Construction and Building Materials 164 (2018) 620–624

Contents lists available at ScienceDirect

Construction and Building Materials

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

Improved estimate and accurate measurement of thermal stresses in FRP tendon

Wen Chen [a], Jianzhong Hao [b], Ming Tang [a,*]

[a] Wuhan National Lab for Optoelectronics (WNLO) & National Engineering Laboratory for Next Generation Internet Access System, School of Optics and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
[b] Institute for Infocomm Research, 1 Fusionopolis Way, #21-01, Connexis South, 138632, Singapore

HIGHLIGHTS

- An improved model makes up the gap between theoretical and experimental results.
- This model can accurately evaluate the transverse thermal pressure at the interface.
- It can also investigate three-dimensional thermal stresses of FRP bar.
- FBG is adopted to exactly measure the transverse thermal stress of FRP tendon.

ARTICLE INFO

Article history:
Received 5 September 2017
Received in revised form 17 December 2017
Accepted 22 December 2017
Available online 6 January 2018

Keywords:
FRP
Thermal stress
Temperature
Mechanical property

ABSTRACT

There is distinctive difference in the coefficient of thermal expansion (CTE) between fiber reinforced polymer (FRP) bar and surrounding mass, which may generate great transverse thermal pressure at their interface and cause significant reduction in bond strength of FRP tendon. However, the transverse thermal pressure predicted from previous analytical model has marked deviation from that obtained from experiment test. This paper presents an improved analytical model to exactly analyzing the transverse thermal pressure at the interface of FRP bar/surrounding mass and the three-dimensional thermal stresses of FRP bar. Then accurate measurement using fiber Bragg grating (FBG) sensor is conducted to obtain the transverse thermal pressure that agrees well with our theoretical result. Our work may be helpful in improving the thermal compatibility and bond performance of FRP tendon.

1. Introduction

Fiber reinforced polymer (FRP) bars are being widely used in civil engineering structures, particularly in highly corrosive and anti-electromagnetic environments due to its many superior material properties, such as high tensile strength, low weight, good resistance to corrosion, creep and fatigue, and low linear expansion coefficient. FRP tendon plays an important role in a variety of applications in civil infrastructure including prestressed concrete structure, cable-stayed bridge and grouted anchors [1–3]. However, the application of FRP tendons in prestressed structures is hindered by the asymmetry of transverse and longitudinal mechanical properties. Until very recently, research on fracture behaviors of damaged CFRP tendons was still underway. The fracture energy in the experiment was calculated based on digital image correlation technique by Han etc [4]. Later they designed and optimized a large angle wedge type of anchorage for applying to large diameter CFRP tendon [5]. One of hindrances is known as the difference of the coefficient of thermal expansion (CTE) of FRP bar in transverse and longitudinal directions [5,6]. The much higher CTE in transverse direction induces a radial pressure stresses at the FRP bar/surrounding interface under temperature increase that may affect significantly the ultimate strength of FRP tendon [7]. For example, tensile stresses induced by the transverse CTE difference between glass FRP bar and concrete may cause splitting crack within surrounding concrete, and eventually lead to failure of concrete [8]. In the last two decades, numerous efforts, either from the angle of improving material and structural property of FRP tendon or from analyzing bond failure characteristics and mechanism as well as their influence factors, have been focused on the thermal incompatibility of FRP tendon in prestressed structure under the temperature variation [9–19]. An analytical model developed from the theory of elasticity of

* Corresponding author.
E-mail address: tangming@mail.hust.edu.cn (M. Tang).

https://doi.org/10.1016/j.conbuildmat.2017.12.151
0950-0618/

Nomenclature

r, θ, z	Cylindrical coordinates
E_i	Young's modulus of FRP in i direction
G_{ij}	Shear moduli of FRP $(i,j = r, \theta, z)$
v_{ij}	Poisson's ratio of FRP $(i,j = r, \theta, z)$
σ_i	Stress of FRP in $i = r, \theta, z$ direction
ε_i	Strain of FRP in $i = r, \theta, z$ direction
E_m	Young's modulus of steel
v_m	Poisson's ratio of steel
E_f	Elastic modulus of FBG
v_f	Poisson's ratio of FBG
α_T	Transverse coefficient thermal expansion of FRP
α_m	Coefficient thermal expansion of steel
P_{in}	Radial pressure on the inner wall of steel sleeve
K_T	Coefficient of radial pressure and temperature
R'	Outer radius of steel sleeve
R	Inner radius of steel sleeve
K	Ratio of R' to R
ΔP	Change of radial pressure
ΔT	Change of temperature
l_0	Bonding length of FRP bar
l	length of FRP bar
m	Superscript m represents material steel
h	Superscript h represents material FRP
Fs	Coefficient of cosine term in Eq. (9)
p_{11}, p_{12}	Elasto-optical coefficient of FBG
λ_B	Bragg wavelength
n_{eff}	Effective refractive index of FBG
Λ	Grating period of FBG

Timoshenko [20] was used to investigate the transverse thermal stress of FRP tendon subjected to only temperature load [9–12]. Recently, a modified analytical model took into account an extra sustained axial mechanical load [19]. However, the transverse thermal strains, at FRP bar/concrete interface, predicted from all of these analytical models are marked deviation from the experimental ones [10–12,19]. Hence, it demands an improved analytical model for making up the gap between the theoretical and experimental analysis on thermal behavior of FRP tendon. Additionally, different from most of previous work studying the development of cracking within the surrounding cover of structural elements only, our model, for the first time to my best knowledge, provides an analytic method to analyze the three-dimension thermal stresses of FRP bar. In experiment, electronic strain gauge is traditionally adopted to measure thermal strain of FRP tendon. However, it requires electromagnetic shielding, power supply and signal transmission in harsh environment, especially in corrosive and strong electromagnetic field. FBG sensor has many excellent characteristics over electronic sensor, including small size, high sensitivity, anti-electromagnetic interference, multiplexing capability, and compatible with FRP bar. In the last decade, the integrating FBG into FRP bar for measuring strain and temperature has been extensively discussed, most of which measured longitudinal stress and temperature of FRP bar [21–25]. Till now the measurement of thermal stress of FRP tendon using embedded FBG was seldom reported. The greatest difficulty lies in finding an exact conversion coefficient to calculate the thermal stress from Bragg wavelength shift due to the temperature-stress coupling of FBG.

This paper proposes an improved analytical model based on the theory of elasticity to investigate the transverse thermal pressure at the interface of FRP bar/surrounding mass. Also three-dimensional thermal stresses of FRP bar are investigated according to our previous work [26]. Accurate measurement using embedded FBG is conducted to testify our analytical model. Comparison between experimental and analytical results is presented.

2. Analytical analysis of transverse thermal stress in FRP tendon

An optical fiber written with two fiber Bragg gratings (FBG) is bundled with a bunch of glass fibers. They are coated with melted epoxy resin and extruded through a small hole to form the so-called FRP bar. In order to calculate accurately the thermal stress at the interface between FRP bar and surrounding mass, steel sleeve with a precise material parameter is chosen to replace concrete. Because its isotropic property is the same as concrete, stress distribution of steel sleeve can also be calculated by the Lamé formulae. FRP bar is inserted into steel sleeve that is uniformly crimped onto the former, as shown in Fig. 1. Their material and structural parameters are listed in Table 1. The plastic deformation of the crimped steel sleeve provides the lateral pressure and shear acting on the surface of the bar. One locates in the axis of the glass FRP (GFRP) bar inside the steel sleeve, the other is outside. Their initial Bragg wavelengths changed into 1536.33 nm and 1535.45 nm respectively after FRP tendon anchoring. To analyze the transverse thermal stress in FRP tendon, an analytical model is established, as shown in Fig. 1, based on the following hypotheses:

(1) A perfect bond between surrounding cylinder and FRP bar $(\varepsilon_r^m = \varepsilon_r^h$ at $r = R)$.
(2) Surrounding cylinder and FRP material have a linear elastic behavior until failure of FRP tendon.
(3) The cross section of surrounding cylinder remains plane after thermal deformation.
(4) There is no initial thermal pressure at the interface of FRP bar/surrounding mass.

This analytical model chooses the example of GFRP and steel sleeve. It also applies to other material if it satisfies above conditions.

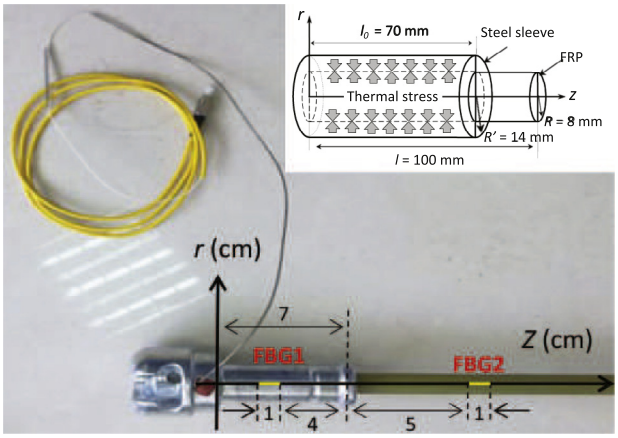

Fig. 1. FRP tendon with two embedded FBGs.