Fatigue life of CFRP laminate strengthened high-strength steel plates under fatigue loadings

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Abstract. Carbon fiber reinforced polymer (CFRP) sheets and laminates are effective and practical for strengthening steel with initial damages under fatigue loading due to its advantageous strength and fatigue resistance. Unfortunately, studies of cracked high-strength steel plates strengthened by CFRP laminates are still limited. This paper studies the strengthening efficiency of CFRP laminate on cracked Q345, Q460 and Q690 steel plates under fatigue loading. It is found that the fatigue life by CFRP laminates is increased to 1.53 to 3.84 times as that of un-strengthened specimen. Compared with CFRP sheet with the similar reinforcement stiffness, CFRP laminate strengthened specimens exhibit longer fatigue life under low stress range (195 MPa), and shorter fatigue life under high stress range (240.5 and 402.5 MPa). The difference is due to the matched adhesive of CFRP laminates (Araldite-2015) has lower elastic modulus but higher strength and ductility compared with matched adhesive of CFRP sheets (E2500S). Thus the material property of adhesive is a key factor determining fatigue life under different range of fatigue loadings. Crack propagation and different failure modes were observed. Serious debonding around the crack tip occurred, which leads to a further study.

1. Introduction

As one of the main problems with steel members and connections, fatigue failure result in considerable casualties and economic loss because of its brittle and sudden characteristics [1]. Facing the fact that many metallic structures are aging, retrofitting existing structures rather than replace them is more economical and practical. Many previous studies [2-4] have proved the strengthening efficiency of CFRP on normal strength steel under fatigue loading. As the development of industry, high strength steel is widely used in civil engineering. As far as now, there is limited work on the high strength steel strengthened by CFRP under fatigue loading. Hu et al. [5] carried out fatigue tests of CFRP sheets strengthened high strength steel plates, which shows that CFRP sheets strengthening can effectively improve the fatigue life 1.3–3.1 times compared with un-strengthened specimens except for those under very high stress range. However, strengthening efficiency of CFRP laminate on high strength steel under fatigue loading is still unclear up to now. Thus, in this paper, fatigue tests of CFRP laminate strengthened Q345, Q460 and Q690 steel plates are conducted, fatigue life, crack
propagation and failure modes are obtained, followed by a comparison of results with CFRP sheet strengthening.

2. Material

High strength steel is defined as steel with a yield stress larger than 460 MPa but smaller than 1000 MPa. Thus Q345, Q460 and Q690 steel are chosen as the test materials. Material tests were conducted to determine the properties of them, which is the same as paper [5], as shown in Table 1.

| Steel grade | Elastic modulus (GPa) | Yield stress (MPa) | Ultimate tensile strength (MPa) | Thickness (mm) |
|-------------|----------------------|-------------------|-------------------------------|---------------|
| Q345D       | 201                  | 390               | 509                           | 16            |
| Q460C       | 201                  | 481               | 612                           | 12            |
| Q690D       | 201                  | 805               | 823                           | 14            |

Unlike CFRP sheet, which refers to only carbon fiber without any adhesive, CFRP laminate is composed of adhesive and carbon fiber, which is thicker and stiffer than CFRP sheet. CFRP laminates in this test are provided by HS Co., Ltd (Jiangsu Province, China). According to the manufacturer, the
thickness is 1.4 mm, the width is 50 mm, the ultimate tensile strength is 2454 MPa and the elastic modulus is 168 GPa.

According to previous studies [6], a suitable adhesive should be used. Suggested by the manufacturer, the adhesive Araldite-2015 is provided for use with the CFRP laminate, which has two components, epoxy adhesive and curing agent. The mass mixing ratio of epoxy adhesive and curing agent is 1:1. After mixing, the mixture is poured into a mould. The geometrical dimension of the mould for test sample is shown in Figure 1(a). After 21 days of curing, the samples are successfully made. Then the static tensile test was performed (see Figure 1(b)), and a total of 6 standard samples of Araldite-2015 specimen were tested. The above are in accordance with GB/T 2567-2008 [7]. The result of material test is shown in Figure 1(c). The elastic modulus is obtained from the initial slope of the curve (2.10 GPa), the ultimate tensile strength is 23.5 MPa, and the ultimate tensile strain is 1.71%. Compared with the adhesive ES2500 for CFRP sheets in paper [5], Araldite-2015 has a lower initial elastic modulus but higher strength and deformation capacity.

3. Specimen and test set up

In this study, three CFRP laminate strengthened (LS) specimens were investigated, as shown in Table 2. The subscripts 345, 460, or 690 are used to denote the nominal yield stress of the steel. The number following yield stress is the maximum stress in fatigue loading. The configuration is presented in Figure 2.

The specimen preparation is the same as paper [5]. Besides, vacuum curing process was applied to achieve a three-dimensional pressure environment for curing, making sure an efficient bonding, as shown in Figure 2. In order to avoid unfavourable end debonding, a 50 mm wide CFRP sheet was wrapped around the end of the specimen for three turns. After one day of pumping, the adhesive was initially cured. Then the pumping was stopped. Finally the specimens were cured at ambient temperature for one week until testing. The testing and measurement are the same as paper [5].

![Figure 2. Configuration of unstrengthened and strengthened specimens; manufacturing process.](image)

**Table 2. Details of fatigue tests.**

| Specimen | Yield stress $f_y$ (MPa) | Maximum stress $\sigma_{max}$ (MPa) | Stress level $\sigma_{max}/f_y$ (%) | Stress range $\Delta\sigma$ (MPa) | Frequency (Hz) |
|----------|-------------------------|-----------------------------|---------------------------------|-------------------------------|---------------|
| SL345-195.0 | 390 | 195 | 50 | 175.5 | 5 |
| SL460-240.5 | 481 | 240.5 | 50 | 216.5 | 5 |
| SL690-402.5 | 805 | 402.5 | 50 | 362.3 | 3 |

4. Test results and analysis

The average fatigue life of un-strengthened Q345, Q460 and Q690 cracked steel plate, and that of CFRP laminate strengthened specimens are from paper [5], shown in Figure 3, where U represents un-strengthened specimen and SS represents CFRP sheet strengthened specimen. According to paper [8], the equivalent elastic modulus of the three-layer CFRP sheet considering the stress reduction...
calculation is 145.46 GPa, and the elastic modulus of CFRP laminate in this test is 168 GPa, so the reinforcement stiffness of the above two materials is:

$$E_S A_S = 145.46 \times 10^3 \text{MPa} \times 70 \text{mm} \times 1.16 \text{mm} = 11.81 \times 10^6 \text{MPa} \cdot \text{mm}^2$$ (1)

$$E_L A_L = 168 \times 10^3 \text{MPa} \times 50 \text{mm} \times 1.4 \text{mm} = 11.76 \times 10^6 \text{MPa} \cdot \text{mm}^2$$ (2)

where $S$ represents CFRP sheet and $L$ represents CFRP laminate. It is shown that the reinforcement stiffness of the above two materials is almost the same. Thus CFRP sheet and CFRP laminate strengthened steel plates should have the same fatigue life. However, as shown in Figure 3, the fatigue life of SL345-195 is lower than that of SS345-195; while the fatigue life of SL460-240.5 and SL690-402.5 is higher than that of SS460-240.5 and SS690-402.5, respectively. The reason for this difference is due to the adhesive properties, as shown in Figure 1(c). If the reinforcement stiffness is certain, when fatigue stress range is small, debonding did not happen too much, thus the strengthening efficiency is mostly controlled by the elastic modulus of the adhesive because of deformation compatibility; however, when the fatigue stress range is large, debonding happens seriously, thus the strengthening efficiency is mostly controlled by the strength and ductility of adhesive. Higher strength and ductility of adhesive can absorb more energy, which makes better bonding efficiency.

![Figure 3. Fatigue life of un-strengthened specimen, CFRP sheet strengthened specimen, and CFRP laminate strengthened specimens.](image)

The crack length vs. fatigue life curves are drawn in Figure 4. It is shown the crack developed with when fatigue cycles increase. The crack develops very slowly at the beginning and then becomes fast followed by a sudden fracture in the end.

Failure modes are shown in Figure 5. It is clear that debonding occurred around every crack front. It did not occur at the end of the CFRP laminate due to the effect of CFRP sheet hoop and vacuum curing process.

![Figure 4. Crack length vs. fatigue life curves](image)
5. Conclusions

Main conclusions can be drawn as the followings:

(1) The fatigue life by CFRP laminates is increased to 1.53 to 3.84 times as that of un-strengthened specimen when the maximum stress in fatigue loading is 50% of $f_y$.

(2) If the reinforcement stiffness is certain, when fatigue stress range is small, the strengthening efficiency is mostly controlled by the elastic modulus of the adhesive; however, when the fatigue stress range is large, the strengthening efficiency is mostly controlled by the strength and ductility of adhesive.

(3) Debonding clearly occurred around the crack tip, which is hard to avoid, thus its influence on crack propagation and fatigue life should be further investigated.

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