Fatigue Life Prediction for Adhesive Bonding in Steel Beams Strengthened With a Carbon Fibre Composite Plate

Jun Deng
Lecturer
South China University of Technology
Guangzhou, China
dengjun@scut.edu.cn

Dr. Jun Deng, born in 1975, received his PhD degree from the Univ. of Southampton, UK.

Summary

This paper presents a theoretical and experimental study on the fatigue performance of the adhesive bonding in steel beams strengthened with a CFRP plate. Two phases of the fatigue life, including crack free life and crack propagation life, are considered. Ten steel beams strengthened with a bonded CFRP plate were tested under fatigue loading. An *S-N* curve based on the peak interfacial stresses is proposed to predict the fatigue life to crack initiation in the adhesive layer of the retrofitted beams. A formula based on the Paris Law is developed to predict the fatigue life during the crack propagation along the interface between the steel beam and adhesive layer as well. In addition, based on the findings obtained from the previous and present studies on adhesive bonding in the retrofitted beams, some design suggestions for steel beams strengthened by bonded CFRP plates are proposed.

Keywords: fatigue life; adhesive bonding; steel beam; CFRP plate; strengthening.

1. Introduction

Since the 1990s, the use of carbon fibre reinforced polymer (CFRP) materials has made large advances in civil engineering construction, particularly in bridge upgrade and rehabilitation. Stress analysis and experiments have led to a good understanding into the static behaviour of steel beams strengthened with CFRP plates. However, less is known about the fatigue behaviour, which might be a crucial factor when designing the strengthening. To avoid fatigue cracking in the adhesive at the end of CFRP plate, the maximum interfacial stresses must be limited. This paper presents the laboratory fatigue tests of ten small-scale steel beams strengthened with a CFRP plate. According to the test results, an *S-N* curve based on the peak stresses of the bonded joints at the end of the CFRP plate is proposed to predict the crack initiation life for the strengthened beams. A formulation is developed to predict the fatigue crack propagation life as well.

2. Experimental details

Ten small-scale steel beams strengthened with CFRP plates were tested under fatigue loading. The clear span was 1.1 m and the loading point was at mid-span, as shown in Figure 1.

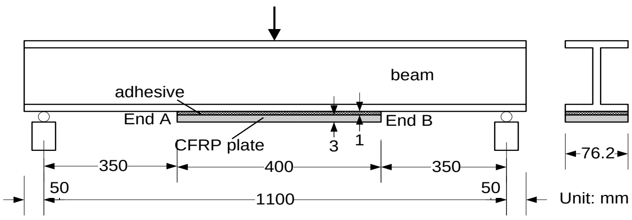

Fig. 1 Geometry of the retrofitted beam

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3. Results and discussions

Before crack initiation, theoretical analysis shows that the maximum principal interfacial stress is constant. The relationship between the maximum principal interfacial stresses σ_n and the log of crack initiation life N_1 is approximately linear and regression analysis produced the following best-fit equation (correlation coefficient, $R^2 = 0.954$):

$$\sigma_n = 78.62 - 4.19 \ln N_1 \tag{1}$$

Two specimens under the maximum load of 40 kN did not fail even after four million cycles. Therefore, the fatigue threshold for the tested beams is 40kN, with a corresponding threshold stress 23.8 MPa for the adhesive. This threshold limit is about 30% ultimate failure stress 80.4 MPa under static load.

In accordance with Paris Law, the relationship between the crack propagation rate da/dN and the energy release rate G can be expressed as:

$$\frac{da}{dN} = D(G_{\max})^n \tag{2}$$

where G_{max} is the maximum energy release rate during one fatigue cycle, D and n are the empirical coefficients. From the experimental data, the empirical coefficients D and n in Eq (2) are 10-11.7 and 2.75, respectively. The curves for the crack length a and the number of cycles N (not including the crack initiation life) obtained from the test are compared to the corresponding predicated results calculated by Eq. (2) and the agreement was found to be good.

4. Design recommendations

The following design suggestions are given in accordance with the findings obtained from the studies.

(1) Fatigue limit of the bonded joint in reinforced beams

- To avoid fatigue crack initiation in the adhesive at the end of the plate, the maximum adhesive stresses must be limited. The *S-N* curve investigated in this study shows the fatigue limit is 30% of the ultimate static failure stress.
- Since only one structural adhesive – Sikadur 31 Normal– was used in this study, similar fatigue tests should be conducted to validate this fatigue limit for reinforced beams bonded with other adhesives.

(2) Monitor reinforced beam

- Backface-strain technique can be used to monitor the deterioration of the adhesive and crack initiation at the plate end, especially for beams under fatigue load.

5. Summary

In this paper, the fatigue testing of small-scale steel beams bonded with a 400 mm long CFRP plate is reported. The backface-strain technique was applied to monitor crack initiation. The results showed that the strain gauges could detect crack initiation immediately. An *S-N* curve was plotted from the test results. Since this *S-N* curve is the relationship between the maximum interfacial stress and the number of cycles, it can be used for different sizes of retrofitted metallic beams using the same adhesive. The fatigue limit, i.e. the threshold, of the *S-N* curve is about 30% of the ultimate static failure stress, which validates the fatigue limit suggested by the CIRIA Design Guidance. In accordance with Paris Law, a crack propagation life prediction equation is derived. The empirical coefficients are determined by the experimental data. The agreement between the experimental data and the analytical results confirms the validity of the predication equation. The fatigue load range will affect the fatigue life, but its significance is much less than the magnitude of the maximum load in the load range. Based on the results obtained from the previous and present studies, design recommendations are proposed for practical applications.