon fibre reinforced polymer (FRP) sheets placed either vertically or obliquely. All beams for fatigue tests were subjected to four-point bending for one million cycles with a frequency of 5 Hz. The results show that the FRP sheets can be used to significantly enhance the fatigue resistance of the beams strengthened. Also the results from the post-fatigue monotonous tests indicate that FRP sheets contribute the significant increase of the ultimate strength and ductility of the beams tested. The diagonal GFRP reinforcing arrangement is more effective than the vertical one in enhancing shear strength and stiffness. Finally, some moment deflection models were adapted to predict the ultimate loads of the beams tested, which give very good correlation to the experimental results.

1. Introduction

In recent years, there are many reinforced concrete (RC) structures are suffering from various deteriorations: cracks, concrete spalling, large deflection, etc., which need to be reinforced to support the designed or even resist possible higher loading or to renovate existing cracks [1–3]. These deteriorations are caused by various factors such as aging, corrosion of steel reinforcement, environmental effects such as seawater and accidental impacts on the structure [4–6]. Especially, during the natural disasters such as the earthquake in Sichuan on 12th May, 2008, many concrete structures, if they were not collapsed, were damaged to some extent [7]. There are several options available for retrofitting or repairing structural members of the existing RC structures. The commonly used options are to bond thin steel and/or fibre reinforced polymer (FRP) sheets onto the damaged members to restrain cracks and to increase the load carrying capacity, ductility and stiffness of structures strengthened [8,9].

To externally bond FRP sheets on the tension and also lateral sides of RC beams and columns is a widely used method for repairing and strengthening of the RC structures. Such reinforcing technique is an effective way to improve the flexural and/or shear performance of the RC structures reinforced, since FRP has better characteristics than the conventional strengthening material steel, in terms of high tensile strength, lightweight, resistance to corrosion and fatigue, etc. [3,5,10,11]. Investigations [12,13] were undertaken in the past to evaluate reliability of such reinforcing technique related to static loading and showed that the RC structures strengthened would demonstrate a better performance in strength, ductility and retarding crack growth as long as an appropriate end anchorage was provided for the FRP sheet [3,11].

More recently, through either experimental, the finite element or analytical approaches [14–19], extensive researches have been undertaken on behaviour of reinforced concrete beams strengthened by externally bonded FRP sheets for enhancing their flexural and shear performance. However, those studies primarily considered static behaviour of the FRP strengthened beams under monotonic loading. In fact, many structures such as bridges and marine structures are subjected to repeated cyclic loadings rather than static ones, and this is often overlooked in the analysis and design of RC beams strengthened with FRP sheets. It has been well established that externally bonding of the FRP on RC beams is an effective strengthening technique to increase their static strength and ductility, as well as fatigue resistance with high energy dissipation [20–25]. However, the scarcity of experimental data on fatigue behaviour of RC beams strengthened by the FRP sheet is unanimously recognized [26], which does not satisfy the design need. Therefore, to study fatigue performance of RC beams strengthened by the FRP sheets is necessary work to increase the knowledgebase in this area.

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At the present, the main research work increasingly focuses on experimental flexural fatigue and shear fatigue. Nanni [27] showed that steel fibre reinforced concrete (SFRC) could enhance the fatigue performance and the fibre content was an effective parameter to influence the fatigue characteristics of beams tested. Chang and Chai [28] developed a test methodology to investigate the flexural fracture and fatigue of the SFRC beams. Leung et al. [29] studied the flexural fatigue performance of concrete beams using engineered cementitious composites (ECC) and found that the ECC could improve the fatigue life of the beam in controlling the growth of small cracks. Manfredi and Pecce [30] studied the failure modes and the relationship between the damage function and the cyclic degradations of the normal and high strength concrete beams under monotonic and cyclic loading. Research on concrete beams strengthened with carbon fibre reinforced polymer (CFRP) was carried out to investigate the influence of loading history on the fatigue life and crack width [31], and to analyze the relationship between the fatigue performance and the electrical property of CFRP under flexural loading [4]. Although a reasonable amount of research has been undertaken on the flexural fatigue [28–35], research on the shear fatigue performance of RC beams strengthened by CFRP and glass fibre reinforced polymer (GFRP) sheets however is limited up to date. Kwak and Kim [36] focused on the shear fatigue loading on the fatigue behaviour and strength of the polymer reinforced concrete (PRC) beams. Czaderski and Motavalli [24] studied RC beams strengthened by the CFRP L-shaped plates under shear fatigue loading. Moreover, some experimental research has also been conducted on the bonding behaviour between the FRP sheet and concrete under cyclic fatigue loading [10,17,20,21,26], since such the bonding behaviour influences the failure mode of the beam strengthened [34]. It was observed in these studies that if there was no obvious interfacial debonding between the FRP and concrete occurred fatigue behaviour of the FRP-strengthened beams would be improved. However, once debonding occurred, the deflection would be increased significantly and the tension cracks appeared near the position of the point loads applied [35]. Lu and Ayoub [37] studied the debonding failure on the response of RC beams and developed a new model to evaluate the reduction factor of FRP-strengthened RC beams due to FRP debonding. Yun et al. [38] demonstrated the effect of different bonding systems under fatigue loading on the long-term behaviour of the bond between the FRP and concrete. Carloni et al. [39] investigated the role of the FRP-concrete interface debonding under fatigue loading and found that debonding occurred during fatigue, which was related to the load range applied.

The work presented here aims research on the shear fatigue behaviour of RC beams made with the normal concrete strengthened with FRP (CFRP or GFRP) sheets. It is focused on investigating the effectiveness of FRP sheets on the fatigue behaviour and their contributions to the ultimate strength of ordinary RC beams. It also helps understand the influence of the initial one million cycles of fatigue loading on the shear performance of RC beams strengthened with FRP sheets, and estimate the fatigue behaviour and crack growth of the RC beams strengthened.

2. Experimental work

Tests were conducted on simply supported short RC beams strengthened with CFRP or GFRP sheets in shear. The beams were tested under static loading and/or fatigue loading to investigate their deflections, strains on the steel rebar, concrete and FRP sheets, crack behaviour as well as shear capacity after one million cycles of fatigue loading.

2.1. Details of test beams, materials and mix

Tests were carried out on five rectangular RC beams reinforced with different patterns and types of FRP sheets. The geometry and reinforcement of the beams tested are shown in Fig. 1. All beams have the same overall cross-sectional dimensions, internal longitudinal reinforcement and stirrup arrangements. The beams are 150 mm wide, 300 mm high and 1700 mm long. The net span of 1500 mm is limited by the testing machine configuration. One of five beams was tested under static load, the rest four were tested under fatigue loading. The ultimate load (P_u) obtained from the static test was used to determine the minimum fatigue loading (P_{min}) and maximum fatigue loading (P_{max}).

Concrete mix was designed with the grade of compressive strength of C30 according to the Chinese Standard [40]. The mix was made of ordinary Portland cement 32.5R, natural sand and gravels with aggregate size between 10 and 31 mm. The water to cement ratio was kept constant at 0.55. Cement, water, fine and coarse aggregates were mixed in their weight proportions of 1:0.55:1.76:3.13. Besides the test beams, six concrete cube specimens with side length of 150 mm were made for compressive strength tests at the time of casting and were kept with the beams during curing. In the sample preparation, all test members were placed on a vibration platform to ensure proper compaction, however special care was taken on the strain gauges attached to steel bars during the vibration. The average of 28-day cube strength was 31.3 MPa.

For all concrete beams, three types of the mild steel bars were used for the longitudinal and the transverse reinforcements. There were two sets of steel smooth bars placed in the tensile and compressive faces of the beam respectively. There were also steel smooth bars placed transversely for the shear reinforcement. The details of the reinforcement and material properties of the rebars (supplied by the Shanxi Zhongyu Ironsteel Co. Ltd.) and concrete are summarized in Fig. 1 and Table 1, respectively.

The FRP materials consist of CFRP and GFRP sheets (supplied by the Shanghai Keep Strong in Building Technology Engineering Co. Ltd.) with a thickness (t_f) of 0.11 and 0.27 mm, respectively. Tensile strength, elastic modulus and ultimate strain of the FRP materials are also given in Table 1.

2.2. The strengthening scheme

All the beams were externally strengthened with a unidirectional CFRP or GFRP sheets, except for the reference beam. Two

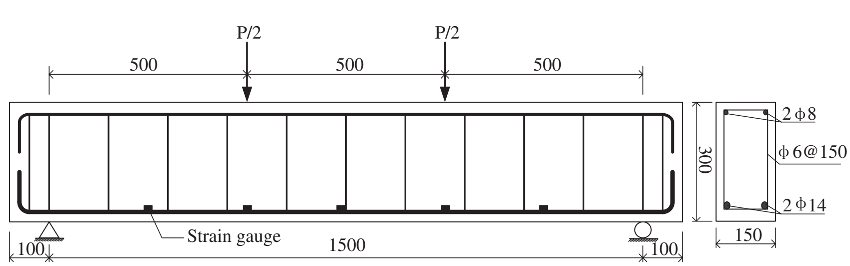

Fig. 1. The geometric, loading and boundary conditions and steel reinforcement of the RC beam.