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# Experimental study of a rehabilitation solution that uses GFRP bars to replace the steel bars of reinforced concrete beams

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ABSTRACT

The corrosion of the steel reinforcement affects drastically the long-term durability of many reinforced concrete (RC) structures in the world, especially the ones near the sea. When this problem is detected at early stages, it is possible and important to repair the structure in order to restore its safety and avoid future hazards and more expensive interventions. The research work described in this paper is inspired on these cases as it proposes a rehabilitation solution to replace the tension steel reinforcement of a RC beam with GFRP bars, which is a material immune to corrosion.

The experimental study consisted on six full-scale RC beams subjected to a three-point bending test until failure. The specimens had stirrups without the bottom branch and were casted in two phases to simulate the replacement of the corroded and cracked bottom concrete. Two different GFRP reinforcement ratios were tested to assess the behaviour of the repaired beam regarding its service and ultimate states in comparison with the original beam with steel reinforcement. The results are presented and discussed in terms of flexural capacity, failure modes, deflection, crack pattern, mid-span crack width and reinforcement strains. It was concluded that the presented rehabilitation solution is easy to implement, can be designed according to general FRP design guidelines, and is able to restore the serviceability and ultimate limit states of the original RC beam.



## 1. Introduction

Structural rehabilitation is becoming increasingly important nowadays. The amount of deteriorated structures, the frequency and the costs of rehabilitation interventions motivate the introduction of innovative materials and methods to rehabilitate structures. The service behaviour and the ultimate performance of reinforced concrete (RC) are shortened by the corrosion of steel reinforcement [1,2]. Corrosion of the reinforcement induced by chloride environments has a significant effect on the mechanical behaviour, and the loss of cross-sectional area and bond strength of reinforcement have a very important effect on the bending capacity [3]. Malumbela et al. [1] concluded that for a maximum mass loss of 1%, the flexural capacity was reduced by 0.7%. Currently, repairing, rehabilitating and strengthening solutions are being developed and tested using different materials and different layouts. Solutions with steel materials can have limited duration. As alternative, Fibre Reinforced Polymers (FRPs) have been used because of their resistance to corrosion, high strength and light weight. The most common is the use of FRP solutions with sheets or laminates which are externally bonded to replace the structural integrity, in cases of theoretical reinforcement mass loss from 5% to 15%. Many experimental studies [4–7] indicate that by optimizing the amount and the layout, the bonded FRP sheets are suitable for balancing the strength recovery and that it is possible to restore the yield and the ultimate capacity with the same or lower deflection than initially. To prevent delamination and debonding problems, Spadea, Bencardino [8] suggested that the strengthening for flexure should be accompanied by the strengthening for shear. Thus, the best layout of bonded FRP sheets as reinforcement is a combination of a bonded sheet on the tension side anchored by U-shaped sheets. Several techniques are being developed to prestress FRP plates prior to bonding, which has already been proven to be an efficient solution [9]. However these solutions may not be effective when applied to damaged beams with more than 50% mass loss of tensile steel and it is emphasized that additional research is needed for cases where corrosion is severe and part of the reinforcement is missing. Moreover, the epoxy-bonded FRPs have limitations when applied at high temperatures, because of the rapid deterioration of the properties of the polymer matrix [10]. The use of cement base

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## Nomenclature

| | |
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| $b$ | width of the rectangular cross-section [m] |
| d | distance from the extreme compression fibre to the centroid of the tension reinforcement [m] |
| $f_{bd}$ | bond strength [Mpa] |
| $f'_c$ | compressive strength of concrete [MPa] |
| $f_{cd}$ | concrete compressive strength design value [MPa] |
| $f_{cm}$ | concrete compressive strength [MPa] |
| $f_{ctm}$ | the mean tensile strength [MPa] |
| $f_f$ | tensile strength of GFRP bars [MPa] |
| $f_{fk}$ | tensile strength characteristic value of the FRP reinforcement [MPa] |
| $f_{fu}$ | the ultimate FRP tensile strength [MPa] |
| $f^*_{fu}$ | guaranteed tensile strength of an FRP bar [MPa] |
| $f_t$ | the maximum tensile [MPa] |
| $f_y$ | yield stress [MPa] |
| $h$ | cross-section depth [m] |
| lb | anchorage length [m] |
| $A_f$ | reinforcement area [$m^2$] |
| $C_E$ | environmental factor [–] |
| E | elasticity modulus [GPa] |
| $E_f$ | elasticity modulus of GRP bars [GPa] |
| $I_e$ | Branson's effective moment of inertia [$m^4$] |
| $I_g$ | cross-section gross moment of inertia [$m^4$] |
| $M_a$ | the moment for the considered load [kNm] |
| $M_{cr}$ | cracking moment [Nm] |
| $M_f$ | function of the bending moment [kNm] |
| $M_n$ | moment capacity (nominal moment) [kNm] |
| $M_u$ | ultimate moment resistance [kNm] |
| $\beta_1$ | factor that takes the value 0.85 when the concrete strength, $f'_c$, is lower or equal to 28 MPa and its value decreases continuously at a rate of 0.05 per each 7 MPa above the 28 MPa [–] |
| $\beta_d$ | reduction coefficient used on the deflection calculation [–] |
| $\delta$ | service deflection [m] |
| $\varepsilon$ | mean strain [MPa] |
| $\varepsilon_{cu}$ | concrete ultimate strain [MPa] |
| $\varepsilon_f$ | FRP reinforcement tensile strain [MPa] |
| $\rho_{fb}$ | balanced reinforcement area [–] |
| $\rho_f$ | reinforcement area [–] |
| $\rho_s$ | reinforcement area of steel [–] |

adhesives can be a solution for the application on structures located in hot regions or when there is a high danger of fire [11].

Rehabilitation solutions using FRP bars are not so frequent. One of the reasons may be that the FRP bar design as reinforcement is still uncommon, although this material has been available on the market for over 15 years. Several factors, such as novelty, production costs, the low modulus of elasticity, the non-ductile behaviour, the different design philosophies, and the need to validate the behaviour, have been responsible for the low levels of its application. Several authors [2,12] suggest that the analytical procedures developed for the design of reinforced concrete with steel bars in terms of ultimate loads, deflection and crack width are not applicable to the design of reinforced concrete with FRP bars (FRP RC) due to the mechanical property differences. Additionally, the design of FRP RC is generally governed by serviceability. However, the majority of codes and guidelines developed until now [12,13], use the same equations developed for steel reinforced members, modified to account for the differences between the materials [12,13]. Several authors [12–15] have been studying the ultimate and service behaviour of FRP RC. Since the behaviour FRP RC beams is bilinear until failure, reducing stiffness after cracking, most of the guides and codes recommend the flexural design according to a compression failure due to its less catastrophic mode [2]. This forces the design of over-reinforced cross-sections, providing a reduction in service load deflections and crack width and lower FRP bars stress. It is suggested that compression failures present better member deformability and gradual member failure than FRP rupture [15]. In serviceability, due to the lower modulus of elasticity of FRPs and to the different bonding properties, larger deflections and crack widths are expected than in steel RC beams. Several models and approaches for predicting deflections and crack width have been proposed, but some controversy remains. Several authors [16] reported that the deflections of FRP RC can be predicted with the original ACI 318 [17] formulas developed for steel reinforced concrete. On the other hand, other experimental analyses [18–20] pointed out that the modifications proposed in ACI 440.1R-06 [12] relative to ACI 318 are needed, achieving accurate predictions with this approach. Other studies [21] propose different methods. The Yost et al. [22] and Toutanji and Saafi's [14] findings suggest that the effective moment of inertia, used in the ACI 318 formula to predict the deflection, is overestimated and that it is possible to establish a correlation between the degree of overestimation and the ratio between the reinforcement area and the balanced reinforcement area ($\rho_f/\rho_{fb}$): the higher the ratio $\rho_f/\rho_{fb}$, the lower the error of the effective moment of inertia value. They also proposed alternative equations for the effective moment of inertia and for deflection.

The serviceability verification depends on bond and elasticity modulus, a certain equation can predict the behaviour well for one type of FRP bars but not for another of a different material or with a different surface [2,13,14]. Among the different fibres used to make FRPs, glass fibres are the most common as they are the least expensive.

Furthermore, other studies [2] indicate the use of high strength concrete (HSC) to make better use of FRPs' properties.

Some experimental works of the near surface mounted (NSM) reinforcement technique were done to rehabilitate concrete structures damaged by corrosion [23]. This technique consists in bonding FRP rods with epoxy resins in undamaged areas of concrete cover. Results indicate that it is possible for repaired beams to achieve the same ultimate capacity as the control beam but differing in the failure modes [24] and showing a ductility reduction in comparison with traditional RC beams. However, a significant disadvantage of this technique is that the placing of the NSM rods is highly dependent on the quality of the concrete cover, which is frequently damaged by steel corrosion. If this is the case, this solution cannot be applied.

The issues listed in the preceding paragraphs justify the research described in this paper. Additionally, rehabilitation or repairing solutions using FRP sheets or textiles, or even the application of FRP bars with NSM, cannot be applied in many cases, such as when the reinforcement mass loss due to corrosion is high, when the concrete cover is extremely damaged or when it is not possible to increase the depth of the section. As a consequence of these facts, the rehabilitation solution adopted in these cases tends to be the replacement of the corroded steel by new steel reinforcement. However, when the deterioration of the RC structure is due to steel corrosion, the replacement of this material by another that is immune to this problem, such as GFRP, is an additional guaranty for a long-term duration of the rehabilitation solution.