Engineering Structures 172 (2018) 981–996

Contents lists available at ScienceDirect

Engineering Structures

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

Experimental and numerical analyses of flexurally-strengthened concrete T-beams with stainless steel

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A R T I C L E I N F O

Keywords:
Concrete beams
Flexural strengthening
Stainless steel
Externally Bonded Reinforcement
Near Surface Mounted
Numerical simulation

A B S T R A C T

This work presents the results and the main conclusions of a series of experimental tests carried out to evaluate the efficiency of post-installed stainless steel reinforcement on the flexural strengthening of Reinforced Concrete (RC) T-beams when the bonding techniques EBR (Externally Bonded Reinforcement), NSM (Near Surface Mounted) and MA-EBR (EBR with Mechanical Anchors) are used. The RC T-beams were also modelled using a commercial Finite Element (FE) software in order to predict their behaviour until the rupture. For this purpose, a set of single-lap shear tests were also carried out to evaluate the local bond-slip relationships developed within the Stainless Steel (SS)-to-concrete interface. Due to the experimental bond-slip relationships, the numerical simulations were able to predict, with good accuracy, the different behaviours of the RC T-beams until their rupture. Moreover, the different rupture modes observed on all the RC T-beams herein tested were very well estimated by the numerical analyses. The tests of the RC T-beams showed that all the strengthening techniques allowed their flexural stiffness to be increased. Nevertheless, the RC T–beams strengthened with the EBR and NSM techniques had premature ruptures, i.e. the rupture in the RC T-beams occurred even before the yielding of their steel reinforcements. The RC T-beam strengthened with the MA-EBR technique showed good ductility and the highest load bearing capacity, which means that the MA-EBR technique is the best bonding technique herein used.

1. Introduction

The strengthening of concrete elements is a current need, not only due to the lack of conservation, design defects or rehabilitation after the occurrence of accidents, but also as a way of reusing older structures that do not satisfy the requirements of the latest codes with demanding serviceability and recent requirements. Therefore, revitalizing older areas in our cities would be wise and should be seen as a clear goal in the near future. When compared to new construction, reconstructing older buildings means it is possible to reduce the environmental impact caused by the demolition and rebuilding. Thus, it is important to continue looking into the field of strengthened structures in order to seek new strengthening techniques as well as to develop more advanced knowledge about the existing ones.

Among the actual wide range of strengthening solutions, the bonding of a new material on existing structures is a technique that has been used in past decades (e.g. [1–9]). Particularly when the structure needs to be flexurally improved, the strengthening with the addition of a new reinforcement is currently used and applied to its tensioned regions increasing the strength capacity of these strengthened elements.

This strengthening method commonly contemplates the use of steel plates or metallic profiles that are bonded with resin to the structure. However, in addition to the bond technique, these cases also require the use of steel mechanical anchors that play an important role in to prevent the detachment of the reinforcement from the strengthened structure [10,11]. More recently, with the introduction of Fiber Reinforced Polymers (FRP) or composite textiles into the civil industry, researchers (e.g. [12–15]) have redirected their focus onto these new materials due to their interesting characteristics, such as high strength/weight ratio and high corrosion resistance. Therefore, carbon steel has been largely superseded in recent interventions. However, there are some characteristics that strengthened elements with composite materials do not possess and, in some circumstances, such as when considering the ductility of the strengthened structure [13,16,17], they may not be advisable. As for durability, strengthening with stainless steel may be of interest due to the alloying elements that, when in the presence of water or oxygen, form a thin, stable and transparent passive layer that protects against corrosion. In addition to the high corrosion

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https://doi.org/10.1016/j.engstruct.2018.06.077
Received 27 September 2017; Received in revised form 18 June 2018; Accepted 20 June 2018
0141-0296/

resistance, good aesthetic appearance, low sensitivity to mechanical damage, high ductility, the high strength of the stainless steel makes it a good material for the strengthening of civil structures [18]. However, the passive layer makes it difficult to bond with adhesives because apart from creating a barrier between the adhesive and the surface of the stainless steel in contact with the atmospheric humidity a thin layer of water on the surface of the stainless steel is also created which makes it even more difficult to ensure a good bonding between the adhesive and the surface of the stainless steel. Therefore, it is no wonder that some authors do not recommend the use of bonded stainless steel [19]. Still, some studies show that it is possible to perform structural bonded joints with stainless steel and epoxy resins with performances similar to those achieved with mild steel [20].

To improve the bond between the stainless steel and another substrate it is best to pre-treat the surface of the stainless steel first in order to expose the base metal to the adhesive agent by removing the rusty layer or by increasing the roughness of the stainless steel surface [20–23], which can be carried out with abrasive treatments or projection of grit or sand. Some authors have reported that abrasive treatments are better than projected grit [24]. Others are of the opinion that the results with a designed grain are better due to the increase of roughness that also provides an increase in the contact surface, increasing the interlocking effect [22,23]. In the literature (e.g. [20–23]), most authors report that the best performance for bonding structural joints is achieved with chemical treatments of the stainless steel surfaces in heated acid baths. However, this procedure is difficult to implement especially when long bars/rods are used which, today, happens in the majority of cases of the flexural strengthening of beams, columns or slabs. Alternatively, the stainless steel may be cleaned with a non-metallic rotating brush to remove free particles and then cleaned with a cleaning agent, e.g. trichloroethylene, tetrachloroethylene or acetone [25].

Unlike the bond between the FRP and concrete, where the bonding behaviour within the context of the strengthened structures has led to several studies (e.g. [10,12,26–35]), research on the structural bonded joints between the stainless-adhesive-concrete is scarce. In most cases, pull-out tests are used to study the bond characteristics between the concrete and the stainless steel but all of those tests have the particularity that the stainless steel is embedded in the concrete, i.e. the bond between the stainless steel and the concrete is ensured without the help of an adhesive [36,37].

All these preparation methods aim to improve the bond between the stainless steel and the concrete, which is crucial for the success of its application as a strengthening material on RC structures. Within this context, Ertzibengoa et al. [37] conducted an experimental study based on several pull-out tests in order to assess the bond behaviour between the stainless steel and concrete and between carbon steel and concrete. From their vast experimental campaign, the authors [37] studied the influence of several aspects on the strength of these interfaces such as the ribbed vs. flat surfaces, the bond length or the diameter of the stainless steel and carbon steel. The results seem to show that the influence of the use of stainless steel or carbon steel is more significant when flat samples are used instead of ribbed ones, where no significant differences could be identified. Also, when the same cross section is compared, rod samples developed higher bond stresses than those with a rectangular cross section.

Unlike, e.g. FRP composites or carbon steel, there is very scarce information about the use of stainless steel as a strengthening material used on RC beams. Still, quite recently, Colajanni et al. [38], conducted an experimental work where stainless steel was used in order to improve the flexural and shear strength of six concrete beams with flexural deficits. The strengthened RC beam had a significant increase in its strength and ductility, which demonstrated the efficiency of strengthening with this material.

Another study by Bencardino and Condello [39] was devoted to the strengthening of RC beams with stainless steel fibre strips embedded into an inorganic matrix (S-FRCM: Steel-Fibre Reinforced Cementitious Matrix). The authors [39] used three RC beams with a poor concrete and two different strengthening techniques were used: (i) traditional Externally Bonded Reinforcement (EBR); and (ii) an innovative Inhibiting-Repairing-Strengthening (IRS) technique. In the former, the external bond of the stainless steel on the concrete surface was made, in the latter, the ISR technique consists of replacing the full cover of the concrete by stainless steel embedded in a polymer-based inorganic matrix with good properties of protection against corrosion. Despite the increase in the load bearing capacity of the strengthened RC beam with the ISR technique of 25% when compared to the control RC beam, the authors also observed that the two strengthened RC beams failed in a ductile mode by concrete crushing after the yielding of steel reinforcements and no premature debonding was observed.

The use of mechanical anchors along the steel plates bonded in the tensioned face of RC beams is common practice also and their use intends to delay or even prevent the premature debonding [40,41] of the stainless steel from the concrete which was demonstrated in the studies carried out by Ammann [40] and Siu and Su [41]. This procedure is also used in the strengthening of RC beams with FRP composites in order to prevent the premature debonding of the FPR free ends [42] with limited success due to the stress concentrations that develop close to the anchor, which lead to the composite rupture more easily. Since FRP sheets do not have a fully plastic behaviour, the determination of these stress concentrations is complicated to define and, consequently, the analytical definition of the corresponding rupture is equally hard to establish [42].

From what was stated above, it is clear the need for continue seeking for new strengthening techniques, as well as improving and learning more about the techniques we do know. The present work is part of a long experimental and numerical work that has been developed by the authors [35,43–47] on the flexural strengthening of RC elements with the addition, by bonding, of post-installed reinforcements. In previous works, RC T-beams were flexurally-strengthened with Glass (G) FRP [44,45] or CFRP [44]. Also, old timber floors flexurally-strengthened with CFRP composites have been already tested by the authors [47,48] where different bonding techniques were studied.

The aim of the present work is to analyse the performance of RC T-beams strengthened with stainless steel using different techniques (EBR, NSM and EBR with Mechanical Anchors). The following sections will show the experimental program and the corresponding results and discussion as well as the numerical simulations carried out in this study.

2. Experimental program

In this study, sixteen single-lap shear tests were performed to analyse the bond behaviour between stainless steel and concrete. Ten of these tests were used to study the bond performance of the EBR technique and the remaining six tests aimed to evaluate the bond performance when the NSM technique is used. The specimens of the single-lap shear tests are identified in this study with the initials of the strengthening technique used following the prefix “Lb” and the bond length in millimetres. Replicated specimens for the same bond length of each of the techniques tested are identified with the lower alphabet characters after the last number of the bonded length. Four reinforced concrete (RC) T-beams with a 3.0 m span were tested in a four-point bending test setup. The first RC T-beam is a control specimen, which is herein designated as V11 RC T-beam. This particular T-beam is unstrengthened and its results will be considered for reference. Regarding the strengthened T-beams, one beam was strengthened with two rectangular flat bars of stainless steel applied with the EBR technique (V12), another was strengthened with four ribbed stainless steel rods applied with the NSM technique (V13) and the fourth beam was strengthened with two rectangular flat bars of the same stainless steel used on the EBR RC T-beam but, in this case, the both ends of the stainless steel bars were anchored with steel mechanical anchors (V14).