Composite Structures 200 (2018) 624–634

Contents lists available at ScienceDirect

Composite Structures

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

Vibration analysis of damaged RC beams strengthened with GFRP

R. Capozucca

DICEA, University Politecnica delle Marche, 60100 Ancona, Italy

ARTICLE INFO

Keywords:
GFRP-rod/strip
Damage
Dynamic tests
Frequency values
FE modelling

ABSTRACT

The aim of the paper is to investigate the dynamic behaviour of undamaged and damaged reinforced concrete (RC) beams with different constraints: hinged and free-free ends. Two RC beams were analysed experimentally, strengthened with near surface mounted (NSM) glass fibre reinforced polymers (GFRP). One of RC beams was also reinforced with GFRP strips in the compressive zone. Damage of the RC beams was obtained by cracking of concrete for one of the beams, under bending tests, and for the other beam by artificial notches.

In this paper, the envelope of Frequency Response Functions (FRFs) obtained by the dynamic experimental tests are shown and the changes of natural frequency values are correlated to the damage degree of beam elements. Finally, modelling of RC beams by finite element method (FEM) is developed for the undamaged beam and for the beam damaged with notches. Experimental results are discussed and a comparison between the experimental results and the theoretical and numerical data obtained is shown.

1. Introduction

In recent years the rehabilitation of damaged reinforced concrete (RC) structures has become an important task in civil engineering and fibre-reinforced composites have been extensively used for many applications. The use of fibre reinforced polymers (FRPs) in civil engineering is relatively recent compared to other fields of engineering i.e. aerospace structures or mechanical structures; the feature of this composite material is extreme available due to high strength-to-weight and stiffness-to-weight ratios.

In general, the applications of FRP in the strengthening or rehabilitation of RC beams is developed following two different strengthening techniques: the first, FRP sheet/strips glued on concrete surfaces as external bond (EB) composite materials; the second, FRP rods inserted into grooves on concrete covers. This last method is known as the near surface mounted (NSM) technique. The NSM FRP technique appears capable of solving a number of aspects: full FRP tension strength encountered in the case of externally bonded FRP reinforcements; their susceptibility to damage deriving from collision, high temperature and, fire. Furthermore, this method has proven to be a promising one for increasing the flexural and shear capacity of RC beams [1–5]. The fundamental aspect in the aim of the NSM technique is the maintenance of bonds between FRP rod and concrete in the groove; many works present in literature have described the factors affecting bond mechanism in NSM strengthening in concrete [6,7] like bond length, the diameter of the rods used, the type of FRP material employed, rod's surface configuration, and groove size [8–10]. In general, NSM FRP rods are prone to exhibit greater slip than steel reinforcement due to FRP material's potentially lower bond shear stress, to the presence of surrounding adhesive layers and local cracking in the cover concrete [11]. Further theoretical and experimental nonlinear bond shear stress versus slip relationships have been evaluated by other researchers [12].

Although composite materials, similar to isotropic materials, are subjected to various damages: cracks in fibre, matrix, and in interfaces of fibres and matrix [13] experimental tests have demonstrated the availability of NSM FRP technique also in presence of local damages of composite rods [14]. Many authors have studied the behaviour between Glass-FRP and reinforced concrete structures [15–19]; however, the use of GFRP in the strengthening of RC beams is still an open field of research. Composite material GFRP with low elasticity modulus in strengthening by the NSM technique calls for additional in-depth analysis, using both experimental tests and theoretical procedures. The availability of NSM GFRP strengthening in beams is based on at least two important factors: the maintaining of bond between NSM rods and concrete, and/or adhesive resin, until failure of beam; the capacity of NSM GFRP rods to increase deformation over the ultimate strain of compressive concrete which is usually conventional ultimate condition for RC beams.

In the present paper NSM technique as a strengthening method of RC beams with GFRP circular rods is investigated through combined static and dynamic tests; a composite technique of strengthening both by NSM GFRP rod in tensile zone of beams and EB GFRP strip in the compressive side was also considered. The behaviour of RC beams

E-mail address: r.capozucca@univpm.it.

https://doi.org/10.1016/j.compstruct.2018.05.112
Received 9 February 2018; Received in revised form 23 May 2018; Accepted 28 May 2018
Available online 29 May 2018

Notation

U, D	index for undamaged state; index for damaged state	exp, th	index for experimental value; index for theoretical value
A	cross section area of beam	λ	eigenvalue
L	length of beam	ω	circular frequency value; angle of phase
I	moment of inertia of beam	f, Δf	frequency value; difference between undamaged and damaged frequencies
P	density	D_i	damage degree for cracking of concrete
EI	bending stiffness of beam	D_i-R	damage degree for notch
ν	deflection of beam axis; vertical displacement of the middle of beam axis	E_f	modulus of elasticity GFRP rod/strip
r, f	index of vibration mode, index for free end	A_f	section area of GFRP rod/strip
		t_f	thickness of GFRP strip
		$f_{b,t}$	tensile strength of GFRP rod/strip

comparing experimental results by bending tests on beams with and without NSM GFRP rods is discussed below.

Although static tests are normally adequate for describing GFRP strengthening, dynamic tests and analysis of vibration response are convenient to monitor and detect effects of damage in RC beams strengthened with FRP rods [20–23]. The basic concept with vibration monitoring is that dynamic characteristics are functions of structures' physical properties; therefore, any change caused by damage, results in change in dynamic response [21,24,25].

This paper relates the results of an investigation on different damage aspects of RC beams, both with strengthening and without strengthening, considering natural frequency values and modes of vibration of two RC beams. The RC beams were affected by different damages both in tensile due to increasing cracking for bending tests and, on the compressive side, by artificial damage due to notches. The results obtained in terms of variations of frequency values correlated to different damage degree obtained by experiments of free vibration with hinged and free-free ends of beams are shown and compared with theoretical and numerical data.

2. Vibration of hinged RC beam strengthened with GFRP

The experimental response of RC beam B1 undamaged and damaged by cracking of concrete due to bending tests with strengthening NSM GFRP rod are analyzed below. The free vibration of RC beam is experimental investigated considering the hinged ends as simple supported beam. Strengthening as a composite technique of NSM GFRP rod and EB GFRP strip in compressed side is also considered for damaged RC beam B1.

2.1. RC beam model and setup of dynamic tests

RC Beam B1 was the experimental model studied with and without strengthening of GFRP under static and free vibration tests. In Fig. 1 the section of the beam is indicated, dimensions of section are 120 mm × 160 mm and steel reinforcements by four 10 mm diameter rods and stirrups measuring 6 mm in diameter; the length of the beam is 2.20 m.

Fig. 1(a) also shows a groove in the cover measuring 20 mm × 20 mm where the GFRP rod was inserted and glued to the concrete using resin [26]. The two beams tested in laboratory, B1 and B2, analyzed under vibration, respectively, with hinged and free ends, were characterised by concrete with a tested average cylinder strength equal to $f_{c,av} \approx 44\,N/mm^2$ and Young's modulus $E_c \approx 35.0{\cdot}10^3\,N/mm^2$; steel bars with an average yielding stress equal to $f_{y,av.} \approx 500\,N/mm^2$ and Young's modulus $E_s = 2.1{\cdot}10^5\,N/mm^2$. The geometric and mechanical parameters of GFRP rod and EB GFRP strip are shown in Tables 1 and 2. They were obtained using tensile tests on specimens according to the ASTM-D 3039 Standard [27].

Fig. 2 shows the setup used for the RC beam's vibration tests hinge-

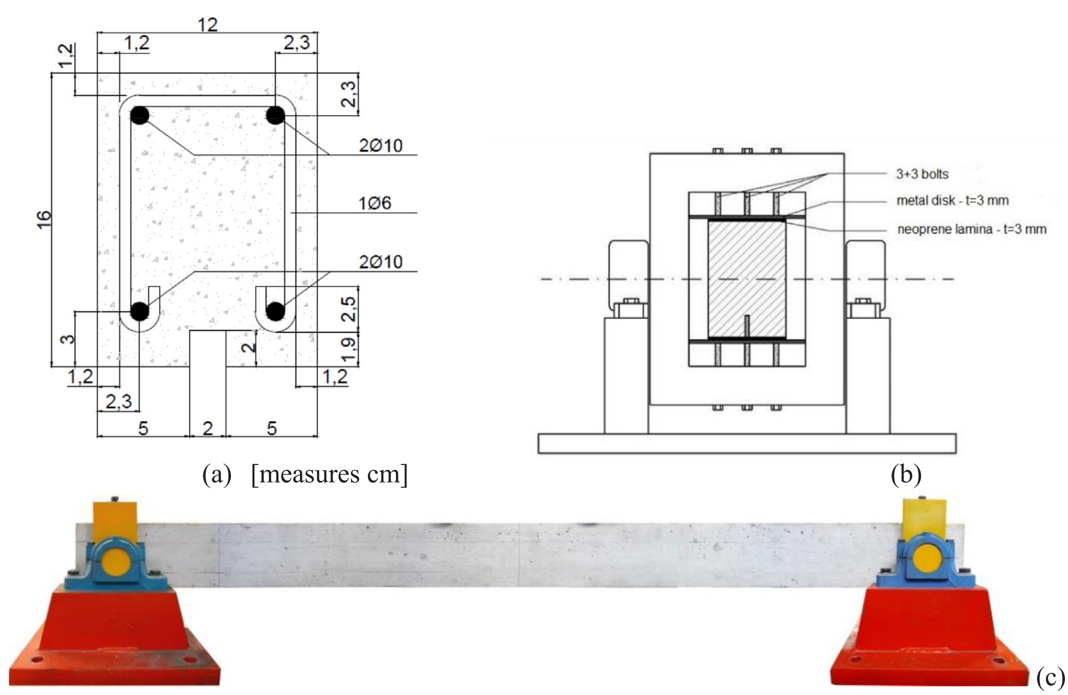

Fig. 1. RC beam B1: (a) RC section of beam; (b) hinge at the end of beam; (c) constraints as hinges of beam.