

Seismic performance of RC bridge piers reinforced through FRCM confinement

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Abstract

Corrosion of reinforced concrete (RC) structures is one of the main issues concerning existing buildings and especially of infrastructures. Corrosion phenomena, that is induced mainly by carbonatation and by high chlorides concentration, can significantly affect the performance of existing structures. In particular, the seismic performance can be significantly affected. Loss of transversal reinforcement in RC elements can reduce the concrete ductility while corrosion affecting bending reinforcement reduces the lateral load-bearing capacity of RC elements. To enhance the performance of corroded elements and extend service life of deteriorated structures confinement is one of the most effective and commonly used techniques. This paper investigates the deterioration of the seismic performance of a RC bridge affected by corrosion and retrofitted through FRCM confinement. Different deterioration and retrofitting scenarios are combined and seismic fragility curves are computed for each case. Finally, time-variant seismic reliability profiles are used to evaluate the best retrofitting scenario and intervention time to maximize reliability gains.

Keywords

Seismic behavior, bridge, concrete, confinement, FRCM, corrosion, repair.

1 Introduction

Bridge structures are of fundamental importance for the infrastructure networks functionality both in normal times for the development of the socio-economic life of the communities and above all during natural disasters during which they are fundamental for the rapid rescue activities of the affected areas. However, the life of existing bridge structures is constantly growing. Most of them were built after the Second World War to replace the destroyed or damaged works, while others were built between the 60s and 70s during the period of rapid economic growth which also required a rapid development of the infrastructural network.

Bridge structures, mainly built using reinforced concrete, have now an average service life of over 50 years. Deterioration due to environmental factors, evolution of building codes, higher traffic loads, lack of design for lateral loading, are some of the main issues that infrastructure managing bodies have to face nowadays. Regarding reinforced concrete structures, the main deterioration phenomena regards corrosion of internal steel reinforcement. Corrosion can be triggered by carbonatation due to high concentrations of CO₂, or due to high chloride content in the environment (i.e. proximity to marine environments or

high use of de-icing salts.). Corrosion, due to reinforcement reduction and ductility loss, makes vertical load-bearing structures particularly vulnerable to horizontal actions, such as seismic ones. Therefore, RC bridge structures situated in harsh environments and, in addition, in seismic prone areas, may be subject to sudden failures during earthquake events.

Retrofitting of under designed and deteriorated RC structures is of fundamental importance to guarantee appropriate safety levels for both vertical and lateral loads. Regarding seismic retrofitting, confinement of axially loaded elements is one of the main, widely used, techniques while composites are the main materials with which confining jackets are obtained. FRPs (fiber reinforced polymers) have been proven effective in retrofitting RC structures and have been widely used since the early 90s [1]. The effectiveness of the confinement technique through FRP composites to enhance axial strength and strain capacity has been experimentally observed in many previous research works [2-6]. Several studies have also investigated the seismic performance of confined RC columns. Wang et al. [7] tested the seismic response of ten rectangular RC columns strengthened with carbon FRPs, analyzing the role of the direction of the horizontal load. He et al. [8] tested three severely damaged square-sectioned RC bridge piers by artificially fracturing and buckling steel

rebars and then applying CFRPs both as confinement and longitudinal reinforcement. Lavorato and Nuti [9] tested a series of RC bridge piers with pseudo-dynamic tests in order to reproduce seismic damage and then repair the specimens through carbon FRP composites.

Recently, due to some drawbacks, the use of FRP composites in retrofitting techniques is being replaced by new cementitious composite materials called fabric reinforced cementitious matrix (FRCM). FRCM composites allow to overcome some disadvantages of FRPs as better compatibility with the concrete substrate, better performance at high temperatures and possibility apply it in both wet or dry surfaces. The effectiveness of FRCM application on retrofitting techniques has been extensively researched in the last years [10-16]. When dealing with seismic actions the cyclic behavior when under axial or horizontal loading is of fundamental importance. The compressive cyclic behavior of FRCM-confined concrete was investigated recently by Colajanni et al. [11] and some of the authors [12-13]. The experimental results showed that the stress-strain curve of FRCM-confined concrete specimens under monotonic loading matches the envelope of the cyclic stress-strain curve. Bournas et al. [15] investigated the behavior, under cyclic load, of RC columns reinforced with FRCM and CFRP wraps in the plastic hinge regions, resulting in similar behavior for specimens retrofitted with the different techniques. More recently Toska et al. investigated the ability of FRCM jacketing to repair RC columns damaged due to excessive axial loading [10] and due to seismic loading [16].

The present work numerically investigated the effectiveness of FRCM confinement jackets to enhance seismic reliability of RC bridge piers affected by corrosion. Deterioration scenarios based on the age of the structure are combined with retrofitting scenarios based on the number of confining layers applied to the elements and the resulting seismic behavior is assessed through nonlinear time-history analysis. The results are discussed in terms of seismic fragility curves and reliability indexes.

2 RC bridge case study

For the present study, a simply supported, double-span, RC bridge is considered. This type of bridge scheme is one of the most diffused in Italy. The middle support is obtained by a RC frame composed by two square-sectioned columns and rectangular pulvinus at the top. The overall length of the bridge deck is 48 meters. To simulate an existing structure, the bridge was designed to support 10% of the vertical loads in the lateral directions, following the Italian old design standard. Bridge piers are reinforced with 113 cm² reinforcement steel in the longitudinal direction, uniformly distributed in all 4 sides of the square sections. In the transversal direction, 10 mm stirrups are applied every 250 mm. Regarding the materials, standard concrete strength, with mean strength of 33 MPa, was considered. Reinforcement steel with characteristic yielding strength of 430 MPa was considered for both stirrups and longitudinal bars.

A detailed nonlinear finite element model was created for the considered structure in its initial conditions. After

which, considering a certain aggressiveness of the environment, scenarios of deterioration over time, due to corrosion, were computed with an interval of 10 years. Loss in reinforcement area and strength were considered. Four seismic retrofitting cases, based on FRCM confinement of the bridge piers and varying on the amount of confining fabric embedded in the jacket, are applied at each deterioration scenario (Δt about 10 years).

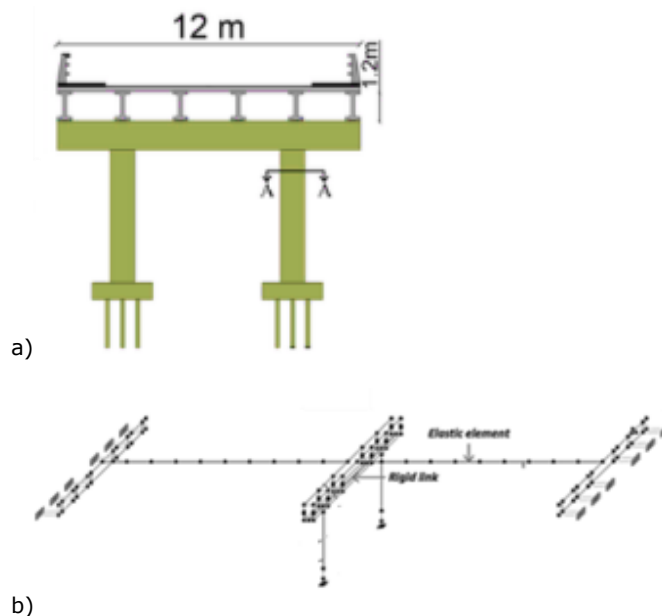


Figure 1 Transversal section of the bridge (a) and FE model considered (b).

2.1 Corrosion modelling

Corrosion is the main deterioration phenomenon that affects reinforced concrete structures during their service life. Among others, chloride induced corrosion, also known as pitting, is the most severe one. Recently, some of the authors, have shown that chloride induced corrosion can significantly influence the seismic reliability not only of existing under-designed bridges but also of new, code-compliant, ones [17].

To model corrosion it is necessary to model the two main stages that describe the process, respectively: "corrosion initiation" and "corrosion propagation". Regarding the first stage, initiation of corrosion depends on the concentration of chloride ions on the reinforcement surface. The process of chloride ions entrance and accumulation inside the concrete material is generally modelled through Fick's second law of diffusion [18]:

$$\frac{\delta C(x,t)}{\delta t} = -D_c \frac{\delta^2 C(x,t)}{\delta x^2} \quad (1)$$

Where:

- $C(x,t)$ = the chloride ion concentration at a distance x from the concrete surface after t years,

- D_c = the chloride diffusion coefficient.

If the concentration of chlorides near the concrete surface can be assumed constant, the solution of equation (1) is:

$$C(x, t) = C_s \left[1 - \operatorname{erf}\left(\frac{x}{2\sqrt{D_c t}}\right) \right] \quad (2)$$

Where:

- C_s = the chloride concentration near the concrete surface,

- erf = the Gaussian error function.

The parameter to be calculated to determine the initiation phase is the time interval needed for the loss of the protective passive film around the reinforcement rebars. Corrosion is considered triggered when the chloride concentration near the steel reinforcement surface reaches a critical value (C_{crit}). Here, the critical content for corrosion initiation is assumed 0.11% on concrete weight [19]. Fixed the chlorides critical value, the initiation time can be computed as:

$$T = \frac{x^2}{4D_c} \left[\operatorname{erf}^{-1}\left(\frac{C_s - C_{crit}}{C_s}\right) \right]^2 \quad (3)$$

After corrosion is triggered, the propagation phase begins. Based on the corrosion rate, the reinforcement cross-section reduction during this phase can be calculated as:

$$D(t) = D_0 - r_{corr}(t - T_i) \quad (4)$$

Where:

D_0 = the initial diameter of the steel bar,

t = the age of the bridge,

T_i = the corrosion initiation time,

r_{corr} = the corrosion rate.

The corrosion rate is a time dependent parameter that depends on the corrosion current intensity [20]. However, for the sake of simplicity, a constant corrosion rate of 0.254 is assumed in this study as suggested by [21].

Strength of reinforcement bars is also affected by corrosion. The strength loss can be computed following:

$$\frac{f_y(t)}{f_{y,0}} = 1 - \frac{0.5(A_0 - A(t))}{A_0} \quad (5)$$

Where

A_0 = the initial area,

$A(t)$ = the residual area at the time t ,

$f_y(t)$ = strength of the corroded bars,

$f_{y,0}$ = the initial yielding strength of the bars.

2.2 Retrofitting scenarios

The chosen retrofitting technique to improve the behavior of RC bridge piers affected by corrosion is confinement through FRCM composites.

Generally, the confined axial strength and axial strain capacity are modelled as a function of the external confining

pressure exerted by the jacket and the initial unconfined concrete strength. The general equation forms are:

$$\frac{f_{cc}}{f_{co}} = 1 + k_1 \left(\frac{f_{l,e}}{f_{co}} \right)^m \quad (6)$$

$$\frac{\varepsilon_{cc}}{\varepsilon_{co}} = 1 + k_2 \left(\frac{f_{l,e}}{f_{co}} \right)^n \quad (7)$$

Where:

f_{cc} = confined axial strength,

f_{co} = unconfined concrete compressive strength,

ε_{cc} = axial strain associated to f_{cc} ,

$f_{l,e}$ = effective lateral confining pressure,

k_1, k_2, m, n = empirical constants.

The effective lateral confining pressure can be estimated as:

$$f_{l,e} = \frac{2n_f \cdot t_f \cdot E_f \cdot k_e \cdot \varepsilon_f}{D} \quad (8)$$

Where:

E_f = fiber elastic modulus,

n_f = number of confinement layers,

t_f = equivalent thickness of the fabric,

ε_f = fiber tensile strain capacity,

k_e = effectiveness coefficient.

The effectiveness coefficient is assumed equal to 1 for columns with cylindrical shape, while for rectangular ($b \times h$) ones it can be calculated as:

$$k_e = 1 - \frac{b'^2 + h'^2}{3 \cdot b \cdot h} \quad (9)$$

Where:

b' = $b - 2r_c$, effective width,

h' = $h - 2r_c$, effective height of the rectangular section,

r_c is the corner radius used for the rounding of the sections edges.

In the specific case, the confinement model provided by the Italian Guidelines [22] for FRCM confined concrete is used. Axial strength enhancement due to confinement is computed as:

$$\frac{f_{cc}}{f_{co}} = 1 + 2.6 \left(\frac{f_{l,e}}{f_{co}} \right)^{2/3} \quad (10)$$

A minimum corner radius of 20 mm is recommended by [22] in order to avoid stress concentration in the edges. The tensile strain capacity of fibers is also limited to:

$$\varepsilon_f = \min\left(k_{mat} \cdot \eta_a \cdot \frac{\varepsilon_{fu}}{\gamma_m}; 0.004\right) \quad (11)$$

$$k_{mat} = 0.217 \cdot \left(\frac{A \cdot n_f \cdot t_{mat} \cdot f_{c,mat}}{D \cdot f_{c0}} \right)^{3/2} \leq 1 \quad (12)$$

Where:

k_{mat} = dimensionless coefficient accounting for the properties of the inorganic matrix,

ε_{fu} = the ultimate FRCM strain,

γ_m = the material partial safety factor ($\gamma_m = 1.5$),

η_a = environmental exposure factor ranging between 0.7 for aggressive environmental conditions to 0.9 for indoor spaces,

t_{mat} = inorganic matrix thickness and the characteristic compressive strength,

$f_{c,mat}$ = inorganic matrix compressive strength.

The ultimate axial strain of the FRCM-confined concrete (ε_{cc}) is computed following the ACI549.4R-13 Guideline [23] for design and construction of externally bonded FRCM systems, as:

$$\varepsilon_{cc} = \varepsilon_{c0} \left(1.5 + 12K_H \frac{f_L}{f_{c0}} \left(\frac{\varepsilon_f}{\varepsilon_{c0}} \right)^{0.45} \right) \leq 0.01 \quad (13)$$

where

ε_{c0} is the compressive strain of unconfined concrete corresponding to f_{c0} . [f] recommends to limit the confined axial strain to 1‰ in order to avoid excessive cracking and loss of concrete integrity.

3 Seismic reliability

For the seismic reliability analysis the failure rate (λ_f) of a given structure has to be computed at any time interval. Based on the Performance Based Earthquake Engineering framework [24] and using the Total Probability Theorem, the failure rate λ_f can be calculated as:

$$\lambda_f = \int_{im} P[f|im] \cdot |d\lambda_{im}| \quad (14)$$

Where:

λ_{im} = seismic hazard curve,

$P[f|im]$ = seismic fragility of a given structural system.

It is possible then to calculate the probability of failure for a given time window of interest (t) due to earthquake occurrences as follows:

$$P_{E,f} = 1 - e^{-\lambda_f t} \quad (15)$$

The seismic reliability index ($\beta_{E,t}$) can be derived, in accordance with the reliability analysis theory, using the following transformation:

$$\beta_{E,t} = -\Phi^{-1}(P_{E,f}) \quad (16)$$

To calculate the failure rate, the hazard and fragility curves are needed. The former representing the seismicity of the

site and the later describes the probabilistic seismic behavior of a structure, giving the probability to reach structural failure given a specific earthquake intensity measure (im). In detailed seismic hazard analysis, λ_{im} is computed using through PSHA (Probabilistic Seismic Hazard Analysis) associating to each ground motion intensity value, the corresponding annual rate of seismic events that exceed it at a certain location. In this case, for the sake of simplicity, local seismic hazard analysis was avoided and instead the hazard curve was derived from the seismic hazard map of the Italian territory, provided by [25].

Regarding the seismic fragility analysis, the framework proposed by Jalayer and Cornell [26], also known as Cloud Analysis, was used. 30 nonlinear time-history analyses (NLTHAs) were carried out on the finite element (FE) models of each corroded-retrofitted scenario of the analyzed RC bridge. Natural 2D seismic records, collected from the European Strong Motion Database were considered for the seismic performance evaluation. Bridge piers were modeled with diffused plasticity, using fiber-section elements, while the deck and the pulvinus were modeled using elastic elements. Concrete and steel fibers were modeled respectively using the well-known Mander et al. [j] and the Menegotto and Pinto model [k].

Fragility curves can be computed from the intensity of the ground motion records and the respective results of the NLTHAs as follows:

$$P[f|im] = 1 - \Phi \left[\frac{\ln(\overline{edp}) - \ln(edp)}{\beta} \right] \quad (17)$$

Where:

\overline{edp} = median threshold value of the assumed structural limit state,

edp = the median estimate value of the demand,

β = standard deviation of the demand.

The demand (edp) can be computed with a ln-linear regression model :

$$\ln(edp) = a + b \cdot \ln(im) \quad (18)$$

While the standard deviation (β) as:

$$\beta = \sqrt{\frac{\sum_{i=1}^n [\ln(edp_i) - (a + b \cdot \ln(im_i))]^2}{n-2}} \quad (19)$$

3.1 Damage state thresholds

To compute fragility curves, damage state (DS) thresholds have to be defined. Generally, in bridge fragility analysis, the kinematic ductility index μ is used [29]. μ is defined as the ratio between the ultimate horizontal displacement of the top of the pier Δ_u , and the horizontal displacement of the same point causing the yielding of the reinforcement at the column base section Δ_y . However, the μ index does not well represent the structural limits when corrosion is taken into account.

According to Cheng et al. [30] the ultimate top displacement of piers can be assumed as the sum of the yielding point (Δ_y) and the succeeding plastic displacement (Δ_p).

Drift thresholds can then be defined as:

$$\Delta_{ds,i} = \Delta_y + k_i \Delta_p \quad (20)$$

where k_i is a factor that considers the admissible plastic displacement in each DS varying from slight to complete collapse of the structure, $k_i = \{0, 0.3, 0.6, 0.8, 1\}$.

Since the frame pier behaves differently in the two horizontal directions, displacement threshold values will depend on the angle the seismic force will act on the structure. To determine the yielding and ultimate displacement a set of pushover analyses, at 5° steps of horizontal inclination, were performed for each case. As a result yielding and ultimate displacement as a function of the horizontal direction of the ground motion record were obtained.

It should be highlighted that, in the present study, only the complete damage state, corresponding to the structural failure, is considered.

4 Results

The bridge location was considered in the Tolmezzo municipality in the north-east region of Italy. Given the cold, mountainous area, a highly corrosive environment, due to the presence of de-icing salts, was assumed and modeled according to section 2.1. Based on the corrosion initiation time, four corrosion level scenarios were created, respectively at the age of 20, 30, 40 and 50 years. At each considered age, four retrofitting interventions, depending on the number of FRCM confinement layers (2, 4, 6 and 8) applied to the bridge piers, were assumed. A standard commercial carbon fabric with 0.047 mm equivalent thickness (t_f), 240 GPa of elastic modulus (E_f) and 1.8% of ultimate tensile strain (ε_f), was adopted. As a result, 16 corroded-retrofitted scenarios for the considered RC bridge were analyzed.

4.1 Seismic fragility

Based on the results of the NLTHA fragility curves were computed for all the considered scenarios. Figure 2 compares the fragility curves at increasing time intervals, that correspond to higher deterioration of the RC structure due to corrosion phenomena. It is clear that the seismic fragility increases with the structures age. The loss of seismic performance is slower in the year after corrosion initiation and gets faster after 30 years of service life. At 20 and 30 years, corrosion regards mainly the transversal steel reinforcement that is positioned closer to the exterior surface of the concrete and, therefore, closer to chloride ions present in the external environment. Increase in seismic fragility at this stage is mainly due to loss of concrete confinement provided by the internal transversal steel. After this point, corrosion affects also the longitudinal bars of the RC piers. The resistance to lateral loads is directly affected and the probability of failure due to a seismic event gets significantly higher.

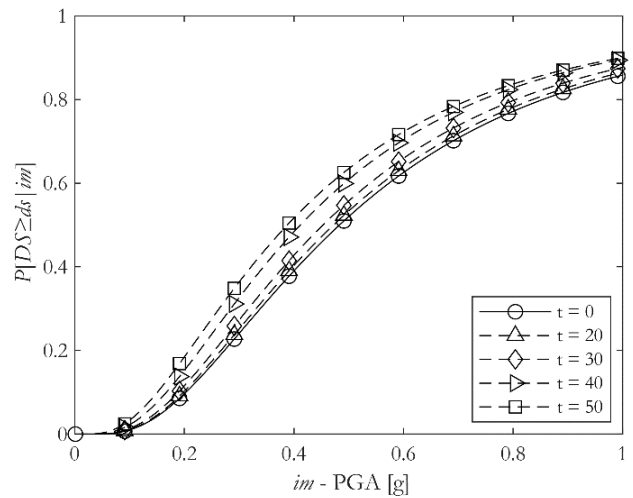
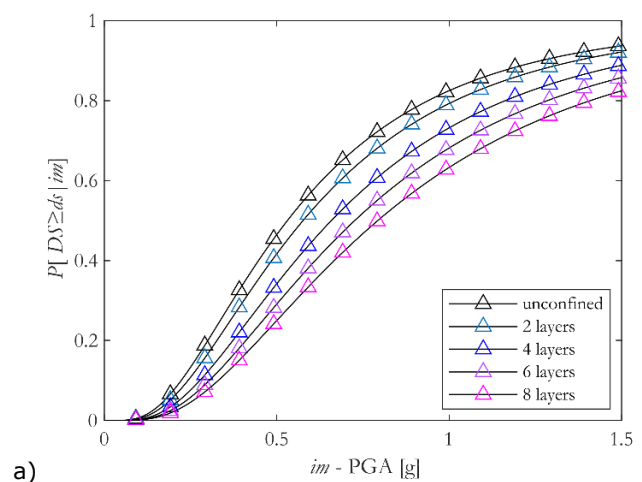


Figure 2 Bridge seismic fragility curves at increasing age.

Given the structural deterioration due to corrosion at 20, 30, 40 and 50 years of age, four FRCM confining jackets with increasing carbon fabric layers are assumed to be applied at each case. Figure 3 shows the fragility curves for the retrofitted scenarios implemented at each time step. The beneficial effect of the FRCM confinement on the seismic behavior of RC piers is clearly shown by the results. Seismic fragility decreases gradually when higher confinement amounts are applied. The enhancement of concrete axial strain capacity, and more in general the enhancement of the RC bridge piers ductility, is the main parameter responsible for reducing the probability of collapse of the structure.

Important gains, in terms of seismic performance, are obtained at each age in which the retrofitting intervention was assumed to be carried out. However, it can be seen that with respect to the corroded scenario the fragility reduction is higher at 40 and 50 years of age. Fragility curves result closer for confinement carried out at 20 and 30 years while they are more distant when the same interventions are carried out at 40 and 50 year.



a)

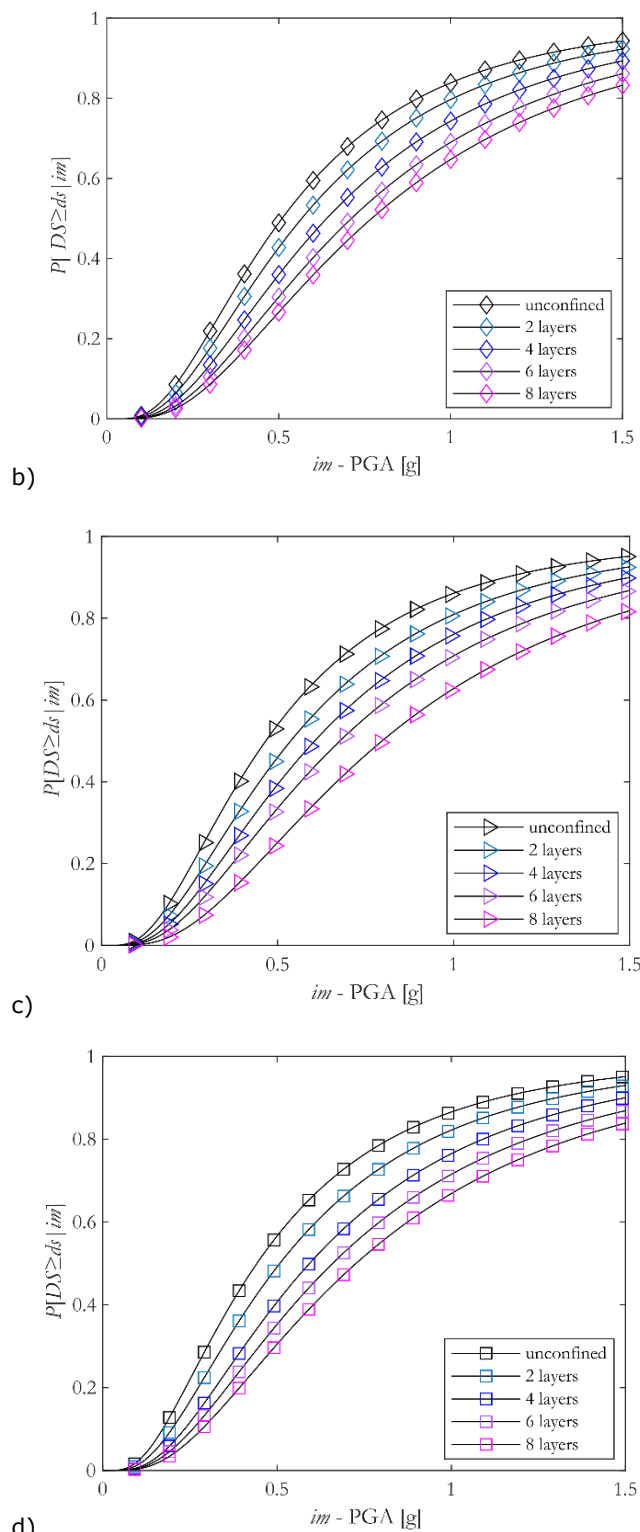


Figure 3 Effectiveness of increasing confining layers at 20 (a), 30 (b), 40 (c) and 50 (d) years.

4.2 Seismic reliability index

Following the framework reported in section 3, the seismic reliability index for 1 year time interval ($\beta_{E,1}$) was computed for all considered cases, combining the fragility curves presented above and the seismic hazard curve of the construction site.

Figure 4 shows the seismic reliability index for each time step and retrofitting scenario considered. With respect to the initial corroded case (black bars) the reliability index

increases almost proportionally with the number of confining layers applied. In almost all cases the effectiveness of the retrofitting intervention slightly reduces when it is participated to a later time. An exception is observed only for the case of confining jackets with 8 fabric layers which guarantees almost the same level of reliability when applied at 20, 30 and 40 years of age. At 50 year the seismic reliability provided by the confinement interventions is lower, however, cases with more than 2 confining layers still provide a higher reliability compared to the initial one at time 0 (i.e without any corrosion).

This particular extrapolation can be very important for intervention programming by the infrastructure owners or managing bodies. If the desirable seismic reliability of the considered structure is 3.3 an 8 layer confinement intervention has to be implemented before 40 years. On the other hand, if the acceptable seismic reliability is 3.2 it could be obtained by a confinement jacket of 4 layer if applied at 20 year, 6 layers if applied at 30 and 8 layers if applied after that.

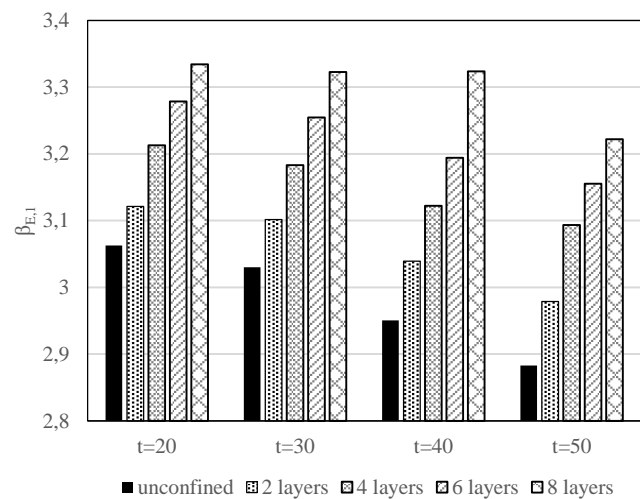


Figure 4 1-year seismic reliability index for all retrofitting scenarios at 20, 30, 40 and 50 years.

5 Conclusions

The present research work numerically investigated the effectiveness of FRCM confinement jackets to enhance seismic reliability of RC bridge piers affected by corrosion. Deterioration scenarios due to reinforcement corrosion and based on the age of the structure are combined with retrofitting scenarios based on the number of FRCM confining layers applied to the bridge piers. The resulting seismic behavior is assessed through nonlinear time-history analysis.

The results, discussed in terms of seismic fragility curves and reliability indexes, showed a clear enhancement of the seismic behavior due to FRCM confinement independently of the time the intervention was carried out. The gain in terms of reliability index $\beta_{E,1}$ are almost proportional to the number of confining layers. However, the overall effectiveness of the retrofitting interventions tends to decrease if the intervention realization is participated in time.

References

- [1] Klaiber, F. W., Dunker, K. F., Wipf, T. J., & Sanders Jr, W. W. (1987). Methods of strengthening existing highway bridges (No. 293).
- [2] Mirmiran, A., Shahawy, M., Samaan, M., Echary, H. E., Mastrapa, J. C., & Pico, O. (1998). Effect of column parameters on FRP-confined concrete. *Journal of Composites for construction*, 2(4), 175-185.
- [3] Rousakis, T. C., Karabinis, A. I., & Kiouisis, P. D. (2007). FRP-confined concrete members: Axial compression experiments and plasticity modelling. *Engineering Structures*, 29(7), 1343-1353.
- [4] Ozbakkaloglu, T., & Lim, J. C. (2013). Axial compressive behavior of FRP-confined concrete: Experimental test database and a new design-oriented model. *Composites Part B: Engineering*, 55, 607-634.
- [5] Micelli, F., & Modarelli, R. (2013). Experimental and analytical study on properties affecting the behaviour of FRP-confined concrete. *Composites Part B: Engineering*, 45(1), 1420-1431.
- [6] Napoli, A., & Realfonzo, R. (2016). Compressive behavior of concrete confined by SRP wraps. *Construction and Building Materials*, 127, 993-1008.
- [7] Wang D., Wang Z., Yu T., Li H. (2018) Seismic performance of CFRP retrofitted large-scale rectangular RC columns under lateral loading in different directions. *Composite Structures*, 192: 475-488.
- [8] He R., Grelle S., Sneed L.H., Belarbi A. (2013) Rapid repair of a severely damaged RC column having fractured bars using externally bonded CFRP. *Composite Structures*, 101: 225-242.
- [9] Lavorato D., Nuti C. (2015) Pseudo-dynamic tests on reinforced concrete bridges repaired and retrofitted after seismic damage. *Engineering Structures*, 94: 96-112.
- [10] Toska, K., Faleschini, F., Zanini, M. A., Hofer, L., & Pellegrino, C. (2021). Repair of severely damaged RC columns through FRCM composites. *Construction and Building Materials*, 273, 121739.
- [11] Colajanni, P., Fossetti, M., & Macaluso, G. (2014). Effects of confinement level, cross-section shape and corner radius on the cyclic behavior of CFRCM confined concrete columns. *Construction and Building Materials*, 55, 379-389.
- [12] Toska, K., & Faleschini, F. (2021). FRCM-confined concrete: monotonic vs. cyclic axial loading. *Composite Structures*, 268, 113931.
- [13] Toska, K., Faleschini, F., & Zanini, M. A. (2023). Confinement of concrete with FRCM: Influence of bond aspects under cyclic axial loading. *Construction and Building Materials*, 368, 130432.
- [14] Zanini, M. A., Toska, K., Faleschini, F., & Pellegrino, C. (2020). Seismic reliability of reinforced concrete bridges subject to environmental deterioration and strengthened with FRCM composites. *Soil Dynamics and Earthquake Engineering*, 136, 106224.
- [15] Bournas D.A., Triantafillou T.C., Zygouris K., Stavropoulos F. (2009) Textile-reinforced mortar versus FRP jacketing in seismic retrofitting of RC columns with continuous or lap-spliced deformed bars. *Journal of Composite for Construction*, 13(5): 360-371.
- [16] Toska, K., Hofer, L., Faleschini, F., Zanini, M. A., & Pellegrino, C. (2022). Seismic behavior of damaged RC columns repaired with FRCM composites. *Engineering Structures*, 262, 114339.
- [17] Toska, K., Zanini, M. A., & Faleschini, F. (2022). Time-Variant Seismic Reliability of Code-Compliant RC Bridges. In *Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures: EUROSTRUCT 2021 1* (pp. 767-776). Springer International Publishing.
- [18] Collepardi M., Marcialis A., Turriziani R. (1972) Penetration of Chloride Ions into Cement Pastes and Concretes. *J.Am.Cer.Soc.*, 55: 534-535.
- [19] Pacheco J., Polder R.B. (2016) Critical chloride concentrations in reinforced concrete specimens with ordinary Portland and blast furnace slag cement. *Heron*, 61(2), 99-119.
- [20] Vu K.A.T., Stewart M.G. (2000) Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety*, 22:313-333.
- [21] Enright M.P., Frangopol D.M. (1998) Probabilistic analysis of resistance degradation of reinforced concrete bridge beams under corrosion. *Engineering Structures*, 20:960-971.
- [22] CNR-DT 215/2018 (2018) Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di Interventi di Consolidamento Statico mediante l'utilizzo di Compositi Fibrorinforzati a Matrice Inorganica, pp. 85, Rome, Italy (in Italian).
- [23] American Concrete Institute (2013) ACI 549.4R-13: Guide to design and construction of externally bonded fabric-reinforced cementitious matrix (FRCM) systems for repair and strengthening concrete and masonry structures, pp. 74. American Concrete Institute, 38800 Country Club Drive Farmington Hills, MI 48331.
- [24] Cornell C.A., Krawinkler H. (2000) Progress and challenges in seismic performance assessment. *PEER Centre News*, 3(2): 1-3.
- [25] Meletti C., Montaldo V. (2007) Seismic hazard estimates for different 50-years exceedance probabilities: peak ground acceleration values. *DPC-INGV Project S1-D2*
- [26] Jalayer F., Cornell C.A. (2003) Direct probabilistic

- seismic analysis: implementing non-linear dynamic assessments. Stanford University, 2003.
- [27] Mander J.B., Priestley M.J.N., Park R. (1988) Theoretical stress-strain model for confined concrete. *J Struct Eng*, 114(8):1804-1826
- [28] Menegotto M., Pinto P.E. (1973) Method of analysis for cyclically loaded reinforced concrete plane frames including changes in geometry and non-elastic behavior of elements under combined normal force and bending. *Proc IABSE Symp Resistance Ultimate Deformability Struct Acted by Well Defned Repeated Loads, Int Assoc Bridge Struct Eng*, Lisbon, Portugal, 13:15-22
- [29] Choi E. (2003) Seismic fragility of typical bridges in moderate seismic zones. *Engineering Structures*, 26(2):187-199
- [30] Cheng H., Li H.N., Yang Y.B., Wang D.S. (2019) Seismic fragility analysis of deteriorating RC bridge columns with time-variant capacity index. *Bulletin of Earthquake Engineering*, 17(7):4247-4267