Construction and Building Materials 25 (2011) 539–546

Contents lists available at ScienceDirect

Construction and Building Materials

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

Fatigue-loading effect on RC beams strengthened with externally bonded FRP

E. Ferrier [a,*], D. Bigaud [b], J.C. Clément [c], P. Hamelin [a]

[a] LGCIE Site Bohr, Université Claude Bernard Lyon I INSA de Lyon, Domaine Scientifique de la DOUA, 82 Boulevard Niels Bohr, 69622 Villeurbanne Cedex, France
[b] IMIS-ESTHUA, Université d'Angers, Angers, France
[c] Université Paris-Est, Laboratoire Central des Ponts & Chaussées (LCPC), 58, bd Lefebvre 75732, Paris, France

ARTICLE INFO

Article history:
Available online 30 October 2010

Keywords:
CFRP strengthening
RC structure
Fatigue
Interface

ABSTRACT

External bonding of fiber-reinforced polymers (FRP) on concrete beams is particularly attractive for the strengthening of civil engineering structures in order to increase their strength and stiffness. Principles for design of such strengthening methods are now established and many guidelines exist. However, fatigue design procedure is still an ongoing research topic.

This paper focuses on the damage behavior of FRP-strengthened reinforced concrete (RC) structures subjected to fatigue loading.

In order to design bonded reinforcements, an iterative computational method based on section equilibrium and material properties (concrete, steel, adhesive and composite) has been previously developed by authors [1–3]. In the present study, this method is extended to describe the fatigue behavior of RC beams.

A specific modeling coupled with an experimental investigation on large-scale beams made it possible to compare the theoretical and experimental fatigue behaviors of RC beams with and without composite reinforcements. The model is developed and calibrated using data of the literature or recorded during experiments specifically carried out for this study. Results showed that the beam deflection and the strain in each material could be calculated with a sufficient accuracy, so that the fatigue behavior of the FRP-strengthened beams was correctly estimated by the model.

1. Introduction

Externally bonded carbon–epoxy fiber-reinforced polymers (CFRPs) have been widely used to restore or increase the capacities of reinforced concrete (RC) beams [1–3]. Fiber-reinforced polymers (FRPs) used in civil engineering construction combine high strength unidirectional fibers with an epoxy matrix which can be cured at temperatures ranging from 5 °C to 30 °C. FRP strengthening systems for field applications have been commercialized by various manufacturers. Under static loads they have proved to be sufficiently reliable, as long as appropriate ends anchorage are provided for the FRP. Several authors [1,2] have shown that, when failure occurs by debonding, it is always the concrete cover over the FRP–concrete interface that shears off. Most of these studies were conducted under static loading conditions [1–3].

A typical RC bridge deck may experience up to 7×10^8 stress cycles during the course of a 120-year life span [4], while an overpass on a typical highway with a design life of 40 years can experience a minimum of 58×10^8 loading cycles of varying amplitude. In contrast to the fairly extensive experimental and analytical studies conducted on the monotonic behavior of FRP-strengthened RC members, relatively few researches has been carried out on the fatigue behavior of concrete beams strengthened with FRPs. However, several key researches [4–6] have clearly demonstrate that FRP-strengthened structures present better fatigue performances than unstrengthened ones. In most cases, it has been observed that the failure of the structure is initiated by successive yielding of the reinforcing steel in tension, in one or several locations. When debonding of the FRP laminate occurred, it was considered to be a secondary failure mode resulting from the yielding and failure of steel rebars.

For serviceability limit state considerations, the overall behavior of a RC beam strengthened with FRPs has to be evaluated. Ferrier and Hamelin [7] observed a redistribution of stresses from the FRP to the steel rebars during the fatigue process. Thus, the assumption that transverse beam sections remain plane after loading may not be valid under fatigue loading, since it relies on the perfect bonding of the external FRP reinforcement. These authors cautioned that, regarding fatigue performance, the behavior of the bonded joint should be investigated to confirm all the observed phenomena.

In the present work, this behavior is studied using a model which was developed for the evaluation of the beams' mechanical properties under fatigue loading. For this part of the research, a specific software developed by Varastehpour and Hamelin [3,8] is improved taking into consideration the fatigue behavior of each

---

* Corresponding author. Tel.: +33 472692071; fax: +33 478946906.
E-mail address: emmanuel.ferrier@univ-lyon1.fr (E. Ferrier).

0950-0618/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.conbuildmat.2010.07.035

Nomenclature

bc	width of the composite plate
b, c, m, n	constant
E_c	initial Young's modulus
E_{cN}	Young's modulus for N cycles for concrete
E_{fN}	Young's modulus for N cycles for FRP
Es	steel Young's modulus
$f_{C_{N\max}}$	compressive strength of concrete for N cycles (MPa)
f_c	compressive strength of concrete (MPa)
F_{ex}	internal effort
f_y	steel yielding stress
F	tensile load
L	anchorage length
N	number of cycle
N_C	effort in concrete
N_S	effort in steel
N_F	effort in composite
N_f	number of cycles to failure
N'_f	number of cycle
M_c	concrete moment
M	external bending moment
M_s	steel moment
M_F	composite moment
ε_{cn}	concrete strain increased for N cycles
$\varepsilon_{\max}$	maximal strain
ε_1	initial strain
ε_{SN}	strain in steel for a N fatigue loading
ε_{Su}	steel strain at failure
$\Delta\varepsilon_c = \varepsilon_{\max} - \varepsilon_1$	strain amplitude
$\Delta\sigma$	ultimate strength
$\Delta\tau$	effective stress on failure stress
$\Delta\tau_{\mathrm{adh}}$	concrete to FRP strength variation in function of numbers of loading
σ_c	concrete stress
$\sigma_{\max}$	maximal stress applied
$\sigma_{\min}$	minimal stress applied
$\sigma_c^r = \sigma_{\max} - \sigma_{\min}$	stress cycles amplitude
$\sigma_c^m = (\sigma_{\max} - \sigma_{\min})^{\frac{1}{2}}$	average loading stress
σ'_f	steel stress yielding
$\sigma_{c\max}$	maximal stress in compression under fatigue loading (MPa)
σ_{cmax}	maximal stress applied on concrete
w	cycles frequency

constitutive material of the beam. The modeling method takes into account mechanical constitutive laws of individual materials as well as the section equilibrium. The software has been validated in the framework of static tests performed on several RC beams reinforced by composites. In order to evaluate the effects of fatigue loading on the structure, an adequate fatigue modeling is implemented as described below.

Triantafillou and Plevris's method [9] for modeling the creep behavior of RC beams reinforced with FRP, uses the delayed properties of each constitutive material to assess the beam section equilibrium. The same principle is used here for modeling the fatigue behavior by taking into account the decreasing mechanical properties of all the materials subjected to fatigue (steel, concrete, polymer adhesive and composite).

Modeling of the RC beam fatigue behavior using the above mentioned computational process can be achieved in three steps. A first step based on a literature review allows to determine (i) the fatigue strength and (ii) the evolution of the Young's modulus of each material *versus* the number of loading cycles $E = f\,(N)$. Such relations are available for concrete [10–13], for steel [14], and for the FRP/concrete interface [6,7] In a second step, the damaging process of the RC beam subjected to cyclic loads is modeled using Hamelin and Varastehpour's software [3]. Fatigue strength and Young's modulus evolution laws of the various materials are computed in a new version of the software. The iterative calculation process allows to consider values of the material strength and Young's modulus for each step of cyclic load. Then, such an iterative method makes it possible to calculate the moment–curvature or load–deflection relationships for a given number of loading cycles.

The principle of the computational method is detailed in the first part of the paper. Then the fatigue modeling of FRP-strengthened beams is validated in the framework of an experimental investigation on six large scale specimens (Section 4).

2. Computational process principle

Mechanical analysis of a RC beam strengthened by a bonded composite plate can be described using a classical beam theory.

First, (Fig. 1, Zone 1), the static force and the moment equilibrium are ensured for all sections of the beam. Then, the adhesive shear stress at the composite plate edge is calculated (Fig. 1, Zone 2) and the concrete/composite interface shear stress is checked as permissible. In our computational procedure, the moment–curvature diagram is established step by step until failure. This is done by initializing the strain of the concrete top fiber ($\varepsilon_{\mathrm{sup}}$) specimen and then recalculating the position of the neutral axis (z_g) with an hypothesis on bottom beam strain ($\varepsilon_{\mathrm{com}}$), taking into account the total internal force equilibrium (concrete in compression, in tension, in steel (Ta), in FRP (Tp) and the force loss in the composite plate after slipping (Fig. 2). The balance of forces is thus satisfied within the beam section. In other words, the first step of the design process is based on a perfect adhesion hypothesis.

Then, the "sliding effect" between the composite and the structure can be estimated considering the shear stress distribution in the adhesive layer and the relationship between shear stress and strain obtained from tests (Fig. 3b). Alternatively, several authors have proposed theoretical methods to calculate the shear stress at the FRP/concrete interface [15–17]; we made comparisons between various methods based on finite element analyses and experimental data. In all cases, high interfacial shear stresses were obtained near the edge of the composite plate. The analytical solution provided by Täljsten [17] was finally retained.

To initiate the calculation procedure, a value of the strain in the top concrete ($\varepsilon_{\mathrm{sup}}$) and the position of the neutral axis (z_g) are assigned arbitrarily. The depth of the beam section is divided into 200 slices. The strain profile along the height of the beam is obtained assuming that plane sections remain plane and that the longitudinal strain is directly proportional to the distance from the neutral axis.

An average strain is calculated for each slice, and the corresponding compressive and tensile stresses are determined using the stress–strain relationship for each material (Fig. 3a). The mechanical behavior of steel is characterized by elastic-yielding. The mechanical behavior of concrete in compression and in tension is deduced from a strain–stress model [3]. The composite material is assumed to be linear and elastic until failure.

Multiplying the stress by the area of the slice gives the compressive and tensile forces. Once all forces are calculated, the section equilibrium is verified as follows: