Engineering Fracture Mechanics 145 (2015) 128–142

Contents lists available at ScienceDirect

Engineering Fracture Mechanics

journal homepage: www.elsevier.com/locate/engfracmech

Experimental study on the fatigue behaviour of cracked steel beams repaired with CFRP plates

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ARTICLE INFO

Article history:
Received 6 November 2014
Received in revised form 24 March 2015
Accepted 8 April 2015
Available online 25 April 2015

Keywords:
Fatigue strengthening
Bonded CFRP strips
Cracked steel beams
Debonding

ABSTRACT

For the repair of damaged steel beams, Carbon Fibre Reinforced Polymers (CFRP) are effective under monotonic loads, but less information is available under fatigue loading. In this paper, fatigue tests were performed on nine CFRP reinforced cracked steel beams. The fatigue crack propagation curves showed that CFRP strips reduce the fatigue crack growth and extend the fatigue life. Experimental results also revealed the presence of a debonded area between the reinforcement and the steel substrate at the crack location. Debonding clearly has a detrimental effect on the reinforcement effectiveness. Finally, numerical and analytical studies are performed and compared to the experimental findings.

1. Introduction

Steel structures and bridges may be damaged by fatigue phenomena due to traffic loadings. In this case, it is often required to study a rehabilitation activity and Carbon Fibre Reinforced Polymers (CFRPs) have been proven to be effective in the reinforcement of damaged steel beams. They are then considered as ideal products for retrofitting steel structures [1,2]. Besides, guidelines are available [3,4] for the design of CFRP repaired steel structures.

Concerning the fatigue failure of steel beams, for reducing the crack growth rate and stopping the fatigue crack propagation, several conventional repair techniques may be taken into account, such as blunting the crack tip with a hole, bridging the cracked section by means of welding, bolting or steel plate bonding [5]. On the other hand, traditional techniques may present several disadvantages mainly due to the self-weight increase or to the fatigue sensitivity of welding and bolting. Corrosion at the edges of the reinforcing steel plates can also be a potential problem. High installation and maintenance costs also have to be considered [1,2].

For all these reasons, the application of CFRP reinforcements bonded to damaged steel members by using epoxy adhesives is an emerging technique that leads to several benefits [1]. This is mainly due to the good mechanical properties of composite materials, such as high strength and stiffness, fatigue resistance, durability with a reduced self-weight. Composite materials are very flexible and their application simplifies the design of the retrofitting system. This results in easier handling and minimal maintenance costs. Moreover, the strengthening operations can be quickly realized, reducing the costs associated with the structure being out of service. The use of CFRP materials is particularly appealing for bridge applications since there is no need to close the bridge to traffic during rehabilitation. The higher CFRP cost is then mitigated by the lower installation and maintenance charges, resulting in a decrease in the global rehabilitation costs.

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http://dx.doi.org/10.1016/j.engfracmech.2015.04.009
0013-7944/

Nomenclature

a	crack size
a_i	initial crack size
a_f	final crack size
ΔP	load range applied to the spreader beam
M	applied bending moment at the cracked section
N_f	number of cycles from a_i to a_f
$\tau_{\max}$	maximum shear stress in the adhesive layer
E_c	Young's modulus of the composite section
A_c	composite section area
b_c, t_c	composite width and thickness, respectively
A_s	steel section area
h	steel section height
W_s	steel resistance modulus
I_s, I_c	second moments of area of the steel section and of the reinforcement with respect to the neutral axis, y, respectively
G_a	adhesive shear modulus
t_a	adhesive thickness
N_{c0}	axial force in the CFRP strips in the cracked section at the midspan
N_c	axial force in the CFRP reinforcement
t_f, b_f	beam flange thickness and width, respectively
t_w, h_w	beam web thickness and height, respectively
CFRP	Carbon Fibre Reinforced Polymer

It is also relevant to consider that CFRP reinforcements do not significantly improve the elastic structural response from the global point of view. This is due to the marginal increment of the cross-sectional area and moment of inertia of the reinforced steel section. Conversely, composite materials noticeably improve the local structural response through a significant increment of the local stiffness and strength. This is quite attractive for flexural strengthening at the ultimate limit state, strengthening against local buckling, confinement of hollow steel tubes and mainly for the fatigue reinforcement.

Finally, it must be taken into account that the CFRP reinforcement is usually bonded to the steel substrate by epoxy adhesive [1,2]. Due to the high strength of the reinforcement and the steel substrate, the adhesive layer is usually the weakest point of the system. Failure modes are associated to cohesive failure in the adhesive joint, interface failure (generally at the steel–adhesive interface) and CFRP debonding. Cohesive failure can be avoided by a proper choice of the adhesive type, as an appropriate selection of the mechanical properties avoids CFRP debonding. At geometrical discontinuities (typically at the reinforcement ends), interface failure is prevented via a suitable reinforcement curtailment or mechanical anchorage. Moreover, the adhesive joint is sensitive to high temperature, water and moisture exposure. Galvanic corrosion is also a potential problem since, when the carbon fibres are in contact with the steel surface, they produce a galvanic cell. On the other hand, FRP reinforcement cannot be efficiently applied to a non-smooth surface, as in the case of riveted girders due to the high rivets density. Finally, a critical point for heritage structures is due to the fact that reversibility of the strengthening system is highly recommended, while bonded FRP materials cannot be easily removed from the steel surface.

1.1. Problem statement

Fatigue damage is an extremely important problem affecting steel girders in bridges. Reinforcement with CFRP materials is regarded as an efficient technique for the retrofitting of fatigue sensitive steel members. Nonetheless, quite limited information is available on the behaviour of CFRP-repaired steel members under fatigue loadings. The crack repair of fatigue damaged steel beams by using CFRP materials can be achieved in three different ways:

- by reducing the stress range around the crack tip;
- by reducing the crack opening displacement;
- by promoting crack closure.

In particular, the high reinforcement stiffness results in the reduction of the stress range around the crack tip. Besides, the use of CFRP strips bonded to the crack has an effect in bridging the crack lips, reducing the crack opening displacement and thus promoting crack closure. When pre-stressed CFRP strips are used, compressive stresses are also generated in the steel substrate and the crack closure effects are emphasized. Finally, in cracked steel elements, a severe stress/strain concentration