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Residual deflection analysis in negative moment regions of steel-concrete composite beams under fatigue loading

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HIGHLIGHTS

- The fatigue deformation behavior of steel-concrete composite beams under negative moment was investigated.
- A prediction model of residual deflection related to pre-cracked loading was proposed.
- An analytical model of residual deflection related to fatigue loading was proposed.

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ABSTRACT

This paper presents the results of an experimental and analytical study on the residual deflection behavior in the negative moment regions of steel-concrete composite beams under fatigue loading. Firstly, fatigue tests with different load amplitudes were performed on two steel-concrete composite plate beam specimens subjected to negative moment. The residual values of slip and deflection at the interval time of the loading procedure were measured by laser displacement sensors. To study the development law of residual deflection under fatigue loading, the total residual deformation f_N is then regarded as the superposition of the plastic deflection f_1 related to pre-cracking loading and the residual deflection f_i related to fatigue loading. The analytical models of f_1 and f_i are presented based on the existing research results of previous researchers. Finally, the applicability and accuracy of the proposed analytical model are validated through the comparison between modeling results and the data of the experimental beams performed in this study and reported in the earlier companion paper. The fatigue design recommendations for the steel-concrete composite beams subjected to negative moment were given based on the fatigue test and model analysis.

1. Introduction

Steel-concrete composite beams have been widely used in buildings and bridges because of the benefits of combining the advantages of the two component materials [1,2]. Served as efficiently lightweight and economical structural members, steel and concrete composite continuous beams are very attractive solutions for short and medium span bridges. However, the concrete slab is in tension and the lower flange of the steel part is subjected to compression in the negative moment regions of continuous composite beams [3]. As a result, the strongly nonlinear mechanical behavior of slip at the beam-slab interface and cracking in the concrete slab even under a low stress level generally has shortcomings in view of durability and strength. Over the last several decades, a lot of researchers have focused on experimental and theoretical studies on the crack control of concrete slab [4,5], as well as the inelastic mechanical behavior of composite beams under static loading [6,7].

Furthermore, in the actual conditions, composite bridges are mostly subjected to vibrating or oscillating forces generated by the live vehicles or the winds in addition to static load. The fatigue effect on mechanical behavior of structures under such repeated loading conditions generally causes the problems of structural serviceability and safety. A large amount of studies have investigated fatigue behavior of shear studs in push-out specimens [8,9] and composite beam specimens under positive bending moment [10,11]. For the fatigue behavior of continuous steel-concrete composite beams in the support region, very limited studies were reported. Zong and Che [12] analyzed the fatigue strength of the prestressed steel-concrete composite beams through experimental tests. The results showed that the repeated load cycles can lead to

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the gradual increase of slip at the beam-slab interface. Meanwhile, the serious cracking of concrete slab under hogging moment was the main reason for the failure of continuous composite beams. Ryu et al. [13] conducted an experimental test on a full-scale model of a two-span continuous composite bridge with prefabricated slabs to study the crack control method under static and fatigue loads. The results showed that crack widths can be controlled appropriately within an allowable crack width in the decks and transverse joints of the composite bridge with prefabricated slabs on an interior support under service loads. Zhou [14] performed an experimental study on fatigue behavior of composite girders with steel plate-concrete composite bridge decks. No fatigue failure was found for composite girders under negative bending moment according to the test results. Meanwhile, fatigue test with two million cycles did not show obvious effects on the static loading behavior. Lin et al. [15] investigated the fatigue performance of composite steel-concrete beams under hogging moment. The test results indicated that fatigue test with certain cycles could decrease the section stiffness and the ultimate load carrying capacity, while the repeated load was larger than the initial cracking load.

Though as an important assessment index for mechanical properties, few studies have performed evaluation for the fatigue deflection of steel-concrete composite beams, especially in the negative moment regions. Wang et al. [11] studied the fatigue behavior of studs in steel-concrete composite beams through a fatigue test on seven specimens. Based on the experimental and theoretical analyses, a calculation method for the deflection of steel-concrete composite beams under positive bending was proposed and validated. In the fatigue tests conducted by Zhou [14], the residual deflection of composite beams under negative moment was measured. But the development laws of residual deflection were not analyzed deeply. Moreover, according to the foregoing research results on the fatigue behavior of composite structures, no analytical solution was presented for the residual deflection under fatigue loading of steel-concrete composite beams subjected to hogging moment till now.

This paper is to understand the residual deflection behavior of steel-concrete composite plate beams subjected to negative moment under fatigue loading. The experimentally investigation concerning fatigue deformation of the tested specimens under cyclic loading with different load amplitudes was performed. The failure mode, fatigue life, and residual static test results were recorded and analyzed. Then an analytical model for the estimation of the total residual deformation f_N is presented, which can be regarded as the superposition of the plastic deflection f_1 in the first cycle and the residual deflection f_i related to fatigue loading. Finally, through comparing with the existing experimental works conducted in this study and reported in the earlier companion paper, the applicability and limitations of the proposed analytical model are analyzed and discussed.

2. Fatigue tests on steel-concrete composite beams under negative moment

2.1. Details and materials of test specimens

In order to investigate the residual deflection behavior in negative moment regions of steel-concrete composite beams under fatigue loading, three specimens SCB1-1, SCB1-2 and SCB1-3 were tested in this study. Each of the specimens was 3900 mm in length and was simply supported at a span of 3500 mm, as shown in Fig. 1(a). The uniform thicknesses of steel plates were 12 mm, 12 mm, and 14 mm for the top flange, web and bottom flange respectively. The concrete slab had the thickness of 150 mm and the width of 600 mm (see Fig. 1(b)). The longitudinal and transverse reinforcement bars, with the diameters of 16 mm and 10 mm respectively, were arranged in both the top layer and the bottom layer of the concrete slab (see Fig. 1(c)). The longitudinal reinforcement ratio was 4.0%. The specimens were designed with studs as shear connectors, and the diameter and height were 16 mm and 90 mm respectively (see Fig. 1(d)). Two rows shear studs with the longitudinal and transverse spacings of 100 mm were welded on the top flange. In addition, the vertical stiffeners with the thickness of 12 mm were welded at the supports and loading points to prevent shear buckling failure and crippling of the web plate.

Strength grade of the concrete was designed to be C50, and the average compressive cube strength was approximately 51.2 MPa at 28 days. The tensile reinforcement bars and steel plates used HRB400 and Q345 respectively of the same factory batch. The measured average yield strength and tensile strength of tensile reinforcement bars were 592 MPa and 718 MPa respectively. The measured average yield strengths of steel plates with the thicknesses of 12 mm and 14 mm were 443 MPa and 391 MPa, and the average tensile strengths were 608 MPa and 520 MPa respectively.

2.2. Loading and measurements

All of the beam specimens were inverted to simulate the hogging moment region adjacent to the internal support of a continuous composite bridge (see Fig. 1(a)). First, the beam specimen SCB1-1 was initially tested under monotonic loading in order to determine the ultimate load-bearing capacity F_u and used as a reference beam for the fatigue tests. A single concentrated load by a hydraulic jack with the loading capacity of 2000 kN was applied monotonically downward on the bottom flange plate, as shown in Fig. 2. The monotonic test was conducted under force control until the applied load reaching 80% F_u and the loading rate was set to about 10 kN/min. After that, force control was switched to displacement control. The other two specimens SCB1-2 and SCB1-3 were tested under fatigue loading conditions with different load amplitudes. Fatigue loads were applied using the computer controlled two-channel electro-hydraulic servo static and dynamic loading test system (model: JAW-500K/4) with the maximum loading capacity of 500 kN, as shown in Fig. 3. The cyclic loading frequency was of 2 cycles/s, the stress ratio was 0.1, and sine waveform was used. The maximum load F_{max} was determined by the ultimate load-bearing capacity F_u according to the monotonic test on specimen SCB1-1, and 25% F_u was for SCB1-2 and 40% F_u was for SCB1-3. The design details of fatigue tests are characterized in Table 1. Finally, residual static loading test was performed on specimen SCB1-2 which had not suffered a fatigue failure after 250×10^4 repeated cycles. The loading procedures and equipment were the same with the monotonic loading test on specimen SCB1-1 (see Fig. 2).

During the static test, an unloading-reloading cycle was performed on specimen SCB1-1 when the load reached 50% F_u and 70% F_u. The residual deflection of SCB1-1 was recorded during the unloading-reloading process for the further modeling analysis in the later section. For the fatigue conditioned specimens, prior to starting the application of fatigue loading, 10–20 kN static load was pre-loaded for 2–3 times repeatedly. After the good bearing contact was ensured, a pre-cracked loading with the upper limit value F_{max} was applied statically. Then fatigue loading started after the force of specimen was adjusted to the fatigue median. During the fatigue loading test, the repeated loading was periodically paused and the specimen was unloaded to zero after typical load cycles of 1×10^4, 5×10^4, 10×10^4, 50×10^4, 100×10^4, 150×10^4, 200×10^4 and 250×10^4. Then after the residual deformation was stable, the specimen was loaded to the maximum load F_{max} monotonically. At the interval time of the loading procedure,