Composites Part B 76 (2015) 249–259

Contents lists available at ScienceDirect

Composites Part B

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

Reliability and adaptability of the analytical models proposed for the FRP systems to the Steel Reinforced Polymer and Steel Reinforced Grout strengthening systems

Francesco Bencardino*, Antonio Condello

Department of Civil Engineering, University of Calabria, Via P. Bucci, Cubo 39B, 87036 Rende, Cosenza, Italy

ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
27 January 2015
Accepted 24 February 2015
Available online 5 March 2015

Keywords:
A. Fabrics/textiles
B. Debonding
B. Strength
C. Analytical modeling

ABSTRACT

The paper presents a theoretical prediction of the structural behavior of reinforced concrete (RC) beams externally strengthened to flexure by using a unidirectional ultra-high tensile strength steel (UHTSS) reinforcing mesh embedded in an inorganic matrix (Steel Reinforced Grout, SRG) or in an organic matrix (Steel Reinforced Polymer, SRP).

For these innovative composite materials are not yet available in literature specific standard documents, guidelines or analytical models capable to predict the structural behavior of the strengthened elements. Therefore, in order to evaluate the flexural strength of the strengthened beams some analytical models to predict the maximum axial strain developed in Fiber Reinforced Polymer (FRP) systems at the onset of intermediate debonding failure, have been used.

The goal is to assess the effectiveness of current analytical models used, up to day, to FRP strengthening systems to the SRG and SRP strengthening systems. For this aim, a database of experimental results on RC beams strengthened in bending by bonded SRG and SRP systems has been collected.

The comparisons between the theoretical predictions and the experimental data, in terms of debonding strain values, load carrying capacity, load-midspan deflection curves, have highlighted the reliability and adaptability of the current analytical models.

Finally, in order to evaluate the effectiveness of the SRG and SRP systems for strengthening RC beams a parametric study was also carried out.

1. Introduction

Various rehabilitation techniques have been proposed for civil structure and infrastructure to overcome problems associated with the aging process, increased load, change in use, and deterioration. Among these techniques, external strengthening provides a practical and cost effective solution when compared to other traditional repair methods. The introduction of advanced composite materials in structural engineering field, particularly, Fiber Reinforced Polymer (FRP), as externally bonded retrofit and strengthening materials, has offered numerous benefits like corrosion-free, excellent weight to strength ratio, good fatigue resistance, flexibility to conform to any shape, and broad applications [1–10]. Despite their satisfactory performance, the material cost is still high in comparison to conventional materials such as steel, thus a need exists for an alternative lower cost material.

Recently, a new class of composite materials has been developed and proposed in the market. This new composite material consists of unidirectional ultra-high tensile strength steel (UHTSS) reinforcing mesh, which can be embedded in an inorganic matrix (SRG) or in an organic matrix (SRP). Some studies on SRP and SRG systems are available in the current literature and all have shown the potentialities of these systems in improving structural performance of masonry and concrete elements [11–23] and, at the same time, their difference with respect to FRPs particularly in terms of bond behavior [24–26].

As is well known, the adhesion between external reinforcing system and concrete substrate is an issue of concern and generally controls the ultimate capacity of strengthened elements. Particularly, intermediate debonding phenomenon is one of the most common and peculiar failure modes observed in RC beams externally strengthened in bending. It is affected by a high level of

* Corresponding author. Tel.: +39 0984 496922.
E-mail address: francesco.bencardino@unical.it (F. Bencardino).

http://dx.doi.org/10.1016/j.compositesb.2015.02.029
1359-8368/

uncertainty due to the complex interaction of several phenomena, such as cracking in concrete, steel yielding in longitudinal rebars, and interface adhesion properties. As a result of this partial understanding, different analytical approaches were proposed within the scientific literature for FRP systems and adopted by the most common codes, standards and guidelines to perform the required safety checks [27–31].

However, proper standard documents or guidelines for the design of externally bonded SRG and SRP systems for strengthening existing structures are not available. Lately, American Concrete Institute (ACI) proposed an appropriate guideline for Fiber Reinforced Cementitious Matrix (FRCM) systems [32]. Not even ACI 549.4R-13 [32] guideline provide an analytical model to evaluate the maximum axial strain developed in the cement-based systems at the onset of intermediate debonding failure.

In order to give a contribution to this topic, a database was assembled by collecting data of experimental tests on RC beams externally strengthened to flexure with SRG and SRP systems. The reliability and adaptability of the analytical models proposed for the FRP systems to the SRG and SRP systems, were checked. Furthermore, the effectiveness of the SRG and SRP systems, in terms of ultimate flexural strength and ductility, was also discussed.

2. Experimental database

The aim of the comparison between analytical results and experimental data is to assessing the capability of the proposed models to predict not only the maximum axial strain of the strengthening system but also the ultimate load of the strengthened beams. For these reasons, the experimental tests have been chosen in order to provide measures concerning both comparison parameters, as well as the geometry of the beams and the mechanical properties of the materials.

Specifically, the following experimental studies have been selected.

(a) Bencardino and Condello [13] analyzed the results obtained from an experimental investigation carried out on four RC beams strengthened to flexure by using SRG and SRP systems and tested under four-point bending. Test parameters included the use or not of external U-wrap end anchorages to prevent delamination premature failure of the longitudinal sheet. Furthermore, with reference to the guidelines ACI 440.2R-08 [27] and CNR DT-200 R1/2013 [28] an analytical prediction of the failure loads and material strains of the strengthened beams were carried out.

(b) Barton et al. [12] investigated experimentally the flexural performance of four RC beams with externally bonded SRP and SRG systems by using four-point bending. The material properties for single-ply SRP and SRG were experimentally determined from coupon tensile tests and torsion tests. Analytical models based on the first-order and higher-order shear deformation theories were developed to predict the behavior of the retrofitted RC beams. Comparisons between the analytical models and the experimental results have shown a good prediction for the midspan deflection until the reinforcing steel reached the plastic region.

(c) Kim et al. [16] analyzed the mechanical properties of SRP system and its application in flexural strengthening of RC beams. Six beams have been tested under three-point bending to study the effect of SRP retrofitting on flexural behavior, failure modes, and crack patterns. Test parameters included variation of the width of SRP sheets and the use of SRP U-wrap end anchorages. A theoretical prediction of the flexural strength by using an analytical model was also carried out.

(d) Pecce et al. [20] compared the experimental results between RC beams strengthened with SRG and SRP systems and other beams strengthened with FRP systems. A total of nine RC beams strengthened for flexure were tested under four-point bending. The experimental results were compared to the predictions provided by ACI 440.2R-08 [27] guideline in terms of flexural strength, deflections, and curvature of the cross section. Under ultimate conditions, the guideline ACI 440.2R-08 provided conservative flexural strength for SRP and FRP systems.

(e) Saber et al. [22] analyzed the feasibility and potentiality of using the SRP system to strengthen RC beams. A total of seven prototypes were tested under four-point bending to evaluate the effectiveness of the strengthening configuration and the influence of the number of plies. Test results have shown that SRP could improve both the flexural stiffness and the ultimate load carrying capacity considerably.

A total number of 25 experimental results were collected (18 RC beams externally strengthened with SRP system and 7 RC beams externally strengthened with SRG system). The experimental data details are shown in Table 1, where for each experimental work are given: prototype name, test mode, geometric dimension of the prototype, type of external reinforcement and matrix, ratio (b_f/b_c) between the width of the external reinforcement (b_f) and the width of the beam (b_c), number of external reinforcement plies and anchorage systems. More details of the experimental tests can be found in the original works [12,13,16,20,22].

2.1. Analysis of the experimental data

In general, it was observed [13,16,22] that the addition of the external reinforcement (SRG or SRP), increases the flexural strength, greatly reducing the ductility of the strengthened beam, compared to the un-strengthened beam. With reference to the beams in Table 1, these results are shown in Fig. 1a and b against the equivalent reinforcement ratio (ρ_{eq}). It is defined as:

$$\rho_{eq} = \rho_s + \rho_{ext} E_{ext}/E_s, \tag{1}$$

where ρ_s and ρ_{ext} are the reinforcement ratios of A_s (total area of the tension steel) and A_{ext} (total area of external reinforcement) over the concrete cross sectional area, E_{ext} and E_s are the elastic modules of externally bonded composites and internal steel bars, respectively.

Specifically, Fig. 1a shows the maximum bending moment, while, Fig. 1b shows the deflection ductility index Δ_δ. It is the ratio of μ_δ (ratio between the deflection of the midspan section at failure and at yielding of the tension steel) of the strengthened beam with that of the un-strengthened beam. This index was only calculated for the strengthened beams of which the required data were available.

However, Fig. 1b can only point out a general trend resulting in high values of Δ_δ for small values of ρ_{eq}, but it is quite hard to recognize a consistent correlation between Δ_δ and $\rho_{eq.}$ This highlights how the increase of the ρ_{eq}, and hence of the external reinforcement area, cause an increase in the flexural strength (Fig. 1a) and a reduction of the ductility of the strengthened beam (Fig. 1b).

As a matter of principle, the maximum bending moment, M_{db}, observed in the experimental tests at debonding is smaller than the ultimate one, M_u, corresponding to external reinforcement rupture or concrete crushing. The following parameter, proposed by Bilotta