Construction and Building Materials 105 (2016) 321–335

Contents lists available at ScienceDirect

Construction and Building Materials

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

Concrete beams stiffened by polymer-based mortar layers: Experimental investigation and modeling

Luca Lanzoni [a,b,*], Marco Soragni [b], Angelo Marcello Tarantino [b], Marco Viviani [c]

[a] DET – Dipartimento di Economia e Tecnologia, University of San Marino, Salita alla Rocca 44, San Marino 47890, San Marino
[b] DIEF-Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, 41125 Modena, Italy
[c] HEIG-VD – Haute Ecole d'Ingénierie et de Gestion du Canton de Vaud, Route de Cheseaux 1, CH-1401 Yverdon, Switzerland

HIGHLIGHTS

- We study concrete elements stiffened by a single or more layers of mortars.
- Polymer-modified cementitious repair mortar are used to strength the concrete elements.
- Experimental non-symmetric bending tests are carried out.
- The characterization of the collapse mechanism affecting the samples is given.
- FE models have been also performed.

ARTICLE INFO

Article history:
Received 24 February 2015
Received in revised form 10 November 2015
Accepted 9 December 2015
Available online 18 December 2015

Keywords:
Repair mortar
Delamination
Damage process
Concrete ceiling beam
Non-symmetric bending test
FE models

ABSTRACT

In the present work, the main results provided by an experimental investigation, assessing the mechanical performances of concrete elements stiffened by a single or more layers of different kinds of polymer-modified cementitious repair mortar, are presented. The study aims to investigate the failure mechanism occurring in the samples under bending loading. In particular, the experimental investigation allows checking if the collapse mechanism is driven by delamination occurring along the interface among the overlays or by cracks propagating from the tensile region to the compressive zone, as it occurs in a typical failure mechanism driven by flexure. Thirty-eight precast and pre-stressed concrete samples were realized and cured to simulate load-bearing concrete ceiling beams widely employed as floor systems for residential buildings. After curing, the samples were subjected to three-point loading bending tests in order to evaluate the mechanical response of the specimens in terms of load vs. mid-span transverse displacement. Through the experimental tests, the crack initiation and propagation during the bending loading have been investigated also. Simplified finite element (FE) simulations were performed to properly reproduce the actual response of ceiling beams under non-symmetric loading bending. It is shown that the proposed FE model can be straightforwardly used to predict the behavior of concrete beams stiffened by polymer-based repair mortar layers.

1. Introduction

Concrete structures and concrete structural members are prone to various kinds of degradation phenomena. Physical, chemical and biological degradation as well as excess of loads might reduce the performances and the lifespan of a concrete structure (e.g. [20]). Degradations might impose to the structure owner a simple, ordinary maintenance (such as concrete patching) or, in extreme cases, the structure demolition and reconstruction. Often, a change of the utilization of a structure implies an attentive evaluation of the structural response under a new set of loads. The service load and the residual service life have to be considered carefully.

In many countries, such as Italy, reinforced concrete (RC) frames are preferred structural members to construct residential and commercial buildings. Therefore, the maintenance and reinforcement of these structural elements is a key issue [15,21]. There are different kinds of reinforcement methods suitable to strengthen a concrete frame; one of the most popular is the Fiber Reinforced Polymer (FRP) retrofitting. In recent years, FRP retrofitting proved to be a reliable and efficient technique to improve both strength

* Corresponding author at: DET – Dipartimento di Economia e Tecnologia, University of San Marino, Salita alla Rocca 44, San Marino 47890, San Marino.
E-mail address: luca.lanzoni@unimo.it (L. Lanzoni).

http://dx.doi.org/10.1016/j.conbuildmat.2015.12.065
0950-0618/

and load carrying capacity of concrete structural members like beams, columns, etc.

Floors of existing buildings consist of precast, pre-stressed, load-bearing concrete ceiling beams among which ceiling bricks are placed. This kind of floors can be stiffened by removing the overlying tile and applying one or more layers of repair mortar on the upper surface of the concrete ceiling beams, as shown in Fig. 1. This repair process is aimed to increase the stiffness and flexural strength of the floor by casting one or more layers of repair mortar, thus preventing excessive deformation, failures and other damaging phenomena and, in turn, increasing the service life of the structure.[1] Before casting the repair mortar layers on the ceiling beams of a floor, the existing pavement must be removed and the intrados of the ceiling beams cleaned, making them free of cracked portions and detached parts. As expected, important issues related to the efficiency of this method of consolidation deal with the kind of the surface of the existing elements, the type of repair mortar, the presence of shear connectors, the use of bonding agents and the technique adopted to realize the strengthening (e.g. [41]).

As known, the adhesive plays a crucial role in order to efficiently transfer the stresses from the strengthened element to the stiffening layer. Indeed, the success of the consolidation based on the use of repair mortar lies in the level of adhesion between the existing element and the reinforcing layer of repair mortar. Owing to this fact, the intrados of the beam should be provided with a micro or macro-texture to improve adhesion and bonding of the repairing cast to the existing elements and, in turn, the efficiency of the gluing [13,9]. Metallic anchors and shear connectors can be used to this aim too. These expedients are necessary due to the high shear stresses arising at the interface among the layers, as revealed by the analysis of the contact problem among coatings, beams and plates bonded to an elastic substrate (e.g. [14,22]). Since a good level of adhesion is generally difficult to accomplish [8], in the last years various kind of bonding agents (with particular reference to agents based on synthetic primers) have been studied in order to avoid delamination and crack formation at the interface. Several experimental studies can be found in literature aimed to evaluate the resistance as well as the crack formation and propagation in layered elements under bending, with specific reference to mode I, mode II and mixed-mode I/II crack formation and growth at the interface (e.g. [11,24]). Furthermore, a wide range of experimental methods exist in order to evaluate the bond strength between a substrate ad an overlay (e.g. [3–5,11,2,19,36,23]). How and ever, as shown by Momayez et al. [18], significant differences in the adhesion evaluation can occur depending on the kind of experimental method adopted to assess the bond strength. In particular, these Authors investigated the effects induced by four different test methods, (i.e. pull-off, slant shear, splitting prism and bi-surface shear test), and also examined the influence of the rough surface preparation. It follows that a comparative bond strength testing should be involve the same experimental procedure and surface preparation.

Pull-off direct and indirect tests are widely used to characterize the bond behavior because their simplicity. For instance, Bonaldo et al. [6] carried out an experimental investigation about bond strength between concrete substrate and repairing steel fiber reinforced concrete (SFRC) via pull-off tests. They found that an increasing in the strength of the overlay does not lead to an increase in the pull-off strength, which is significantly affected by the strength of the substrate.

As known, geometric discontinuities produce stress concentration and strain localization that can drive the delamination process, which generally starts in the neighboring of the discontinuities of the overlay, particularly at its edges [12]. However, the delamination phenomenon is strongly affected by cracks occurring both at the interface and within the substrate bulk [9].

Delamination formation and growth can be detected by different techniques. Among these, there are non-destructive methods (visual check, infrared thermography, chain drag, electromagnetic and acoustic methods like Acoustic Emission (AE) technique), semi-destructive methods (coring, pull-off test), and a variety of experimental tests based on the monitoring of the displacement field at the interface between the substrate and the overlay by means of transducers (e.g. LVDT) or extensometers. Delamination can be induced either by external loads or by coactive stresses. In the first case, the delamination process is driven by the achievement of the ultimate tensile strength at the overlay as the external load increases; whereas in the second case, delamination is induced by a misfit strain between the substrate and the overlay (e.g. during thermal variation acting on the system) and it is driven by peeling stress which produces crack formation and growth in the overlay. A variety of analytical and numerical studies devoted to model the delamination phenomenon can be found in Literature. All these studies assume a specific behavior of the interface, which plays a key role to properly describe the formation and growth of crack delamination.

Delamination propagation can occur under mode I, II, III or mixed-mode loading conditions [24]. In the framework of the non-linear fracture mechanics see, for example, [29–32,34]. Recently, various models have been proposed to account for the mode loading conditions and the interlocking between the crack surfaces in the overlay, which strongly affect the bond strength in laminated systems [9]. In particular, some Authors (e.g. [42,25]) proposed analytical models taking into account the interaction between the interlocking shear force at the interface and the tensile force acting in the overlay layer. Granju et al. [12] carried out FE simulations to assess the stress at the crack tip of a debonding propagation. The interlocking effect was reproduced by inserting proper elements joining the faces of the crack in order to inhibit the crack opening. The interlocking effect on the delamination propagation between a substrate and an overlay was also analyzed by Tran et al. [38], which found that drying shrinkage strongly affects the debonding propagation, increasing the rate of cracking growth.[2] Through the same method, the effect induced by cycling loads on the debonding phenomenon between a concrete substrate and a thin cement-based overlay has been considered [39]. Moreover, the effect induced by the Young modulus of the overlay, the fiber reinforcement, the ultimate tensile strength of the overlay and the bond strength between the overlay and the substrate were taken into account by these Authors, founding that a low Young modulus and a high strength can lead to a significant improvement of the resistance to delamination [37].

The present study deals with an experimental investigation aimed to assess the mechanical performances of concrete elements stiffened by casting one or more layers of polymer-modified cementitious repair mortar on its upper surfaces. The concrete elements reproduce load-bearing concrete ceiling beams widely employed as flooring systems for residential buildings. The investigation is focused on the mechanical behavior of such elements under bending loading, with the aim to understand the failure mechanism occurring in the samples. In particular, the experimental study allows assessing if the collapse mechanism is driven by interfacial delamination between the overlays or by cracks formation and propagation from the tensile region to the compressive zone of the samples.

[1] Concerning the mechanical theory of damaged bodies see, for example, Tarantino [35], Lanzoni and Tarantino [16,17].

[2] Concerning the effects induced by shrinkage, see also Decter et al. [10].