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Fatigue design of CFRP strengthened steel members

Lili Hu[a], Peng Feng[a,*], Xiao-Ling Zhao[b]

[a] The Key Laboratory of Civil Engineering Safety and Durability of China Education Ministry, Department of Civil Engineering, Tsinghua University, Beijing 100084, China
[b] Department of Civil Engineering, Monash University, Clayton, VIC 3800, Australia

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ABSTRACT

Fatigue failure is brittle and sudden and is one of the main problems with steel members and connections. Carbon fiber reinforced polymer (CFRP) sheets and laminates have been shown to be effective and practical for strengthening steel under fatigue loading regardless of the existence of initial cracks. Many studies have examined the fatigue behaviors of CFRP strengthened steel, but fatigue design guides or available programs for designers and engineers are limited. Thus, based on existing design codes and guidance for pure steel under fatigue loading (e.g., Design Guide for Circular and Rectangular Hollow Section Welded Joints under Fatigue Loading and Recommendations for Fatigue Design of Welded Joints and Components), this paper proposes fatigue design guides and programs for CFRP strengthened steel structures. First, for steel without initial fatigue cracks, Classification method is adopted along with a related calculation method for obtaining the reduced stress range of steel after strengthening. Then, a classification table for hybrid CFRP-steel members is given to illustrate where to glue CFRP sheets or laminates and the correct fiber orientation. Second, for steel with initial fatigue cracks, fracture mechanics are adopted to obtain the reduced stress range. This paper considers debonding at the crack tip using the finite element method (FEM) and introduces a coefficient d to enlarge the range of the stress intensity factor (SIF). Then, a program called "EasyFatigueforFSS" (Easy Fatigue design for FRP Strengthened Steel) is developed to calculate the available life or allowable stress. Finally, typical design examples are given for reference.

1. Introduction

Fatigue failure is one of the most serious failure types for steel structures and may result in casualties and considerable economic loss [1]. Fatigue failure is most likely to occur in steel members and connections, such as crane steel beams and welded connections of beams and columns, under cyclic tensile loading. When the fatigue loading of an old structure increases or when some short cracks develop in the structure, steps must be taken to prevent fatigue failure. Retrofitting existing structures instead of replacing them is the more economical and practical solution [2]. Therefore, many studies have focused on the feasibility and efficiency of different strengthening methods, and many scholars have shown that carbon fiber reinforced polymer (CFRP) is effective and practical for reinforcing steel members under fatigue. Liu et al. [3] explained the mechanism through which CFRP increases the fatigue life of cracked steel plates and then proposed a method based on fracture mechanics to predict the fatigue life. Nakamura et al. [4] used CFRP to reinforce welded web gusset joints with fatigue cracks and found that the increase in the fatigue life was significant. Yang et al. [5] quantified the behavior of the bonded steel–fiber reinforced polymer (FRP) interface and established a foundation for analyzing the behavior of steel-FRP hybrid plates under fatigue loading and static loading. Feng et al. [6] studied the thermal effects on the fatigue behavior of cracked steel plates strengthened by CFRP sheets and found that at temperatures ranging from −40 °C to 60 °C, the fatigue lives of the strengthened samples were 2.0–3.4 times greater than those of the unstrengthened ones. Yu et al. [7,8] used the boundary element method to analyze edge-cracked steel plates strengthened with CFRP laminates. Their results indicated that CFRP overlays can effectively slow crack growth and extend the fatigue life of edge-cracked steel plates regardless of the initial damage. Hu et al. [9] analyzed the fatigue behavior of CFRP strengthened high-strength steel. Their study showed that CFRP strengthening can effectively increase the fatigue life (1.3–3.1 times) for all specimens except for those under very high stress range. Other studies have also shown that CFRP can be used to strengthen metal columns and girders [10–14]. Recent studies have focused on new aspects related to this field. Zheng et al. [15] studied debonding at the crack tip of a CFRP strengthened steel plate by digital image correlation technology. Wang et al. [16] also applied this technology to study the bond behavior between CFRP plates and steel substrates under fatigue

* Corresponding author.
E-mail address: fengpeng@tsinghua.edu.cn (P. Feng).

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Nomenclature

a	half crack length
a_i	initial half crack length
a_d	debonding half crack length, after which micro-debonding at the crack tip occurs.
a_f	final half crack length
b_a	width of the adhesive between the steel and the FRP composite
b_c	width of the FRP composite consisting of FRP fiber and matched adhesive
b_f	width of the FRP fiber
b_s	width of the steel
b_d	semimajor axis of the ellipse (debonding area)
c_d	semiminor axis of the ellipse (debonding area)
C	material parameter
d	ratio of the SIF considering the debonding area at the crack tip to that without considering the debonding area at the crack tip
D	fatigue damage accumulation
E_a	elastic modulus of the adhesive between the steel and the FRP composite
E_c	elastic modulus of the FRP composite consisting of FRP fiber and matched adhesive
E_f	elastic modulus of the FRP fiber
E_s	elastic modulus of steel
f_y	yield strength of steel
f_d	design strength of steel
F_d	static design force of steel
G_a	shear modulus of adhesive
G_c	shear modulus of FRP composite
k_i	factor between the strain in the ith layer of the fiber and the strain of the steel
K	stress intensity factor (SIF)
K_{max}	maximum SIF based on the maximum stress in a stress range
K_{min}	minimum SIF based on the minimum stress in a stress range
ΔK	range of SIF, which equals K_{max} minus K_{min}
ΔK_{eff}	effective range of SIF
$\Delta K_{eff,s}$	effective range of SIF after strengthening
ΔK_{th}	threshold value of range of SIF
$K_{with,d}$	SIF under any static σ considering the debonding area at the crack tip
$K_{no,d}$	SIF under any static σ without considering the debonding area at the crack tip
$K_{max,with,d}$	range of SIF under any static σ considering the debonding area at the crack tip
$K_{max,no,d}$	range of SIF under any static σ without considering the debonding area at the crack tip
K_{debond}	SIF when micro-debonding occurs
l_c	length of the FRP composite
l_s	length of the steel plate
n	number of CFRP layers
n_i	number of fatigue cycles under the design load stress range in load spectrum block i
N_i	number of fatigue cycles calculated using S_i
N	number of fatigue cycles calculated using SIF
N_a	available fatigue life/cycles
N_p	predicted fatigue life/cycles of unstrengthened steel
$N_{p,s}$	predicted fatigue life/cycles of strengthened steel without considering debonding
$N_{p,s,d}$	predicted fatigue life/cycles of strengthened steel considering debonding
m	material parameter
R	stress ratio, which is the ratio of σ_{min} to σ_{max}
R_p	size of the plastic zone
r	distance from the calculated microelement to the crack tip
S_a	axial stiffness of the adhesive
S_c	axial stiffness of the FRP composite
S_s	axial stiffness of steel
S_i	ith nominal stress range
S_{DC}	nominal stress range at 2×10^6 cycles, called the detail category
S_{CA}	nominal stress range at 5×10^6 cycles, called the constant amplitude fatigue limit
S_{CO}	nominal stress range at 10^8 cycles, called the cut-off limit
$S_{without\ CFRP}$	nominal stress range of unstrengthened steel
$S_{without\ CFRP,i}$	nominal stress range of unstrengthened steel in load spectrum block i
$S_{with\ CFRP}$	nominal stress range of strengthened steel
$S_{with\ CFRP,i}$	nominal stress range of strengthened steel in load spectrum block i
t_a	thickness of adhesive between the steel and the FRP composite
t_c	thickness of the FRP composite consisting of FRP fiber and matched adhesive
t_f	thickness of the FRP fiber
t_s	thickness of the steel
β	damage ratio
γ_{Mf}	partial safety factor
σ	nominal stress of the steel plate
σ_a	stress of the adhesive from FEM
σ_d	nominal stress shared by the steel under F_d
σ_{max}	maximum stress in a stress range
σ_{min}	minimum stress in a stress range
$\sigma_{max,d}$	maximum nominal stress shared by steel under F_d
$\sigma_{without\ CFRP}$	nominal stress of unstrengthened steel
$\sigma_{with\ CFRP}$	nominal stress of strengthened steel
$\Delta\sigma$	nominal stress range, which equals σ_{max} minus σ_{min}
$[\Delta\sigma]$	allowable nominal stress range
$\Delta\sigma_{without\ CFRP}$	nominal stress range of unstrengthened steel
$\Delta\sigma_{with\ CFRP}$	nominal stress range of strengthened steel
σ_x	stress of the microelement in the x direction
σ_y	stress of the microelement in the y direction
σ_z	stress of the microelement in the z direction
ε_a	strain of the adhesive from FEM
$\varepsilon_{a,max}$	maximum strain of the adhesive, which refers to the ultimate strain of the adhesive
θ	angle shown in Fig. 3
ϕ	capacity factor in AS 4100
ν_s	Poisson's ratio of steel
ν_c	Poisson's ratio of FRP composite
ν_a	Poisson's ratio of adhesive

loading, which is a critical and fundamental issue. Zheng et al. [17] applied a thermally activated shape memory alloy to achieve the prestressing of the CFRP, whose use is more efficient than that of CFRP without pre-stress. Aljabar et al. [18] analyzed a case of mixed tension and shear loading and found a shifting phenomenon in terms of crack propagation. Borrie et al. [19] conducted a large number of fatigue tests on CFRP patched pre-cracked steel plates after extreme environmental exposure and proved that CFRP reinforcement can be adapted even under extreme exposure scenarios. Many other studies focused on the repair of steel girders and bridges. For example, Yue et al. [20] studied the fatigue performance of CFRP reinforced steel crane girders and concluded that the CFRP layers can perfectly restrain the development

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