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Environmental benefit and fatigue behavior of steel-concrete composite beams

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Abstract. This paper presents the environmental benefit and mechanical behavior of steel-concrete composite beams, and the fatigue deflection in the negative moment regions was studied emphatically. Firstly, through the comparison with concrete bridges, the environmental and economic benefits of steel-concrete composite girder bridges were analyzed. Then fatigue behavior of steel-concrete composite beams subjected to hogging moment was studied, and fatigue tests with different load amplitudes were performed on two composite beam specimens subjected to negative moment. Finally, the failure modes, load-deformation responses, and residual deformation under fatigue loading were cautiously measured and analysed.

1. Introduction

In recent decades, steel-concrete composite beams have been extensively used in buildings and bridges due to the benefits of combining the advantages of the two component materials [1]. Simply supported composite bridges under positive bending moment can enable full application of the mechanical properties of steel and concrete. In comparison with simply supported beams, continuous composite beams are very attractive solutions for longer span bridges for the advantages of higher span to depth ratio, less deflection, noise reduction, more economical condition and better seismic resistance.

In the actual conditions, composite bridges are mostly subjected to vibrating forces generated by the live vehicles in addition to static load. A lot of studies have investigated fatigue behavior of shear studs in push-out specimens [2] and composite beam specimens under positive bending moment [3, 4]. For the fatigue behavior of continuous steel-concrete composite beams in the support region, very limited studies were reported. Ryu et al [5] 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. Lin et al [6] investigated the fatigue performance of composite steel-concrete beams under hogging moment. Though as an important assessment index for mechanical properties, few studies have performed evaluation for the fatigue deformation of steel-concrete composite beams, especially in the negative moment regions.

Based on the analysis of environmental benefit, this paper emphatically deals with the results of a series of experimental and analytical work with three steel-concrete composite beam specimens under static and fatigue loading. The experimental program was introduced detailly, and the major experimental results were cautiously analyzed and discussed.

2. Analysis of environmental benefit

Due to the abundant resources of labor, sand and stone in China, the medium and small-span concrete structures have played a huge role in bridge construction for a long time. But the unrestrained mining of sand and stone, and a large amount of cement production would cause great damage to the ecological environment. In recent years, the concrete consumption in China is far higher than that of other countries due to large-scale investment in infrastructure. From 2011 to 2013, the consumption of concrete in China reached 6.6 billion tons, while the total usage in America were only 4.5 billion tons from 1901 to 2000. In other words, China used more concrete in three years than America did in 100 years, and the unrestrained usage of limited natural resources will result in high environmental cost in the future.

In recent decades, national economy and steel industry have been developed rapidly in China. On the one hand, with the continuous increase of steel production in China as shown in Fig. 1, the unit price of steel has been greatly reduced. From 2007 to 2008, the unit price of domestic plate was more than 7000 yuan/ton, while it was reduced to 4000 - 4500 yuan/ton in 2013. By the end of 2015, the problem of steel overcapacity was even more prominent. On the other hand, with the improvement of national economic level, the prices of cement and sand and stone are rising sharply, as well as the cost of labor. The unit price of concrete has exceeded 600 yuan/ton, which leads to the relative increase of the cost in concrete bridges directly. These backgrounds will provide a good foundation for the popularization and application of steel-concrete composite bridge in China. Due to the light weight of steel structure, the weight of steel structure system of the same building area is only about half of that of concrete structure. In addition, the steel structure components are mainly manufactured in factory, and the construction period is greatly shortened with a high efficiency of on-site assembly. Because of the aboved advantages, the comprehensive cost of steel-concrete composite beams is lower than concrete bridges significantly.

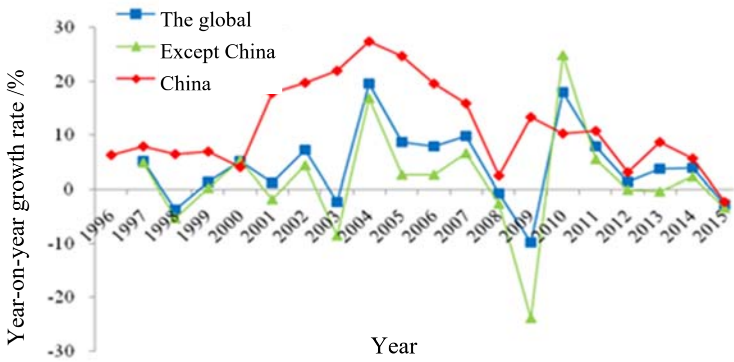


Figure 1. Growth rate of crude steel production.

3. Analysis of fatigue behaviour

3.1. Experimental Program

3.1.1. Details and materials of test specimens. In order to investigate the fatigue behavior of steel-concrete composite beams under hogging moment, 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. 2. 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. Two rows shear studs with the longitudinal and transverse spacings of 100mm were welded on the top flange. 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. 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.

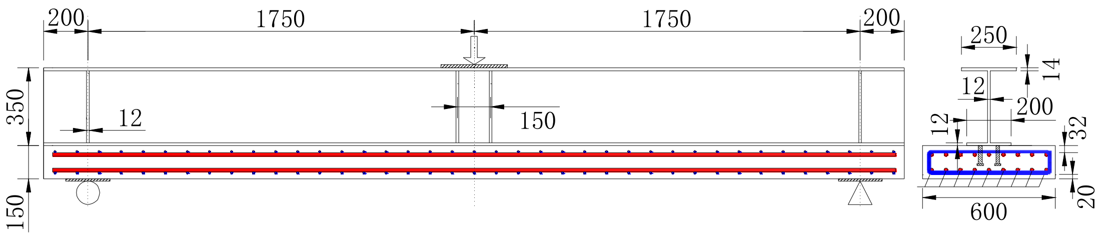


Figure 2. Dimension details of the test specimens (unit: mm).

3.1.2. Loading and measurement plan. All of the beam specimens were inverted to simulate the hogging moment region adjacent to the internal support of a continuous composite bridge. First, the beam specimen SCB1-1 was initially tested under monotonic loading in order to determine the ultimate load-bearing capacity Fu 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. 3(a). After that, the other two specimens SCB1-2 and SCB1-3 were tested under fatigue loading conditions with different load amplitudes. The set-up of the fatigue test is shown in Fig. 3(b). The cyclic loading frequency was of 2 cycles/s, the stress ratio was 0.1, and sine waveform was used. The maximum load Fmax was determined by the ultimate load-bearing capacity Fu according to the monotonic test on specimen SCB1-1, and 25% Fu was for SCB1-2 and 40% Fu was for SCB1-3. During the fatigue loading test, the repeated loading was periodically paused and the specimen was unloaded to zero after typical load cycles of 1×104, 5×104, 10×104, 50×104, 100×104, 150×104, 200×104 and 250×104. Finally, residual static loading test was performed on the specimens after fatigue test. All the data was recorded automatically by a computer through a signal system, including the residual deflection at the mid-span and the residual strain of reinforcement bar.

3.2. Analysis of experimental results

3.2.1. Failure modes and residual static test results. The load-deflection responses at the mid-span of beam specimens after fatigue test and the corresponding failure modes are shown in Fig. 4, in which SCB1-1 is the tested beam without fatigue loading. The curvature of load-deflection curve of SCB1-1 becomes smaller when the applied load reached the initial cracking loading of 70 kN, which indicates that the section rigidity was decreased by the cracking of concrete slab. The ultimate load of specimen SCB1-1 was 1033.0 kN. In the ultimate loading stage, it can be seen that the compressive bottom flange of SCB1-1 was buckled locally near the loading point, where no vertical stiffeners were welded.

As for SCB1-2, no fatigue failures of the steel beam, shear connectors or reinforcement bars in the concrete slab had occurred after 250×104 cycles. When the applied load was between the initial cracking loading and the yielding of reinforcement, the load-deflection relationships of the two specimens SCB1-1 and SCB1-2 are almost the same. However, in the yielding stage of tested beam, the rigidity of specimen SCB1-2 became smaller than SCB1-1 gradually, which may be ascribed to the fatigue damage of specimen SCB1-2. The ultimate load of specimen SCB1-1 was 973.3 kN, which is 6.2 % smaller than the ultimate capacity of specimen SCB1-1. The failure mode of SCB1-2 was similar to SCB1-1 in the final static test, which can be described in Fig. 4. When load amplitude was equivalent to 360 kN for specimen SCB1-3, after about 150×104 cycles, a fatigue crack occurred at the location of tensile top flange where the shear studs were weld. Thereafter, the fracture of longitudinal reinforcement occurred suddenly followed by the fatigue cracks of top flange and concrete slab developed rapidly after the next 2×104 repeated cycles, as shown in Fig. 4.

(a) Static testing setup (b) Fatigue testing setup

Figure 3. Testing setup of the specimens.

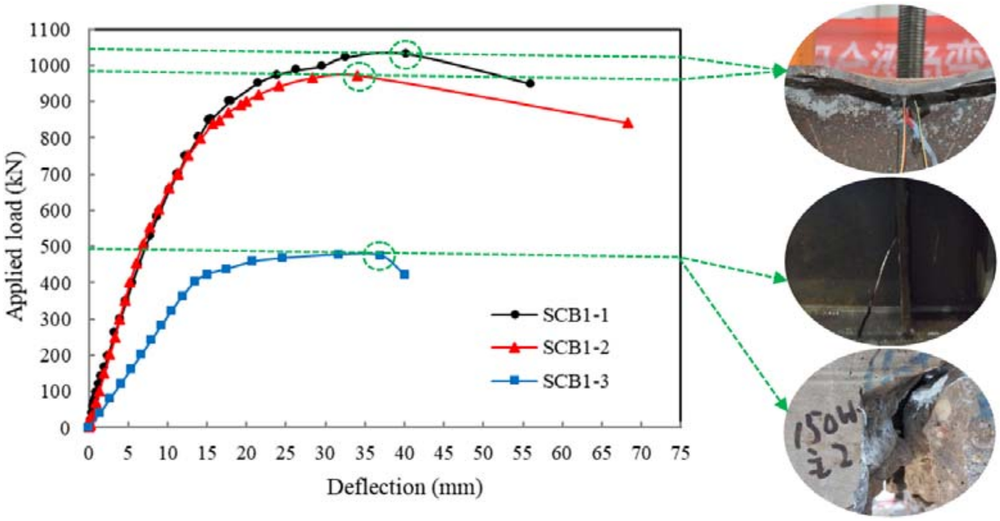
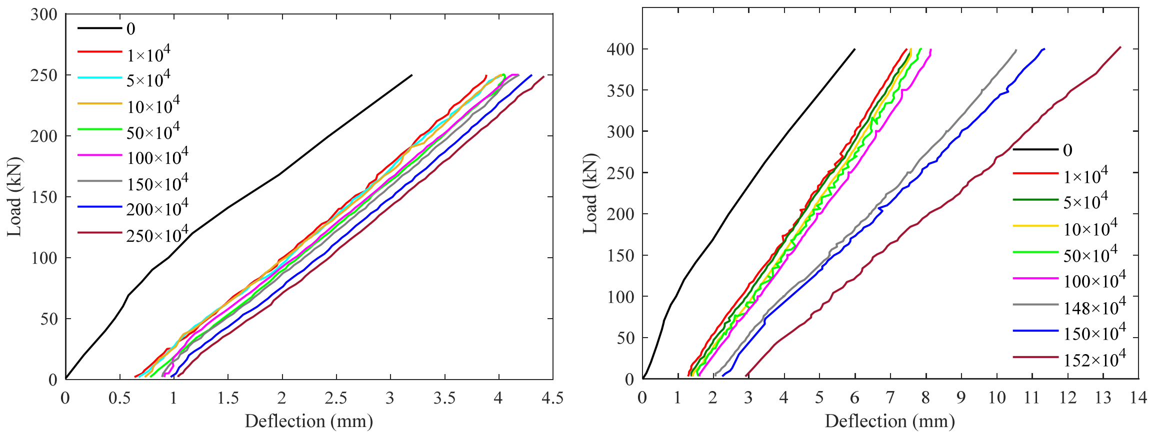


Figure 4. Load-deflection response and failure modes of specimens.

3.2.2. Load-deformation responses under fatigue loading. Fig. 5 shows the load-deflection curves of specimens SCB1-2 and SCB1-3 under different loading cycles. It indicates that there is a large difference between the load-deflection curves in the initial static tests (0 cycle) and the later fatigue loading tests. The main reason for the phenomenon is that the concrete slab was pre-cracked and the bond on the steel-slab interface was broken in the initial stage of fatigue loading. In addition, it can be found that the load amplitude showed a significant influence on the girder stiffness under fatigue loading. When the fatigue load of specimen SCB1-2 was limited to 25% Fu, no practical difference was found in the curves shown in Fig. 5(a) after a certain number of repeated load cycles. For the specimen SCB1-3 with a bigger fatigue load of 40% Fu, the beam stiffness became less stiff when the number repeated load cycles reached 148×104 as can be observed in Fig. 5(b).



(a) Load-deflection curves of SCB1-2 (b) Load-deflection curves of SCB1-3

Figure 5. Load-deformation curves after different load cycle numbers.

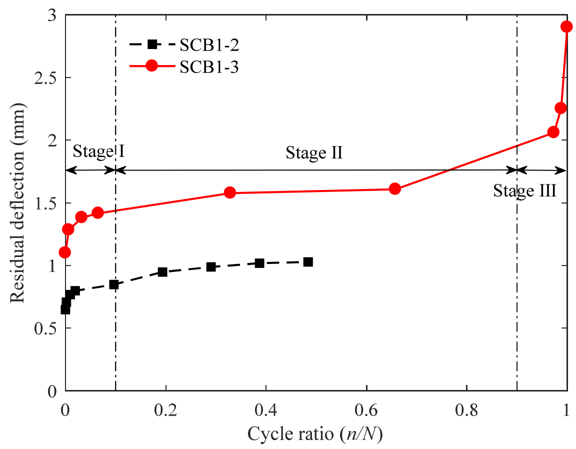


Figure 6. Residual deformation versus cycle ratio.

3.2.3. Residual deformation under fatigue loading. The residual deflection at mid-span is plotted with respect to normalized loading cycles (n/N) in Fig. 6, where n is the number of cycles and N is the fatigue life. It can be observed from the figure that the change laws of the residual values of deflection are similar, and the evolution of residual deformation during the whole progress of fatigue loading can be typically characterized by three stages: in the stage I, i.e. $0 < n/N \le 0.1$, the residual values increase rapidly with increment of loading cycles; in the stage II, i.e. $0.1 < n/N < 0.9$, the growth rate of the residual values become slow and stable gradually, and this stage accounts for about 80% of the fatigue life of the tested beams; and in the stage III, i.e. $0.9 \le n/N < 1$, the residual values increase rapidly again until the fatigue failure occurred.

4. Conclusion

In this paper, the environmental benefit and mechanical behavior of steel-concrete composite beams were analyzed. The fatigue deflection in the negative moment regions was emphatically investigated through the static and fatigue tests conducted on three specimens. Based on the presented results, the following conclusions can be drawn.

(1) Compared to concrete bridges, steel-concrete composite girder bridges have a lower comprehensive cost and can achieve better environmental benefits.

(2) The fatigue life and failure modes of the tested beams under negative moment were significantly affected by the load amplitude. The tested specimens still showed good ductile failure characteristic in the residual static tests.

(3) With increasing number of repeated cycles, the residual deflection at mid-span gradually increased and the corresponding evolutions during the whole progress of fatigue loading exhibited three distinctive stages.

Acknowledgments
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