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Research Article

Fatigue Tests of Concrete Slabs Reinforced with Stainless Steel Bars

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Experimental studies on fatigue behavior of reinforced concrete slab with stainless steel rebar and carbon steel rebar have shown that, at the same reinforcement ratio, the slope of the deflection-cycle number curves of stainless steel-reinforced concrete slab is lower than that of ordinary steel-reinforced concrete slab. The higher the reinforcement ratio is, the smaller the maximum crack width would be. Higher stress level contributes to larger deflection and reinforcement strain in midspan and shorter fatigue life. Compared to the ordinary steel-reinforced concrete slab, the stainless steel-reinforced concrete slab shows narrower maximum crack under the same number of loading cycles. Less significant midspan deflection, reinforcement strain, and longer fatigue life are observed in stainless steel-reinforced concrete slab at the same reinforcement ratio, stress level, and cycling time. With the increase of reinforcement ratio, the deflection and fatigue life extended.

1. Introduction

It is well known that the excellent corrosion resistance behavior of stainless steel rebar contributes a lot to the effective improvement in structural durability and structural life [1–3]. Stainless steel rebar has been widely used in reinforced concrete structures in the United States, Britain, and other countries, along with corresponding standards [4, 5]. The 1.4362 duplex stainless steel rebar also be applied to Hong Kong-Zhuhai-Macao Bridge. Researchers worldwide have done numerous studies regarding the performance of stainless steel-reinforced concrete [6, 7]. As civil engineering structure such as bridge and marine is usually underfacing repeating cyclic loading, such as vehicle vibration, wave actions, and currents. These structures always collapse when the failure load is lower than the ultimate load, which end up a severe cost to peoples' lives and property. Countless research studies have been devoted to the fatigue performance of reinforced concrete [8], but few studies on the fatigue performance of stainless steel-reinforced concrete slabs were reported. Studies on the fatigue performance of stainless steel-reinforced concrete slabs and ordinary steel-reinforced concrete slabs are carried out in this paper.

2. Experimental Situation

Experiment is designed with a total of 5 specimens which were divided into 3 groups, to simulate a simply supported single-span bridge deck [8–14]. Design parameters of the specimens are shown in Table 1. C30 concrete was used in 150 mm × 500 mm × 2500 mm specimens, with a 20 mm thick longitudinal reinforcement protective layer (Figures 1 and 2).

The 1.4362 duplex stainless steel rebar is provided by UGITECH, with yield strength of 750 MPa, tensile strength of 880 MPa, elongation of 17%, and elastic modulus of 1.93×10^5 MPa. The corrosion resistance of the 1.4362 duplex stainless steel rebar is better than that of 304 and 316 stainless steel, with reasonable price as well. Thus, it has been widely used in marine concrete in recent years. Carbon steel rebar used in this study was hot rolled steel rebar HRB335, as shown in Table 2.

Cyclic loading was applied to the specimens [15, 16]. After a given amount of loading cycle, the midspan deflection, the strain in the tensile area, and the crack under the upper limit of the cyclic loading would be measured by replacing with static load of the same value to obtain the development of the deflection, strain, and crack.

Table 1: Design parameters of the specimens.

Specimen ID	Longitudinal rebar	Distributing rebar	Reinforcement ratio
B-1-1	4S10*	ϕ8@200	0.5%
B-1-2	4S10*	ϕ8@200	0.5%
B-1-3	4S10*	ϕ8@200	0.5%
B-2-1	4S14*	ϕ8@200	0.98%
B-3-1	4ϕ10	ϕ8@200	0.5%

*1.4362 duplex stainless steel rebar.

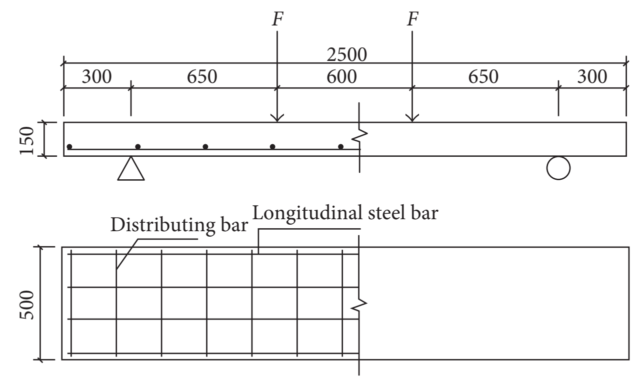

Figure 1: Reinforcement of specimens.

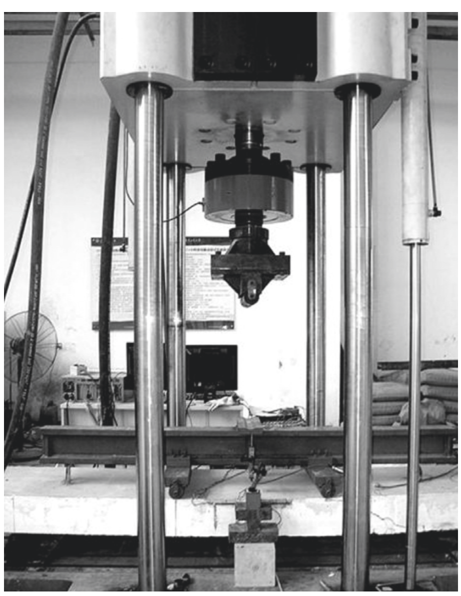

Figure 2: Practicality picture of the test.

Table 2: Mechanical properties of HRB335 and 1.4362 duplex stainless steel.

Reinforcement type	Yield strength (MPa)	Tensile strength (MPa)	Elongation (%)	Elastic modulus (GPa)
HRB335	335	455	20	200
1.4362 duplex stainless steel	750	880	17	193

3. Experimental Results and Analysis

3.1. Experimental Procedures. Based on the damage tolerance design principle, the fatigue loading cycles are determined by the SDS500 Dynamic and Static Test Machine with Electro-Hydraulic Servo Controlled. Two fatigue failure criteria were applied.

3.1.1. Fatigue Failure of Reinforcement. By increasing the fatigue loading cycles, the deformation and steel reinforcement damage in cracking area were greater than those in the remaining parts due to stress concentration. Fatigue failure occurred in reinforcement when the deflection and damage accumulated to a certain point, which appeared in the specimen B-1-3.

3.1.2. Limited Crack Width in Normal Section. According to the limit stipulated in the Chinese Code GB/T 50152 (2012) [10], specimen would be considered as damaged when the width of normal section crack reaches 1.5 mm. This failure mode appeared in specimens B-1-1, B-1-2, B-2-1, and B-3-1.

The imposed conditions and the fatigue life of specimens are shown in Table 3. When increasing stress level (the ratio of maximum load stress to the ultimate load capacity of specimens), the fatigue life of the stainless steel-reinforced concrete slab decreased. With the same reinforcement ratio and stress level, the fatigue life of the stainless steel-reinforced concrete slab was longer than that of the ordinary steel-reinforced concrete slab. Therefore the increasing of the reinforcement ratio is beneficial for the fatigue life [15].

3.2. Deflection. The deflection-cycle number curves of stainless steel-reinforced concrete slabs are shown in Figure 3(a), and the specimens with the same reinforcement ratio were under different stress levels. Before a loading cycle of 0.1×10^6 times was applied, the midspan deflection of slab significantly increased and the slope was steep at this stage. With the increase of loading cycles, the slope of the deflection curve decreased and the deflection increased, mainly because there was less significant residual deflection at this stage. Due to the high stress level, the specimen B-1-3 had a failure mode of reinforcement fatigue failure. Its midspan deflection greatly increased at the later stage of the cyclic loading. The final deflection was similar to the deflection in static load. Compared to the specimen B-1-3, the stress level of specimens B-1-1 and B-1-2 was relatively lower, and no significant increase in the midspan deflection at the later stage of the cyclic loading was observed. With the same reinforcement ratio, the higher

Table 3: Imposed conditions and the corresponding fatigue life.

Specimen ID	Maximum loading (kN)	Minimum loading (kN)	Stress level	Fatigue life (times)
B-1-1	52	19	0.52	2.06×10^6
B-1-2	45	19	0.45	2.18×10^6
B-1-3	85	19	0.85	1.66×10^6
B-2-1	52	19	0.52	2.32×10^6
B-3-1	52	19	0.52	1.87×10^6

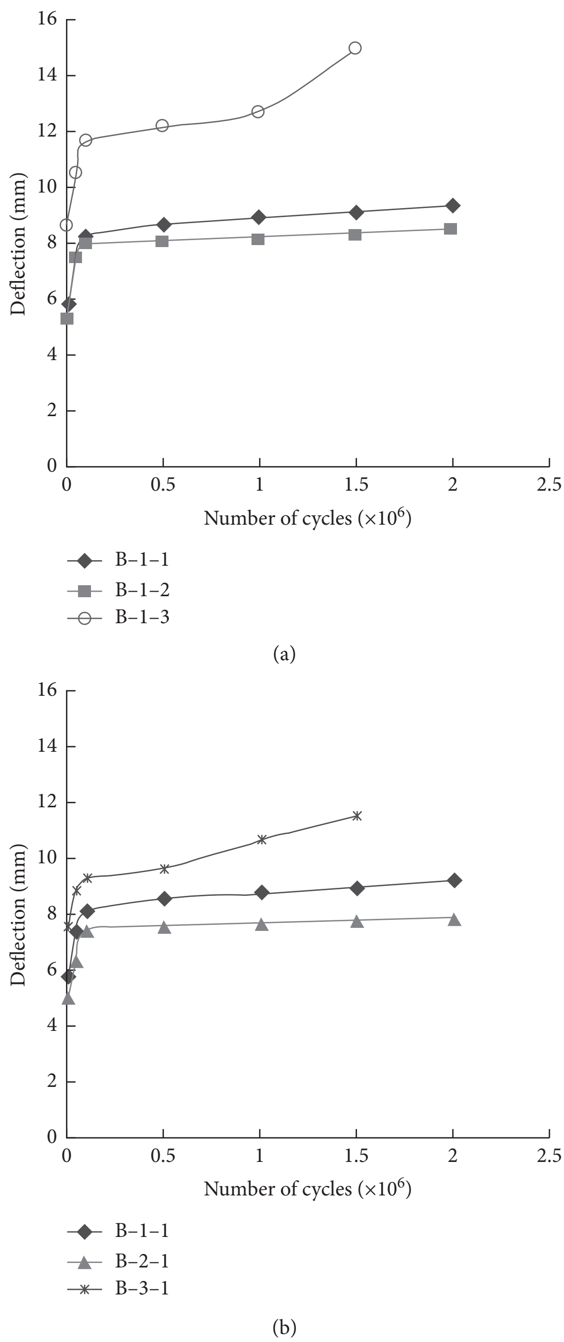

Figure 3: Deflection-cycle number curves.

the stress level was, the larger the midspan deflection would be. By increasing the stress level, the slope would be steeper and the residual deflection would be more significant as well [15].

Figure 3(b) shows the comparison of deflection-cycle number curves between the stainless steel-reinforced concrete slab and the ordinary steel-reinforced concrete slab. The specimens were at the same stress level, but different reinforced ratios and reinforcement types. The figure shows steep deflection increases at the beginning of the cyclic loading and tends to be relatively stable afterwards. With the same reinforcement ratio, the slope of the deflection-cycle number curve of stainless steel-reinforced concrete slabs was small. This indicates that the rigidity degradation of ordinary steel is faster than stainless steel, and the cumulative fatigue damage is more significant. The higher the reinforcement ratio of the stainless steel-reinforced concrete slab was, the smaller the midspan displacement would be, and the slower the stiffness degradation would be.

3.3. Strain of Reinforcement. The reinforcement strain-cycle number curves shown in Figure 4 are similar to the deflection-cycle number curves in Figure 3. For the specimen B-1-3, with the increasing of cycles, three typical stages can be found in the dynamic change of tensile reinforcement strain: initial stage, stable stage, and accelerated development stage. In the middle stage of the cyclic loading, the development of steel strain is mainly attributed to the development of residual strain [6, 7]. As the fatigue failure was different from the static loading failure, no apparent necking phenomenon was observed [16]. Therefore, although the strain value of the tensile steel increased during the failure of B-1-3, it is far less than that under static load.

3.4. Cracks. Crack distribution pattern in the specimen B-3-1 is shown in Figure 5. Vertical cracks were first observed in pure bending section of the slab with the width of approximately 0.2 mm. Most of the cracks occurred near the loading point. 5 smaller diagonal cracks extended out to the loading points were noticed in the flexure-shear section, of which the widths were all smaller than 0.1 mm [17, 18]. It was observed that the width and the quantity of the crack increased rapidly along with the cyclic loading at an early stage. The growth tended to be smooth at midstage and became significant again at later phase. In the fatigue test, a number of tiny cracks emerged during the increase of fatigue cycles, which differentiate its result pattern from the static load tests [19–22]. During fatigue loading, the initial cracks in pure bending section gradually get widened and extended upward. New cracks were found growing among the major fractures. From the midstage to the late stage of the cyclic loading, one of the cracks grew to be a major crack; meanwhile, other fractures became stabilized [13, 16]. From the flexure-shear section, new cracks can be found when increasing the cycle [17, 18]. These cracks developed slowly and were relatively narrower. In general, certain quantity of cracks exists when a structure is at its service stage, whereas when the structure is under fatigue cyclic loading, decreased fatigue strength and wider cracks can be found when increasing the cycles due to the degradation of mechanical property.

Under cyclic loading, the maximum width of crack increased with the higher stress level. The higher the

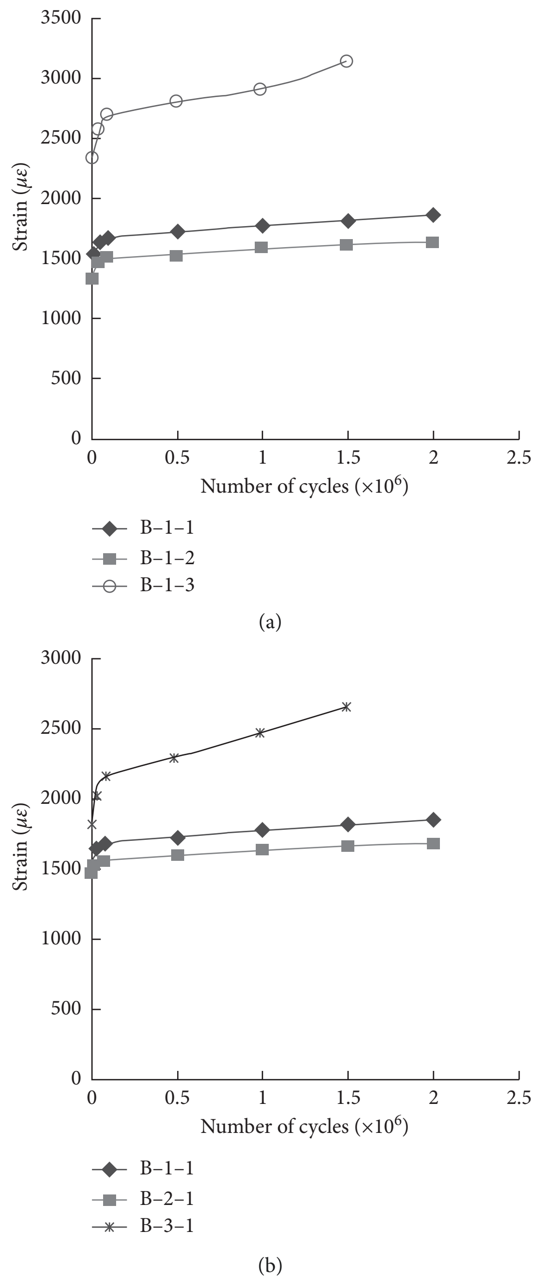

Figure 4: Reinforcement strain-cycle number curves.

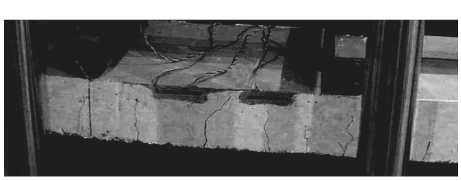

Figure 5: Crack pattern of the specimen B-3-1.

reinforcement ratio was designed, the smaller the maximum crack width would be. With the same cycles, the maximum crack width of the stainless steel-reinforced concrete slab was smaller than that of the ordinary steel-reinforced concrete slab. It indicates that the stress level, type of reinforcement, and

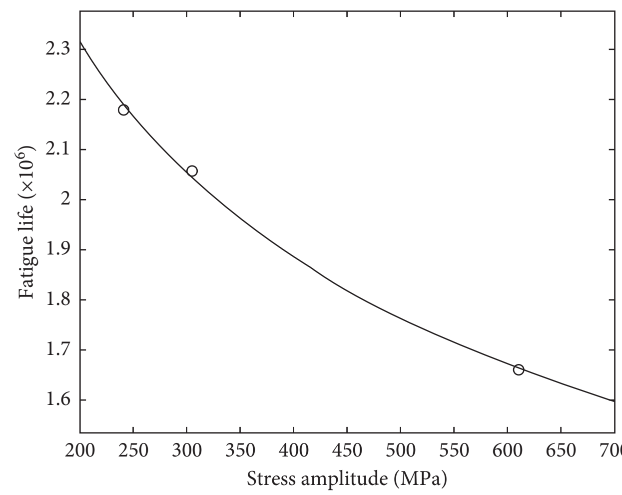

Figure 6: S-N fatigue curve.

reinforcement ratio have significant impacts on the crack extension in the slab.

4. S-N Fatigue Curve

Stress amplitude of reinforcement is the main factor affecting the fatigue strength of a specimen. The S-N curve (or the Wohler curve) is a hyperbola in the rectangular coordinates with an expression of $N\sigma^{\mathrm{m}} = \mathrm{C}$ (m and C are the material constants, and the fatigue life N is defined as the number of cycles the specimen bear before fatigue failure). According to the theoretical stress formula of the Chinese Code GB50010 (2010) [11], we can calculate the stress amplitude $\Delta\sigma$ of the steel bar by (1). The residual fatigue life of the specimen can be calculated by subtracting the load cycles from the total fatigue life N.

From the results obtained in this study, as is shown in Figure 6, the fit S-N curve for stainless steel-reinforced concrete slabs under fatigue loading is as follows:

$$\lg N = 3.0481 - 0.2969 \lg \Delta\sigma, \tag{1}$$

where N is the fatigue life (10^4 times) and $\Delta\sigma$ is the stress amplitude of the steel bar (MPa).

5. Conclusions

With the increase of loading cycles, the midspan deflection and tensile steel strain of the specimens increased simultaneously. With the same reinforcement ratio, the higher the stress level was, the larger the deflection would be, so as the steel strain and the crack width, and thus the shorter the fatigue life was. Compared to the ordinary steel-reinforced concrete slab, stainless steel-reinforced concrete slab showed smaller midspan deflection, steel strain, maximum crack width, and longer fatigue life under the same cyclic loading. Increasing the reinforcement ratio of the stainless steel-reinforced concrete slab would further reduce the deflection and the crack width, which would elongate the fatigue life. With the same number of cyclic loading and reinforcement ratio, the maximum crack width of the stainless steel-reinforced concrete slab was smaller and the fatigue life was longer than those of the ordinary steel-reinforced concrete slab.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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