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Fatigue property study and life assessment of composite girders with two corrugated steel webs

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ABSTRACT

This paper presents the results of experimental investigations on fatigue behaviors of composite girders with corrugated steel webs (hereafter referred to as "composite girders") subjected to bending based on the experimental work on the shear connector and corrugated steel beam. The experimental results indicated that failure started with cracks initiation and propagation at the concrete bottom plate, with the ultimate failure mode characterized as the shear failure on the bottom plate and interfacial slippage between the web and bottom plate. There was no obvious reduction in stiffness when the fatigue life approached 6×10^6 (equiamplitude load) or 2×10^6 (variable amplitude load) cycles, and the cracks grew slowly, which exhibited good fatigue resistance under the cyclic loading at quasi-static load. In addition, the cracks initiation location and fatigue life are predicted based on the fatigue damage theory, which shows good agreements with test results. The C degree of American standard AASHTO2004 is also suggested to be used in the fatigue life design of corrugated steel web in composite girders. The Palmgren-Miner cumulative linear damage theory is adopted in the partial fatigue life assessment, the fatigue life of box girder subjected to variable amplitude cyclic load is predicted when D exceeds 1. In addition, the fracture extension theory by Paris and amplitude theory of stress intensity factors are summarized to assess the fatigue life, which can be good evidence contributing to the engineering practice.

1. Introduction

The new form of bridge box girder with corrugated steel web has been used in many fields for a long time because of its favorable properties [1]. This structural layout has also been implemented in bridge construction, especially in hybrid and composite bridge for its improved behavior in traditional structures with flat webs [2,3]. The pure bending and combined bending and shear over e first composite girder with corrugated steel web was built in France named Cognac in 1986 [4]. Due to lower weight, external pre-stressing and fewer on-site construction, the composite girder can combine the advantage of concrete and steel web. Comparing with the flat steel web composite girder, it's difficult to improve the shear capacity substantially when the steel web is thicker with no stiffening ribs [5–7]. Also, it has a lower effect on the structure by residual stress, geometric defects and weld defects. However, the composite girder has a beautiful shape and high bending stiffness in the transverse direction [8,9]. A more advantageous structure style needs to be adopted for engineering purposes like the corrugated steel web composite girder because the corrugated steel web increases the buckling strength of the structure and shows a better fatigue resistance [10–12].

Now the researchers put their main attention to the style design, shear lag effect, flexural behavior and shear behavior of composite girders [13–15], and few tests were performed to examine the fatigue behavior of composite girders. To our limited knowledge, the first research was undertaken with two specimens by Harrison [16] to investigate the effect of wave angle on composite girder fatigue life. Because of the great application prospect, many researchers in Japan joined in this field for analyzing the effect of wave angle on the failure mode and cracks initiation under cyclic life [17–20]. Also, some tests were designed to analyze the fatigue behavior of the connection between concrete and steel to find a better way of connection in reducing stress concentration and improving the fatigue life [21].

However, a lot of researchers focused on either static or fatigue behavior of shear connector and corrugated steel webs [22–24]. The

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detailed failure mode of the component, including slip performance between steel and concrete, is concluded, and some critical mechanisms have not been made certain. Base on the existed achievements, static and fatigue tests were performed on three composite girders respectively to analyze the failure mode, crack initiation and propagation in this study. With the finite element method (FEM) calculated results, the fatigue life of composite girder was estimated by using traditional fatigue, fatigue damage and fatigue fracture theories respectively.

2. Experimental work

2.1. Materials

Table 1 shows the material properties of concrete, steel rebars and corrugated steel web which were used in the experiments respectively. Concrete mixes were designed with the grades of compressive strength according to the Chinese Standard [25]. Ordinary Portland cement PR52.5 was used to produce specimens. River sand with the maximum size of 2.36 mm was used as fine natural aggregate, and the coarse have the fraction size from 2.36 to19 mm, in accordance with the Chinese standard GB/T 14685-2001 [26]. The average compressive strength (f_c) at 28 days is 54.5 MPa. The yield strength (f_y), ultimate strength (f_u), elastic modulus (E) of steel rebars and corrugated steel webs supplied by providers are shown in Table 1 respectively.

2.2. General

Table 2 shows the test program of the three composite girders subjected to either four-point bending in static or cyclic load. The research study has three different parts, which are related to different aims respectively. The first specimen was investigated under four-point-bending to analysis the bearing capacity and failure mode. The second aim of tests is the analysis mechanics performance and fatigue life estimation under equiamplitude load or variable amplitude load.

Each specimen was loaded with 500 cycles under a maximum load magnitude of 50 kN. The purpose of the pilot trial was to calibrate and reduce the test errors. All the fatigue tests were executed with monotonic cyclic loading followed by load fluctuation between F_{min} and F_{max}. The maximum load was set to be 50% of bearing capacity (static test), and the minimum load was set to be 10% of F_{max}. All the specimens were simply supported in four-point bending as shown in Fig. 1. The load was applied using a servo controlled Shimadzu hydraulic actuator (200 kN). The loading for each level is set to be 5 kN, with a loading duration of 3 min to record the displacement and strain stalely during the static loading. The applied test conditions are summarized in Table 2.

2.3. Specimen preparation

The specimen of composite girder with corrugated steel web was designed with a length of 1600 mm, a height of 335 mm and span of 1400 mm. The width of the top slab is 520 mm and the thickness is 45 mm. And the counterpart dimensions for the base slab are 330 and 60 mm, respectively. The height of web is 213 mm, the width of flange is 42 mm with a thickness of 2 mm. The inter-space of perfobond shear connectors is 26.54 mm. Dimensions of the specimens are shown in Fig. 2.

Table 1
Material properties of concrete, steel rebars, corrugated steel web and CFRP sheets.

Material	Dimensions(mm)	F_c (MPa)	f_y (MPa)	f_u (MPa)	E (GPa)	N (%)
Concrete	C50	54.5	–	–	3.8	–
Steel bars	D = 6, D = 8		240	420	210	30
Corrugated steel web	–	–	420	570	201	

Table 2
Test program-applied test condition.

NO.	r	F_{max} (kN) and load cycle ($\times 10^6$)	Load bearing capacity (kN) or load cycle	Test condition
BS1	–	–	219	Static
BF1	0.1	90 (0–1),100 (1–1.5),110 (1.5–2)	2×10^6	Fatigue
BF2	0.1	100 (6)	6×10^6	Fatigue

2.4. Strain gauge measurements

The strain gauge was used to measure the local deformation during the test. The locations of measured strain in this test are listed as the following:

- Normal stresses at the top and base slab concrete;
- Normal stresses on the mid-span and loading point of steel web;
- Normal stresses in the perfobond leiste (PBL) shear connectors.

The details arrangements of strain gauges were shown in Fig. 1. Moreover, three linear variable displacement transducers (LVDT) were placed to measure deflections at the loading points and mid-span. A hand-held microscope with a resolution of 0.02 mm was used to measure the width of cracks.

3. Results and discussion

3.1. Failure mode

3.1.1. The specimens under static load

The representative failure patterns for all the specimens tested are shown in Fig. 3. The failure mode of Girder BS1 (Fig. 3a) is a typical local failure pattern. The longitudinal crack which is numbered as 1 initiated at the supports point of base slab concrete, then it propagated to the whole slab until the fracture of concrete. When the load increased up to 180 kN, all the cracks coalesce to the shear connector at mid-span, and the maximum crack width is 0.89 mm. When the load reached 219 kN, many tiny cracks appeared on the roof slab. A Slip could be observed between concrete and shear connector, and concrete dowel was damage in shear. From the top side, it can be seen that the concrete was in one-way slab stress.

3.1.2. The specimens under fatigue load

The failure mode of the composite girder under fatigue loading is different from the specimens suffering static load, as shown in Fig. 3b. The first fatigue crack initiated at the support point of the bottom slab when the cyclic life is almost 2000 cycles and many tiny cracks propagated to the soffit of the concrete slab, by which the concrete slab was divided into several regions. When the cyclic load reached 1.65×10^6 cycles, a crack initiated on the corrugated steel web at the transition region between steel web and concrete of pure bending section. When the cyclic

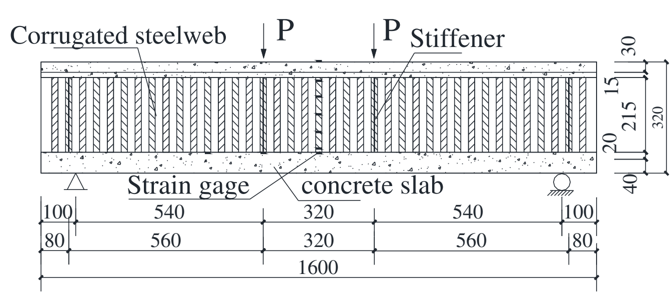

Fig. 1. Strain gauge arrangement and Loading sketch map.