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Retrofit of RC bridge half-joints: Applications and remarks with emphasis on post-tension techniques

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ABSTRACT: Due to their advantages, many reinforced concrete road bridges were built according to the Gerber scheme in which the so-called half-joints represent a key structural component. Besides their advantages, some drawbacks can be found in this type of bridge, mainly related to the deterioration process of the half-joints that leads to reinforcement corrosion and consequent concrete cracking and spalling. Therefore, many bridges may need over time specific retrofit interventions to guarantee the required level of safety. This paper first describes the retrofit techniques currently available in the literature. Numerical simulations are then carried out to investigate the effectiveness of a specific technique based on post-tensioning. Refined nonlinear finite element models were used to characterize the post-tension effects on the load-bearing capacity of a case study half-joint also in presence of simulated chloride-induced corrosion, and to outline the optimal prestress level to be used to obtain the wanted performance improvements.

1 INTRODUCTION

In the past, the Gerber scheme was widely used for the construction of reinforced concrete road bridges due to its advantages in terms of both stress distribution and the related statically determinate conditions. According to this scheme, the cantilever and the simply supported spans are connected to each other through the so-called half-joints, which represent a key component of these bridges (Kun et al. 2015).

Despite the advantages, a frequent problem related to this kind of bridge is the malfunctioning of drains, which causes seepage across expansion joints (Lee 1994). In particular environmental conditions, the presence of chloride ions may enhance the degradation phenomena leading to reinforcement corrosion and consequent cracking and spalling of concrete (Gjørv 2009), especially in the cantilever part (Figure 1).

Another issue is related to the very narrow space in correspondence with the joints' position, which causes difficulties in inspections leading to incorrect quantification of degradation (Desnerck et al. 2018). In the literature, two cases of bridges' collapse are related to the half-joint failure. The first is the de la Concorde overpass collapse in 2006, a bridge situated in Laval (Canada). The other case is related to the Gerber bridge overpass in Annone Brianza (Italy), which collapsed in 2016 following the passage of a 108-ton truck. In both cases, the deterioration of the half-joints and damage already present on the bridge coupled with some design and construction flaws were responsible for the collapse (Mitchell et al. 2011, Di Prisco et al. 2018).

For this reason, the assessment of these structural components, also accounting for degradation modelling, coupled with rehabilitation, through careful planning and design of the interventions by the bridge owners and practitioners, are crucial, in order to increase their structural performance and therefore to extend the lifespan of bridges.

To this end, this paper first reports a brief review of the currently available intervention techniques for bridge half-joints, accounting for both previous experimental studies in the literature and interventions carried out on existing bridges. Through the analysis of each technique's main advantages and disadvantages, it is possible to identify the one which results the

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least disruptive and expensive and the most easily applicable. This is the post-tension technique, based on the use of external high-strength post-tensioned rods, which are restrained on the top and the bottom of half-joint's surfaces through steel plates.

Therefore, the paper presents an application of this technique to half-joints of a case study bridge, the Musmeci bridge in Italy (e.g. Marmo et al. 2019), in which, through nonlinear numerical simulations, the performance improvements at both serviceability and ultimate limit state have been evaluated, accounting for the variation of the prestress applied and also considering the presence of different chloride-induced corrosion scenarios.

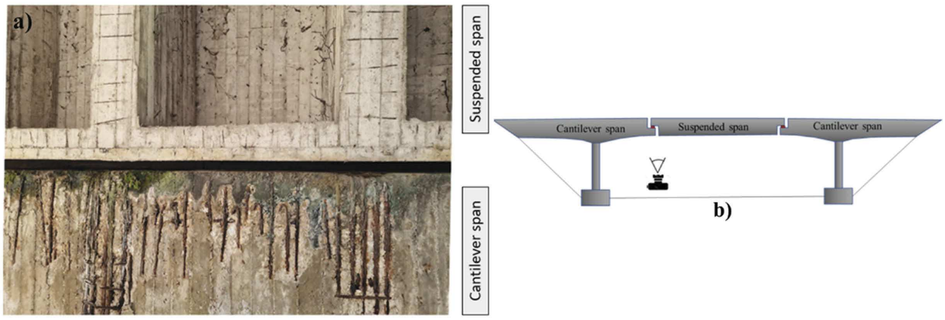

Figure 1. Degradation of an RC bridge's half-joint: a) view from the intrados and b) bridge scheme and viewpoint.

2 REVIEW OF THE AVAILABLE RETROFIT OPTIONS FOR HALF-JOINTS

When it comes to bridge half-joints, there can be several reasons for which repair or strengthening interventions are needed: increased traffic loads compared to the time of design and consequent increase in strength demands; decrease in concrete and reinforcement's strength due to the accumulation of decay; the presence of widespread cracks which may cause a loss of serviceability or, in extreme cases, the collapse of the structure. As a result, researchers have developed and studied different techniques to account for all these aspects.

In the literature, there are techniques developed and tested on the half-joints properly belonging to bridge structures, and techniques more suitable for dapped-end beams often used on the roofs of industrial buildings or in the floor systems of buildings used for parking or otherwise prefabricated. In addition, the various techniques differ from each other in the particular materials used, in the different performance objectives, or even in the different installation configurations taking into account the geometry of the structural element at hand.

Among the available retrofitting techniques, a rather invasive intervention consists of joining the cantilever and suspended span in such a way as to completely change the bridge's statically determined scheme to one of a continuous bridge. This intervention has been developed and patented by Fukuoka (1999) and the connection is made through the use of horizontal high-strength steel bars restrained to the existing concrete of the half-joints. In addition to being very invasive, the intervention is also very costly since new bearings must be placed on the piers to allow the absorption of thermal expansions.

On the other hand, a non-invasive and easy technique consists of the use of high-strength post-tensioned bars installed along the undapped part of the half-joints in a vertical or inclined direction, in order to increase the load-bearing capacity of the half-joint. The only installation operation consists of drilling holes on the side of the joints, through the curb or transverse beam, if present, for the positioning of the bars (Figure 2). Such an intervention was carried out on the existing Scafa bridge located in Fiumicino (Italy) (Alessandrini & Burba 1994) and the PRC Gerber bridge on the Po River near the town of Pieve Porto Morone (Italy) (Di Prisco 2019).

The main objective of this technique is to provide an increase in the load-bearing capacity of the half-joint and, in addition, the prestressing action also favours the limitation of cracks during service conditions. In order to quantify the performance gains offered by the technique, Atta & Taman (2016) carried out an experimental tests campaign on Gerber beams in which the post-tensioned bars were installed in different configurations and positions. In particular, they showed that the three configurations illustrated in Figure 2 exhibited improved behaviour by providing strength gains of 81%, 65%, and 83%, respectively, with respect to the beam without intervention.

A technique able to intervene on the deteriorated concrete of the half-joint, provide an increase in strength and, at the same time, provide protection against long-term degrading agents consists in the realisation of a steel jacketing system bonded to the lateral surfaces of the half-joint through the use of transversal bars. Such an intervention was carried out on the Generale Franco Romano viaduct in the Piedmont region (Italy) (Lafranconi et al. 2018). The increase in load-bearing capacity can be provided by the installation of post-tensioned vertical bars restrained above and below the saddle, as shown in Figure 3a. The only disadvantage of the technique is that the intervention is mainly carried out along the lateral surfaces of the half-joints, which are not always accessible due to the presence of a connection curb or the transverse beam connecting the deck's girders.

Finally, there are techniques in the literature based on the use of composite materials in the form of plates, laminates or fabrics bonded externally to the surfaces of the half-joints (Figure 3b). The most commonly used solutions are carbon fibre-reinforced polymer (CFRP) or fibre-reinforced polymer (FRP). The advantage of these materials lies primarily in their ability to provide strength improvements while occupying very small volumes, which makes them suitable for Gerber saddles. Some authors have tested the performance of these materials by carrying out experimental campaigns on dapped-end beams used in precast buildings. In particular, Taher (2005) analysed the performance of different configurations of CFRP laminates, differing in the inclination of the laminates with respect to the beam axis or in the installation position, obtaining an increase in strength in the range of 17-42%. Nagy-György et al. (2012) performed experimental tests using FRP plates or fibres in different configurations, obtaining that the highest performance was provided using a combination of vertical and inclined fibres. The disadvantage of using composite materials is mainly related to their excessive cost. Furthermore, the application of materials on the side surfaces of the half-joints is not always permitted due to the structural constraints mentioned above.

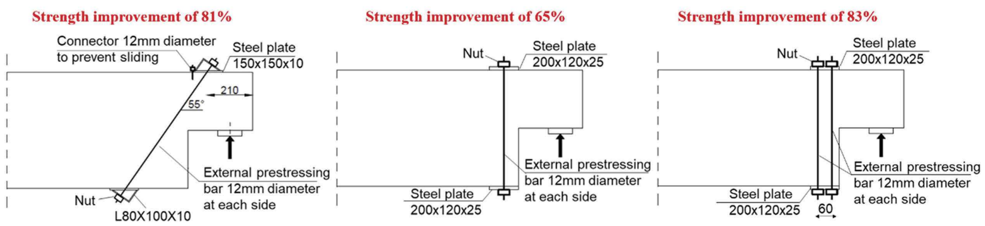

Figure 2. The most performed post-tensioned solutions tested by Atta & Taman (2016).

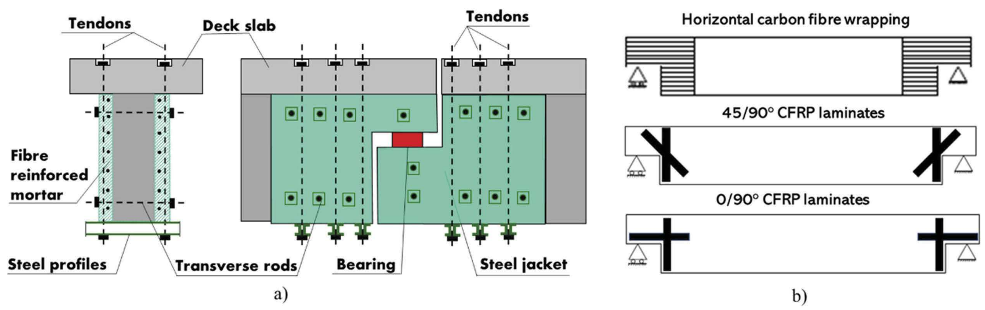

Figure 3. a) Schematic view of the jacketing system, adapted from Lafranconi et al. (2018) and b) different configurations of externally bonded composites (Taher 2005, Nagy-György et al. 2012).

2.1 *Remarks on the choice of the optimal intervention*

If we want to compare the techniques described above, in addition to the advantages and disadvantages of each one, we have to analyse further aspects related mainly to the construction in place. In particular, Santarsiero et al. (2023) compared the techniques taking into account several aspects: the construction costs; the disruption caused to the bridge and road traffic; the need to lift the suspended span; the need to carry out repair work before the actual intervention; and, finally, also considering the performance improvement by comparing the half-joints' failure modes before and after the intervention.

What emerges is that the techniques which require the lifting of the suspended span (i.e. jacketing and application of composites) are the most expensive and disruptive. In contrast, the post-tensioning technique is the least invasive, the most economical and adaptable to the different geometric configurations present in existing bridges.

In fact, in the majority of cases, the deck of a Gerber bridge is in the configuration illustrated in Figure 4, in which the girders are connected by a transverse beam and/or a curb at the dapped-ends. This configuration impedes the realisation of all those techniques which work on the lateral surfaces of the beams. Therefore, it is very important to assess the feasibility of an intervention, i.e. its applicability in reality, when one is called upon to choose between different types.

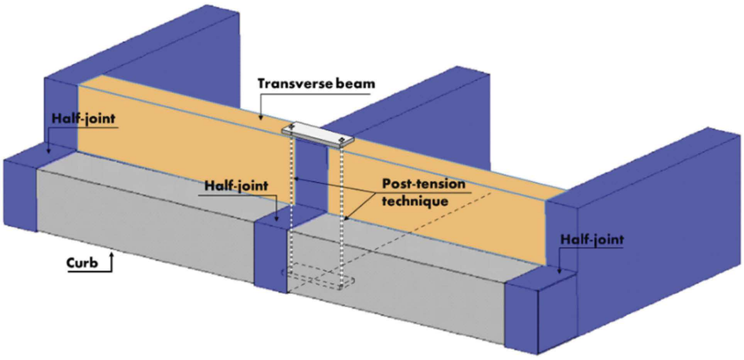

Figure 4. Typical Gerber bridge deck configuration and applicability of the post-tension intervention technique.

3 POST-TENSION TECHNIQUE: NUMERICAL SIMULATION

In order to deepen and quantitatively evaluate the performance improvements provided by the post-tension technique, this section describes a numerical simulation carried out by nonlinear finite element analyses. The intervention is applied on a half-joint belonging to the bridge on the Basento river in Potenza (Italy), carefully described in previous articles (Santarsiero et al. 2021, Marmo et al. 2019), designed by Sergio Musmeci matching older codes (Circolare n. 384 del 1962). It is worth reminding that the bridge's RC box deck is 16 m wide and supported by the vault every 17.30 m for a total length of 300 m. Moreover, the deck is provided with suspended spans (10.38 m long) connected by half-joints which are shown in detail in Figure 5a.

Numerical simulations were carried out using the finite element software ATENA (Červenka et al. 2021), which is able to accurately reproduce the reinforced concrete structures' behaviour according to the nonlinear fracture mechanics theory (Bazant & Oh 1983). In particular, it is possible to simulate the nonlinear behaviour of concrete both in compression (crushing) and in tension (cracking). Further details on the constitutive models used are provided in a previous article by Santarsiero et al. (2021). The main results of the numerical simulations are here briefly summarized as they are widely described in Santarsiero & Picciano (2023).

Figure 5b shows the FEM model of the studied half-joint in the presence of intervention. Within the analyses, the presence of degraded conditions due to chloride-induced corrosion was also simulated. In fact, the software makes it possible to simulate the chloride ions ingress into the concrete and the initiation and propagation of reinforcement corrosion through a refined mechano-chemical model (Červenka et al. 2017), which takes into account the acceleration of the phenomenon induced by the presence of concrete cracks caused by the loads acting on the half-joint.

In particular, the model is based on the 1D chlorides diffusion process within the concrete, modelled through Fick's second law (Zhang et al. 2010) accounting for three fundamental parameters: the surface chlorides concentration C_s (as % of cement mass), the chloride diffusion coefficient D_{ref} (m^2/s) and the critical chloride content C_{crit} (as % of cement mass).

In the previous study by Santarsiero et al. (2021), the significance of the three parameters was investigated in detail and, in particular, analyses were carried out with different combinations of their values in order to identify the one which produces the worst effects in terms of corrosion and loss of bearing capacity.

Therefore, in this study, in order to analyse the ability of the post-tension-based intervention to improve the condition of a severely degraded half-joint, a triad of values was deterministically selected based on literature data (Angst 2019, Bertolini et al. 2004, Hájková et al. 2018, Van der Wegen et al. 2012) relating to aggressive environmental conditions concerning road bridges in harsh climates exposed to de-icing salts.

Evaluating the nonlinear concrete and steel behaviour, the design strength values calculated according to the Italian Guidelines (Ministry of Infrastructure, CSLP 2020) were used. The design strength of the analysed concrete structure is $f_{cd} = -17.24$ MPa (Santarsiero & Picciano 2023). As a function of the latter value, the other material properties required for the numerical simulations were calculated. In particular, $f_{ctd} = 1.59$ MPa, $E = 29{,}253.88$ MPa and $GF = 1.31E\text{-}4$ MN/m (Fib, Fédération Internationale du Béton 2010).

Similarly, the reinforcement properties were calculated: the design yielding stress is the same as the characteristic one $f_{yd} = f_{yk} = 375$ MPa, as the former can be obtained by the ratio between the latter and the maximum value of confidence factor, $CF = 1$, depending on the achieved knowledge level (Ministry of Infrastructure 2018); the failure stress is equal to $f_{td} = 460$ MPa and the failure strain ε_t is set to 18%.

As for the intervention, this is carried out according to configuration No. 2 tested by Atta & Taman (2016) (illustrated in the central scheme of Figure 2), through the use of two external 26.5 mm diameter high-strength Dywidag-type steel bars, equipped with corrosion protection system, with yielding stress $f_y = 950$ MPa and failure stress $f_t = 1050$ MPa. The bars were restrained at the top and bottom (Figure 5b) through two S275JR ordinary steel plates (EN 1993-1-1 2005, Ministry of Infrastructure 2018) 500 mm wide, 150 mm long and 100 mm thick.

11 analyses were performed taking into account the variability of two parameters in particular: the corrosion period (t_{corr}) and the prestress value applied to the external bars (σ_p). With regard to the first parameter, a corrosion period of 45 years was considered, which would correspond to the current state of the bridge taking into account that it was completed just 45 years ago; and a period of 95 years, in order to assess the effect of the intervention following a further 50 years of corrosion. Concerning the second analysis parameter, the prestress value was varied in terms of percentages with respect to the yield strength of the external bars, considering the following four cases: $0.05f_y$, $0.15f_y$, $0.30f_y$, $0.40f_y$.

Ultimately, the following analysis intervals can be distinguished in each of the performed analyses: a first interval, identical to all the analyses, in which the half-joint is loaded by the vertical reaction, at the intermediate point of the nib, equal to 270 kN (relative to the permanent structural and non-structural loads transferred by the suspended span); a second interval in which the chlorides ingress, which is a function of the cracks generated in the previous interval, and the effects in terms of corrosion and consequent load-bearing capacity reduction are simulated, accounting for the two selected periods; a third interval in which the post-tension intervention is made active by applying the selected prestress values in the external bars; and, finally, a last interval in which, through a displacement control analysis, the half-joint is brought to failure to assess the ultimate capacity P_u.

4 ANALYSIS OF RESULTS

This section describes the main results of the performed numerical analyses, referring to the recent work by Santarsiero & Picciano (2023) for a more in-depth discussion. In particular, the performance of the post-tension intervention was analysed at both the serviceability (SLS) and ultimate limit state (ULS) as a function of the applied prestressing.

Concerning the performance improvements at SLS, the cracking load P_c was monitored for each of the analyses. The latter represents the load at which a limit crack width of 0.20 mm is

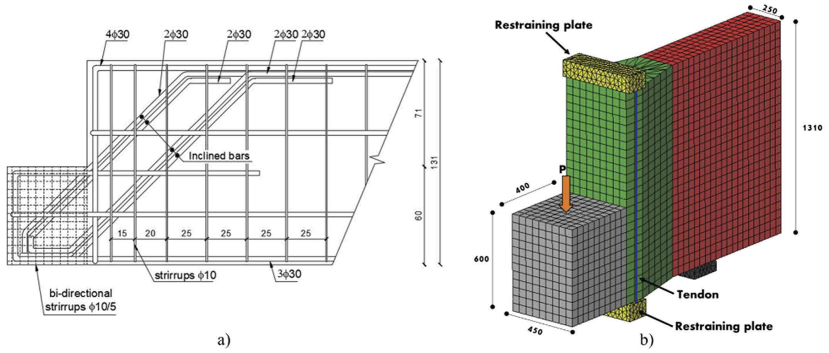

Figure 5. a) Musmeci bridge's half-joints (dimension in cm) and b) FEM model (dimension in mm).

reached as reported within the current codes (Ministry of Infrastructure 2018, EN 1992-1-1 2004) depending on the aggressiveness of the environment and the corrosion sensitivity of the reinforcement bars. As shown in Figure 6a, the cracking load of retrofitted models increases, with respect to the as-built corroded ones, with an almost linear trend as the prestress in the bars increases. In particular, there is a significant enhancement for prestressing values of $0.15f_y$ or more. Furthermore, ΔP_c values are greater for analyses with 95 years of corrosion than for those considering 45 years, especially for high post-tension values. Ultimately, the half-joint's conditions at the serviceability limit state improve due to the intervention, which reduces the cracks' width and, thus, also limits the ingress of degrading agents.

Figure 6b shows the variation of the ultimate load P_u as a function of the applied post-tension. As can be seen, the load-bearing capacity of the half-joint is not greatly affected by the tendons' prestress, showing a significant improvement even for low post-tension values. Furthermore, a greater increase in P_u is obtained after 45 years of corrosion, with an average ΔP_u equal to 25%, compared to the average increase of 18% in the case of 95 years of corrosion. In fact, in the latter case, the reinforcement is more corroded, limiting the increase in load-bearing capacity offered by the intervention.

Thus, the post-tensioning intervention makes it possible to recover the share of load-bearing capacity lost due to reinforcement corrosion as a result of 95 years of chloride pollution. In fact, the ultimate capacity assumes the same value as the as-built condition, as can be also seen from the load-deflection curves of the retrofitted (coloured-dashed lines) and as-built (black continuous line) models in Figure 7b. In the case of a 45-year corrosion simulation, it provides an increase in performance, which is also higher than that of the as-built condition (Figure 7a).

In order to generalize the results here obtained, the effects of the reinforcement layout were investigated in Santarsiero & Picciano (2023), in which the same analyses were performed considering the absence of the inclined bars depicted in Figure 5a. It has been observed that post-tension interventions are able to provide an even more significant performance enhancement when inclined bars are absent, in terms of both cracking load and ultimate load improvement.

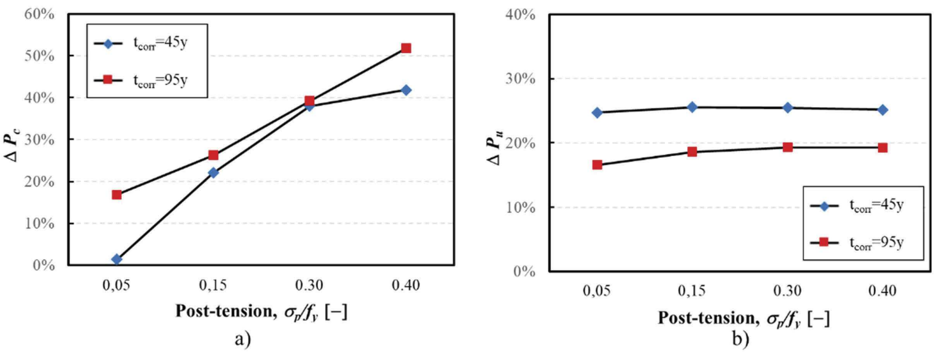

Figure 6. Cracking load (a) and ultimate load (b) improvements for retrofitted models with respect to as-built corroded conditions after 45 and 95 years, as a function of the applied prestress values.

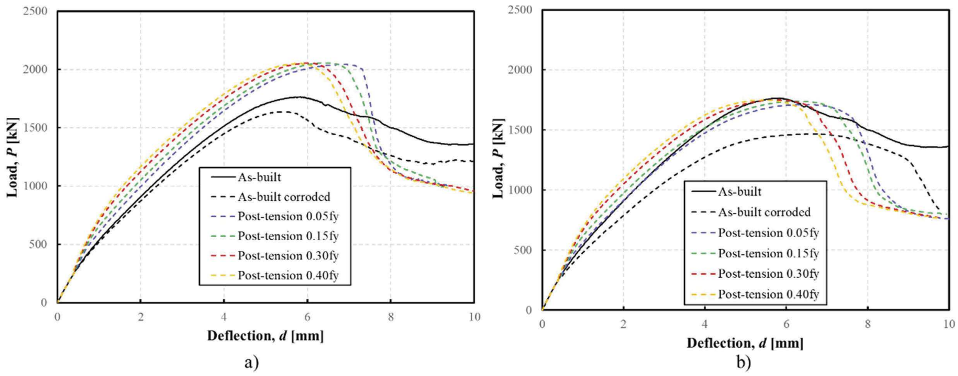

Figure 7. Load-deflection curves of the performed analyses after (a) 45 and (b) 95 years of corrosion.

5 CONCLUSIONS

This paper firstly reports a review of the currently available retrofitting techniques for half-joint bridges, with a specific focus on post-tension techniques, which have a higher ease of application when curb and transverse beams are present close to the bridge half-joints. Hence, post-tension is the most suitable technique to improve the load-bearing capacity of reinforced concrete half-joints. Subsequently, the results of a numerical investigation carried out on an existing bridge half-joint have been described. Results point out the effect of the installation of post-tension rods to improve the serviceability and ultimate capacity, also considering the effect of corrosion due to chlorides. The analyses demonstrated that cracking load values are almost linearly dependent on the prestress values imposed on the rods with a great benefit to durability enhancement due to the smaller crack width in the post-intervention condition. As for the ultimate load capacity, the prestress value shows a lower influence. In fact, also small prestressing values provide a significant increase in the load-bearing capacity. Finally, it has been found that, if the intervention is carried out after 45 years of simulated corrosion, evident advantages in terms of capacity improvement can be obtained, contrarily to what is found intervening after 95 years, when the heavier degradation effects, occurred on steel reinforcement, limit the recovery of load-bearing capacity.

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