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Fatigue behavior of crane beam strengthened with CFRP

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Abstract: In order to study the fatigue behavior of the damaged reinforced concrete (RC) beams strengthened by carbon fiber reinforced polymer (CFRP) laminate, three T-shaped beams strengthened by CFRP and one contrasting beam are tested under fatigue loading, with the parameters of different modes of strengthening and different fatigue load levels considered. The main results obtained from the tests are: the width of the crack decreases 50.2% to 66%, and the development of the crack is limited; the stress of steel decreases 24.1% to 28.2%, and the stiffness increases 14.9% to 16.1% after being strengthened. Based on the technical specification for strengthening concrete structures with CFRP and the conclusions from the tests, a calculating scheme of the flexure stiffness is given, which can be used for reference in engineering design. Finally, some suggestions are given for design in fatigue strengthening.

Key words: RC crane beam; structure strengthening; fatigue test; carbon fiber reinforced polymer (CFRP)

The flexural stiffness is one of the most important parameters in evaluating the structural health of a reinforced concrete crane beam. Many crane beams suffer excessive deformations or have insufficient load carrying capacity as time elapses so that they need to be strengthened for further use[1].

From the beginning of the 1990's many scientific research centers have been involved in wide researches of the material properties of carbon fiber reinforced polymer (CFRP) laminate as well as the behavior of structures strengthened with those materials. Many tests of strengthened members under monotonic loads have been performed and have given rise to many conclusions. A number of technical specifications are available for practical applications[2]. However, these specifications do not explicitly address the stiffness of the strengthened member. There has been relatively little investigation into the fatigue behavior of reinforced concrete crane beams with CFRP retrofits[3-7]. But the results obtained in different studies appear to be different. This contradiction causes the authors to start a research program aiming to studying the damage mode and the fatigue behavior of RC crane beams strengthened with CFRP.

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1 Experimental Program

Three CFRP strengthened beams and one control beam (without strengthening) are tested under fatigue loading. Of particular interest in this study is the scale effect. The T-shaped beams used in this study are half scale models of a crane beam from an old industrial mill factory. The details of the beams are shown in Fig. 1.

Grade HRB335 deformed reinforcing bars are used as tensile steel. The yield and tensile strengths are 409.5 and 578.7 MPa, respectively. The compression bars and stirrups are from grade HPB235 steel, with yield and tensile strengths of 338.3 and 509.1 MPa, respectively. Concrete of grade C30 is used for all beams. The beams are cast together and the actual 28-day strength obtained by standard specimens is 20.64 MPa, and the average elastic modulus is 39.500 GPa. The thickness of CFRP is 0.111 mm with strengths and an elastic modulus of 4.192 5 and 243. 149 2 GPa, respectively. The actual strengths of the adhesive are 3 134 MPa, with an elastic modulus of 2 350 GPa and a fracture strain of 1.5%. The whole strengthening procedure is done by specialists. The beams are cured for more than 28 d, and the adhesive is cured for more than one week. All of the rebars are tied rather than tack-welded, in order to reduce the risk of a premature fatigue failure. Furthermore, four steel plates are cast into the concrete at the supports and the load application points of the beams to prevent local failure of the concrete.

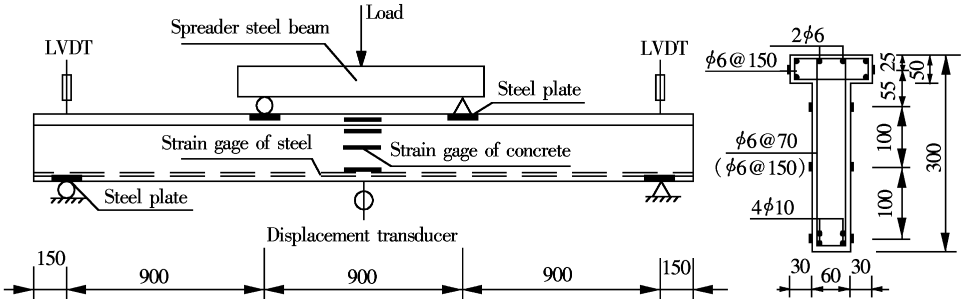

Fig. 1 Details of specimens and test setup (unit: mm)

Three beams are retrofitted with CFRP materials on the soffit of the T-beam web. Two different CFRP systems are used. The retrofit extends over most of the length of the beam but not to the supports. No additional anchorage, apart from the adhesive system, is used in B1a. In contrast, the longitudinal CFRP of beams B1b and B1c is additionally anchored by U-shaped CFRP in the shear spans. B0 is left without retrofit and used as a control specimen. The test setup is shown in Fig. 1 and the particulars of the four beams are summarized in Tab. 1.

Tab. 1 Summary of test beams kN

Beam identification	P_{min}	P_{max}	Strengthening
B0	5	30	Not strengthened
B1a	5	70	One layer of CFRP
B1b	5	70	One layer of CFRP and U-shaped anchorages
B1c	5	55	One layer of CFRP and U-shaped anchorages

In order to simulate the real condition of the crane beam, all the beams are preloaded to ensure that the widths of primary cracks correspond to the maximum width of 0.2 mm allowed by the specification[2]. After that, B1a, B1b, B1c are strengthened and tested under fatigue loading conditions. Various technical specifications [8] and other representative tests [3-7] are used as references during the tests.

The fatigue load is applied by means of electronically controlled hydraulic pulsates at the Structural Laboratory of Southeast University. The beam is loaded at two points via a spreader steel beam, each located 900 mm from the support. The load cycle frequency ranges from 4 to 6 Hz.

During each test, the following values are measured: ① Number of cycles; ② Applied force measured in a dynamometer; ③ Deformations and dynamic deflections measured by linear voltage displacement transducers located at the midspan of the beam and at the two supports; ④ Steel strains and dynamic strains measured by electrical resistance strain gauges; ⑤ Strains in the concrete compression zone measured at the top edge of the beam and on the side faces; ⑥ Strains of CFRP laminates.

The static data and dynamic data are collected by a DH3818 data logger and a DHDAS data logger, respectively, which are linked by a computer. The data are automatically recorded by the computer. Tests are carried out continuously up to beam failure or until 2 million cycles are reached.

In Fig. 2, the strains at the critical section are plotted over the height of the section for different numbers of load cycles. The relative life is used rather than the number of cycles, which is the actual number of applied cycles normalized by the maximum number of cycles to failure. It can be concluded from Fig. 2 that the average strain at the critical section satisfies the plane section assumption. The steel strain is higher because the strain gauges are located close to a crack, so that the bar slip at the crack influences the measured steel strain.

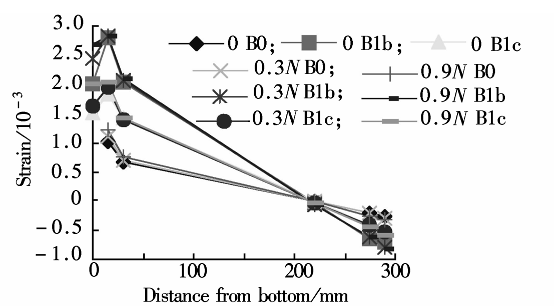

Fig. 2 Strain distribution at the critical section

Fig. 3 shows the load-deflection curves of the strengthened beams before and after strengthening. In Fig. 3, "U" and "S" mean unstrengthened and strengthened, respectively. The stiffness of the beams after retrofitting is greater, as may be expected. The average flexural stiffness of the CFRP strengthened beams is 14.9% to 16.1% greater than before strengthening, which demonstrates the effectiveness of the retrofit using CFRP.

Tab. 2 summarizes the analytically calculated and the measured mid-span deflections for increasing a nor-

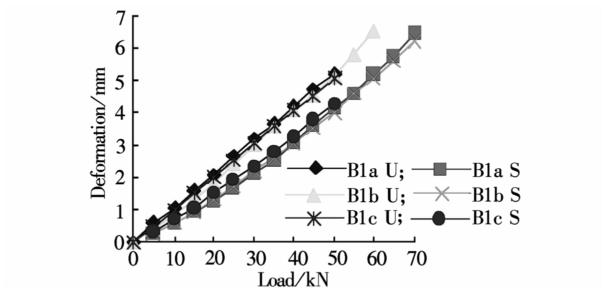

Fig. 3 Load-deflection curves of strengthened beams before and after strengthening

malized number of load cycles. The analytical response correlates well with the experimental data at all stages of behavior up to failure.

The residual concrete compression strains are illustrated in Fig. 4. It can be seen that strain development follows three distinct phases: a rapid increase from 0 to about 10% of the total fatigue life; a uniform increase from 10% to about 80% of the fatigue life, and finally a rapid increase up to fatigue failure.

Tab. 2 Comparison of calculated and measured mid-span deflections mm

Beam identification		Before strengthening	After strengthening	0. 1*N*	0. 3*N*	0. 5*N*	0. 7*N*	0. 9*N*
Measured results	B0	3. 18	—	3. 65	3. 69	3. 79	3. 82	3. 91
	B1a	5. 21	4. 53	7. 88	8. 34	8. 42	8. 51	8. 81
	B1b	5. 14	4. 31	8. 21	8. 77	9. 23	9. 81	10. 21
	B1c	5. 05	4. 44	6. 11	6. 33	6. 61	6. 91	7. 28
Analytical results	B0	3. 08	—	3. 71	3. 76	3. 82	3. 88	3. 93
	B1a	5. 51	4. 11	7. 99	8. 28	8. 55	8. 83	9. 02
	B1b	6. 91	5. 17	7. 99	8. 28	8. 55	8. 83	9. 02
	B1c	6. 21	4. 59	6. 22	6. 48	6. 75	7. 02	7. 41

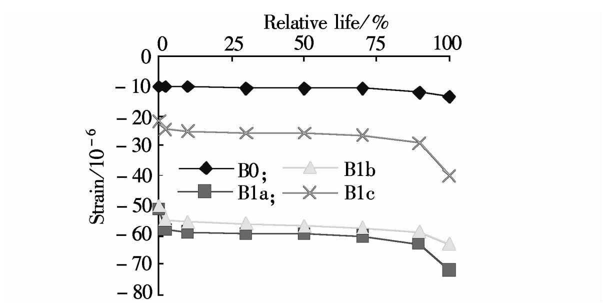

Fig. 4 Residual concrete compressive stain

Fig. 5 shows the mid span deflection versus the normalized number of load cycles for each beam. The applied upper load is given in the diagram for each beam for reference. It is evident that the development of deformation is similar to the development of the residual concrete compression strain during the test. It can also be seen that the U-shaped CFRP anchorages provided for B1c effectively prevent the debonding of the CFRP laminates. By comparison the residual concrete strains as well as the deflections of B1a and B1b which do not have any U - shaped CFRP anchorages, are significantly greater, which can be attributed to some slip of the CFRP laminates.

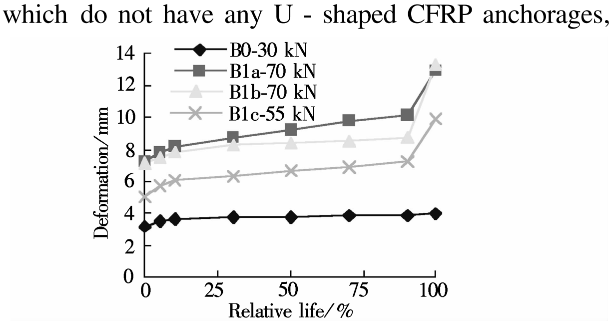

Fig. 5 Deflection versus normalized number of load cycles

2 Fatigue Stiffness Analysis of Crane Beams Strengthened by CFRP

2. 1 Constitutive properties of materials

When RC beams are subjected to repetitive cyclic loading, the stress conditions of the materials are not identical to those applying to monotonic loading conditions, resulting in a different failure mechanism. Therefore, the constitutive properties of materials are assumed to be as follows:

① Experimental results presented in many studies suggest that the modulus of elasticity for steel remains unchanged until just before failure by high cycle fatigue. In the following analysis, the modulus of elasticity for steel is therefore assumed to remain unchanged during cyclic loading.

② The CFRP fabric utilized in the tests is composed of unidirectional dry carbon material formed by weaving individual yarns into a fabric. The fracture of one yarn cannot influence the neighboring yarns, which causes good fatigue resistance. The fatigue strength of CFRP can reach 70% or 80% of its rupture strength[9]. Test data suggest that the behavior of CFRP is virtually unaffected by fatigue loading. Hence, the modulus of elasticity for CFRP remains constant.

③ The fatigue behavior of concrete has been investigated by many researchers. Test results indicate a strongly nonlinear stress-strain relationship for concrete when subjected to fatigue loading, and various fatigue models have been developed. Most scholars propose that the elastic-plastic deformation of concrete is the sum of two components: elastic and residual deformations, which are denoted as $\varepsilon_{\mathrm{e}}^{\mathrm{f}}$ and $\varepsilon_{\mathrm{r}}^{\mathrm{f}}$:

$$\varepsilon^{\mathrm{f}}=\varepsilon_{\mathrm{e}}^{\mathrm{f}}+\varepsilon_{\mathrm{r}}^{\mathrm{f}}=\frac{\sigma_{\mathrm{c}}^{\mathrm{f}}}{E_{\mathrm{c}}}+\varepsilon_{\mathrm{r}}^{\mathrm{f}} \tag{1}$$

The modulus of elasticity of concrete can then be expressed as

$$E_{\mathrm{c},N}^{\mathrm{f}}=\frac{\sigma_{\mathrm{c}}^{\mathrm{f}}}{\varepsilon^{\mathrm{f}}}=\frac{\sigma_{\mathrm{c}}^{\mathrm{f}}}{\sigma_{\mathrm{c}}^{\mathrm{f}}/E_{\mathrm{c}}+\varepsilon_{\mathrm{r}}^{\mathrm{f}}} \tag{2}$$

Baluch et al. [10] established the residual deformation of concrete depending on the stress range, stress level and the number of load cycles as

$$\varepsilon_{\mathrm{r}}^{\mathrm{f}}=129S_{\mathrm{m}}t^{1/3}+17.8S_{\mathrm{m}}\Delta N^{1/3} \tag{3}$$

where $\Delta=S_{\max}-S_{\min}=(\sigma_{\mathrm{c,max}}-\sigma_{\mathrm{c,min}})/f_{\mathrm{c}}$ is the stress range; $S_{\mathrm{m}}=(S_{\max}+S_{\min})/2=(\sigma_{\mathrm{c,max}}+\sigma_{\mathrm{c,min}})/(2f_{\mathrm{c}})$ is the average stress level; $\sigma_{\mathrm{c,max}}=M_{\max}^{\mathrm{f}}\,x/I_0$ and $\sigma_{\mathrm{c,min}}=M_{\max}^{\mathrm{f}}\,x/I_0$ are the maximum and minimum stresses of the concrete; t is the duration of cyclic loading in hours; and N is the number of load cycles.

Because the stress distribution in the cross section of a beam subjected to bending moments is not uniform, Eq. (3) must be modified to allow for the stress gradient:

$$\varepsilon_{\mathrm{r}}^{\mathrm{f}}=K_N(129S_{\mathrm{m}}t^{1/3}+17.8S_{\mathrm{m}}\Delta N^{1/3}) \tag{4}$$

where $K_N=8.7$ is a modification factor obtained from a regression analysis of the test data. Concrete under tension is assumed to have no significant tensile strength during cyclic fatigue calculations. Furthermore, the epoxy between the CFRP laminates and concrete is assumed to be rigid and unaffected by cyclic loading. This is a reasonable assumption for beams where failure is initiated in the zone of large bending moments where shear stresses in the epoxy are low.

2.2 Main assumptions

The main assumptions are given as follows:

① Plane sections are considered to remain plane after bending.

② Perfect bond and no slipping is assumed between concrete and other materials (steel reinforcement and CFRP laminates).

③ The tensile action of concrete is not accounted for. The tensile reinforcement and CFRP provide the tensile forces in the section. The stress-strain diagram of concrete in compression is triangular.

④ The constitutive properties of the materials are as stated above.

2.3 Theoretical analysis

After a specific number N of load cycles, the neutral axis depth can be calculated by

$$b_{\mathrm{f}}h_{\mathrm{f}}\left(x_N-\frac{h_{\mathrm{f}}}{2}\right)+\frac{b(x_N-h_{\mathrm{f}})^2}{2}+\alpha_{\mathrm{E}}^{\mathrm{f}'}A_{\mathrm{s}}'(x_N-a_0')=\alpha_{\mathrm{E}}^{\mathrm{f}}A_{\mathrm{s}}(h_0-x_N)+\alpha_{\mathrm{cf}}^{\mathrm{f}}A_{\mathrm{cf}}(h-x_N) \tag{5}$$

where $\alpha_{\mathrm{cf}}^{\mathrm{f}}=E_{\mathrm{cf}}/E_{\mathrm{c}}^{\mathrm{f}}$, $\alpha_{\mathrm{E}}^{\mathrm{f}'}=E_{\mathrm{s}}'/E_{\mathrm{c},N}^{\mathrm{f}}$, $\alpha_{\mathrm{E}}^{\mathrm{f}}=E_{\mathrm{s}}/E_{\mathrm{c}}^{\mathrm{f}}$ are the modulus ratios for CFRP, and for steel in compression and tension; $E_{\mathrm{c},N}^{\mathrm{f}}$ is the modulus elasticity of concrete given by Eq. (2).

The second moment of the area of the cracked section can then be calculated as follows:

When $x>h_{\mathrm{f}}$,

$$I_N^{\mathrm{f}}=\frac{1}{3}[b_{\mathrm{f}}x_N^3-(b_{\mathrm{f}}-b)(x_N-h_{\mathrm{f}})^3]+\alpha_{\mathrm{E}}^{\mathrm{f}'}A_{\mathrm{s}}'(x_N-a_0')^2+\alpha_{\mathrm{E}}^{\mathrm{f}}A_{\mathrm{s}}(h_0-x_N)^2+\alpha_{\mathrm{cf}}^{\mathrm{f}}A_{\mathrm{cf}}(h-x_N)^2 \tag{6}$$

When $x\leqslant h_{\mathrm{f}}$,

$$I_N^{\mathrm{f}}=\frac{1}{3}b_{\mathrm{f}}x_N^3+\alpha_{\mathrm{E}}^{\mathrm{f}'}A_{\mathrm{s}}'(x_N-a_0')^2+\alpha_{\mathrm{E}}^{\mathrm{f}}A_{\mathrm{s}}(h_0-x_N)^2+\alpha_{\mathrm{cf}}^{\mathrm{f}}A_{\mathrm{cf}}(h-x_N)^2 \tag{7}$$

The neutral axis depth of the beam at a given time can be obtained from Eqs. (2) to (7), and then the expression for the fatigue stiffness depending on the number of load cycles is

$$B_N=f(N)=E_{\mathrm{c},N}^{\mathrm{f}}I_N^{\mathrm{f}} \tag{8}$$

The deformation of the beam is then given by

$$f=\frac{Sl_0^{\,2}M}{B_N} \tag{9}$$

where $S=23/432$ is a factor derived from test results.

3 Conclusions

This paper demonstrates the feasibility of using unidirectional CFRP fabric for the rehabilitation and strengthening of RC structures with respect to both static and fatigue performance.

1) The beams fail primarily due to brittle fatigue fracture of the tensile reinforcing steel. However, owing to the presence of the CFRP sheets, these beams are able to continue supporting load cycles after failure of one or more of the reinforcing bars. Debonding of the CFRP composite sheet is a secondary mechanism in the strengthened beams, which leads to the function lapsing of CFRP. The failure is sudden and no signs of severe damage appear before failure.

2) The service load is limited to no more than 60.1 % of the ultimate capacity after being strengthened on the assumption that the CFRP is anchoraged enough.

3) The positive contribution of the CFRP strengthening is a probable decrease in the stress in the steel and the width of the cracks. The reduction of stress in the steel is 24.1% to 28.2%, and the crack

width is 50.2% to 66%, which improves the performance of the beams.

4) The stiffness is enhanced after strengthening with CFRP laminates by 14.9% to 16.1%.

5) The fatigue stiffness of beams strengthened by CFRP is analyzed by a feasible method with an acceptable precision, which can be used in engineering.

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碳纤维布加固钢筋砼吊车梁抗弯疲劳性能试验

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摘要:为研究碳纤维布(CFRP)对加固后钢筋混凝土梁的抗弯疲劳性能的影响,进行了3根CFRP加固梁及1根对比梁的抗弯疲劳试验.研究了碳纤维布加固方式、构件使用荷载等参数对碳纤维布加固损伤钢筋混凝土吊车梁的抗弯疲劳性能影响.试验研究表明:采用碳纤维布加固后,构件裂缝的宽度减小50.2%~66%,发展速度也得到控制,钢筋应力减小24.1%~28.2%,构件的刚度提高14.9%~16.1%.依据试验结果,从现有规范中关于构件刚度计算方法出发,进行了CFRP加固钢筋混凝土吊车梁的疲劳刚度计算分析,该计算方法可用于吊车梁加固工程设计.最后给出了CFRP加固梁的疲劳设计的合理化建议.

关键词:钢筋混凝土吊车梁;结构加固;疲劳试验;碳纤维布

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