Structures

Optimum selection of bridge pier retrofit measures considering performance, cost and sustainability criteria

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Abstract:	Bridges, mainly exposed in a multiple hazard environment, are the most vulnerable component of the road network. Damage of critical bridge components (i.e., piers, bearings, and abutments) may result in loss of bridge functionality after a hazard event and, therefore, the rapid decision for the most appropriate retrofit measure is crucial in order to limit the related direct and indirect losses in short time after the event. In line with the above, a holistic methodology is proposed herein for the selection of the optimum retrofit measure for bridge piers, among reinforced concrete or FRP jackets. The proposed methodology is based on advanced, inelastic analysis results, multi-objective optimization techniques and genetic algorithms to derive the retrofit measure's properties in order to meet selected performance, cost and sustainability criteria. Based on literature recommendations, the common practice is to select the retrofit measure on the basis of the seismic assessment results and, in particular, the fragility curves of bridges retrofitted with various schemes (i.e., reinforced concrete, steel, or FRP jackets) and varying properties. However, a component-specific selection of the optimum retrofit measure properties is proposed herein, also accounting for the as-built properties of the bridge pier studied and the targeted performance, cost and CO_2 emissions criteria. The source code developed for applying the proposed approach is also provided (in Github). Since both the components and the criteria are parametrically defined within the code, it could be practically used for different case studies, investigating the effect of as-built properties, retrofit measure properties, and selection criteria on the results. The proposed methodology is indicatively applied to a case study bridge pier, estimating the optimal retrofit measure among RC and FRP jackets and its properties for selected performance, cost, and sustainability criteria, comparatively assessing the results.
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To:
Editor of Structures
Thessaloniki, 14 December 2022

SUBJECT: Submission of a paper entitled*:* **Optimum selection of bridge pier retrofit measures considering performance, cost and sustainability criteria**

Dear Editor,

Please find electronically submitted the manuscript of my article, entitled **"Optimum selection of bridge pier retrofit measures considering performance, cost and sustainability criteria",** which I would like to submit for possible publication in Structures.

This paper presents a methodology for the rapid, initial selection of the retrofit measures and their parameters, based on a rational approach that includes consideration of multiple structural, economic, environmental, etc. criteria and a stratified decision-making method. The properties of the retrofit alternatives are estimated on the basis of a multi-objective, multi-criteria decision-making method. To this end, functions related to performance, cost, and CO2 emission criteria are defined and optimized, also defining strength and ductility criteria that should be explicitly met (constraints). The source code in GitHub for the application of the methodology is also provided.

We hope that this manuscript is suitable for possible publication in **Structures** and look forward to receiving the comments of the reviewers.

Sincerely yours,
Dr. Sotiria Stefanidou

Optimum selection of bridge pier retrofit measures considering performance, cost and sustainability criteria

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Abstract

Bridges, mainly exposed in a multiple hazard environment, are the most vulnerable component of the road network. Damage of critical bridge components (i.e., piers, bearings, and abutments) may result in loss of bridge functionality after a hazard event and, therefore, the rapid decision for the most appropriate retrofit measure is crucial in order to limit the related direct and indirect losses in short time after the event. In line with the above, a holistic methodology is proposed herein for the selection of the optimum retrofit measure for bridge piers, among reinforced concrete or FRP jackets. The proposed methodology is based on advanced, inelastic analysis results, multi-objective optimization techniques and genetic algorithms to derive the retrofit measure's properties in order to meet selected performance, cost and sustainability criteria. Based on literature recommendations, the common practice is to select the retrofit measure on the basis of the seismic assessment results and, in particular, the fragility curves of bridges retrofitted with various schemes (i.e., reinforced concrete, steel, or FRP jackets) and varying properties. However, a component-specific selection of the optimum retrofit measure properties is proposed herein, also accounting for the as-built properties of the bridge pier studied and the targeted performance, cost and CO_2 emissions criteria.

The source code developed for applying the proposed approach is also provided (in Github). Since both the components and the criteria are parametrically defined within the code, it could be practically used for different case studies, investigating the effect of as-built properties, retrofit measure properties, and selection criteria on the results. The proposed methodology is indicatively applied to a case study bridge pier, estimating the optimal retrofit measure among RC and FRP jackets and its properties for selected performance, cost, and sustainability criteria, comparatively assessing the results.

Keywords: bridge piers, retrofit, jackets, multi-objective optimization, genetic algorithms

1 Introduction

During the last decades, a significant number of bridge infrastructures have been constructed in Europe, creating new or expanding existing road and railway networks. Bridges are exposed to a multiple hazard environment and are directly affected by the extreme environmental conditions and climate change effects. Therefore, the probability of bridge component damage due to multiple hazards (i.e., earthquake, flood), ageing, temperature, etc., is increased, and the need for inspection, maintenance, retrofit, and recovery planning is urgent.

Several methodologies are available for assessing the bridge performance against earthquake or flood hazards, providing frameworks and relevant fragility curves [1,2,3] for estimating damage probability for different intensity levels. However, selecting the most appropriate retrofit strategy and relevant properties for bridge structures and various levels of (earthquake or flood) intensity is a rather complex and case-dependent procedure. The most common approach is to select specific measures and properties, i.e., reinforced concrete (RC) or FRP jacket thickness and material properties for bridge piers, to evaluate the structural performance, and eventually propose the optimum strategy and solution. However, it is evident that the result is strongly dependent on the initial selection of parameters; in many cases, the selection is simply the best among a limited number of retrofit schemes tested. Several approaches are available in the literature for the selection of the optimum retrofit solution, mainly based on the use of fragility curves of bridges retrofitted with various schemes (i.e., RC, steel, or FRP jackets) and varying properties as a tool for the selection of the most effective retrofit solution for bridge piers [3,4,5,6]. The use of seismic isolation has also been proposed, evaluating different isolation measures and properties using the fragility function method [7]. Finally, the selection of the most appropriate retrofit measure considering performance-based criteria has been proposed, initially for buildings [8], while it has currently been extended to bridges offering a framework for fragility-informed selection of bridge retrofit schemes for specific performance criteria based on fragility curves for as-built and retrofitted bridges [9].

Optimization frameworks and measures have been proposed in the literature to design and retrofit structures. Structural optimization techniques have been proposed for the optimum design of steel and truss structures [9,10,11]. Furthermore, the performance-based seismic design concept using optimization frameworks has also been proposed [11], including reliability-based criteria and constraints to obtain designs of improved performance and reduced cost [12]. Optimization (evolutionary) algorithms have been applied to select optimum methods for the retrofitting of building structures considering constructional/architectural and economic limitations in structural simulation, incorporating a series of objective function evaluations and providing optimal, earthquake-resistant solutions [13]. Very recently [14], the use of multi-objective optimization measures and multi-criteria decision-making procedures have been proposed to select the optimum retrofit solution, considering earthquake-induced economic losses as a decision criterion. The fact that the selection of the optimum retrofit solution for building structures is challenging is discussed in [15], highlighting that the retrofit strategies may vary, targeting either strength or ductility enhancement and that their selection at the preliminary/conceptual retrofit design phase is not straightforward. The selection of the most appropriate retrofit strategy is therefore proposed based on a fragility-oriented approach that maps the increase of the capacity-to-demand ratio to the reduction of building-level seismic fragility, relating it to loss metrics. A very similar approach has already been proposed in [9] and [16] for bridges, relating the selection of the retrofit measure and properties to the targeted performance level and evaluating the effect of different retrofit measures intended for strength and ductility enhancement and/or seismic isolation methods on the basis of fragility curves for retrofitted bridges. Regarding bridge infrastructures exposed to natural hazards, multi-objective optimization (genetic) algorithms have been proposed [17], introducing a framework that identifies the optimal retrofit and/or repair solutions, that ensure public safety and minimize lifetime environmental, economic, and social performance measures of sustainability. Finally, multi-objective optimization measures and decision-making have been proposed for the optimum selection of interventions at the transportation system level, considering cost, safety, and environmental impact [18,19].

The critical question that this research paper aims to answer, providing both the framework and the computational tool, is the following: Can a designer make a first selection of the optimum retrofit measure for bridge piers (e.g., RC or FRP jacket) and its properties (jacket thickness, reinforcement ratios, material properties) without performing analysis, but accounting for performance, cost, and sustainability criteria? The scope of this research paper is to propose a holistic approach based on multi-objective optimization algorithms, also providing the relevant source code (available on GitHub). The main concept is to account for all the critical parameters that affect bridge pier performance and to estimate the properties of the optimum retrofit solution, defined as the solution that optimally satisfies cost, performance, and sustainability criteria for selected retrofit targets. Therefore the bridge pier properties, i.e., geometrical, material, reinforcement, etc. properties of the core and jacket, are considered the design variables, and the cost, CO_2 emissions, and targeted performance indicators as objective functions. Constraints related to the capacity-to-demand ductility and strength ratio (depending on the retrofit measure used) are defined, and the optimization procedure is applied, estimating the Pareto front. Finally, the best-worst multi-criteria decision-making method is proposed for the estimation of the optimum solution, considering weighting at the criteria considered. The methodology is applied for different research measures (i.e., RC and FRP jackets) using the tool developed, setting specific criteria regarding the targeted strength and ductility. The optimum retrofit solution in terms of performance, cost, and sustainability criteria is defined, along with the jacket parameters (thickness, number of bars, reinforcement ratio, FRP strength, and stiffness). It is noted that the evaluation of different measures, resulting in comparable performance, cost, and sustainability criteria, should be subsequently performed using fragility curves of the retrofitted bridge system. Based on the above, the proposed approach is a rapid, reliable, and open (available on GitHub) first-stage selection of retrofit measures and properties, consisting a valuable tool for stakeholders and managers of infrastructures. The proposed methodology is indicatively applied to a case study bridge pier, estimating the optimal RC and FRP jacket properties for the selected performance, cost, and sustainability criteria. The results are presented and comparatively discussed.

2 Problem statement and available tools

2.1 Problem statement

The scope of the framework presented herein is to select the retrofit measures of structural bridge components and their parameters at a first stage, accounting for performance, cost, and sustainability criteria at component and, eventually, at system level with a view to proposing the optimal retrofit solution related to the criteria considered. The inherent difficulty in the selection of the most appropriate retrofit measure and properties is that it is not a straightforward procedure, requiring several steps and, therefore, computational effort. In particular, the practices proposed in the literature require either **a)** the selection and design of retrofit alternatives for the same expected damage state under the design level-IM or **b)** the a priori selection of the retrofit measures to be applied based on expert elicitation, and the subsequent evaluation of the results on the basis of fragility curves of retrofitted bridges. The critical issue that is practically resolved within this study is the rapid, initial selection of the retrofit measures and their parameters, based on a rational approach that includes consideration of multiple structural, economic, environmental, etc. criteria and a stratified decision-making method. The properties of the retrofit alternatives are estimated on the basis of a multi-objective, multi-criteria decision-making method. To this end, functions related to performance, cost, and CO_2 emission criteria are defined and optimized, also defining strength and ductility criteria that should be explicitly met (constraints). It should be outlined that the final evaluation and selection of the retrofitted structure's performance should be based on fragility analysis results of retrofitted bridges as described in [8] as well as other criteria related to losses or functionality.

2.2 Multi-objective Optimization measures

To define the optimum parameters of alternative retrofit measures described above, multi-objective optimization algorithms are employed. A multi-objective optimization problem tries to minimize a set of objective functions satisfying a set of constraints (linear/nonlinear, equality/inequality) that define the feasible region. In general, the problem is nonconvex and provides, as a result, a set of non-dominated points, the Pareto set (decision space). The values of the objective function at the Pareto points define the so-called Pareto front (objective space) (Fig.1).

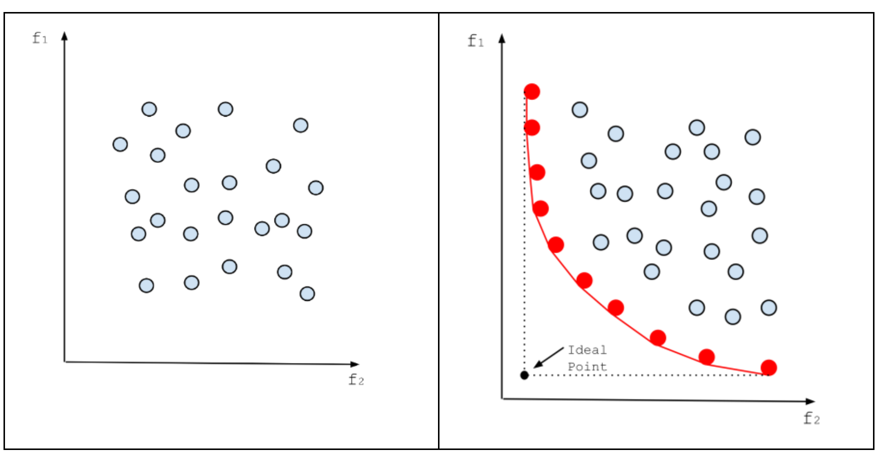


Figure 1. (left) Problem Initialization Definition, (right) Pareto front in minimization problem

The problem described herein involves integer variables (parameters of retrofit measures); therefore, a multi-objective integer programming (MOIP) problem should be solved. The problem statement is presented in Eq.1 in its general form, describing the design variables (*x*), the objective functions (*f(x)*), and the constraints (*c(x)*) that should be defined to obtain the solutions. As already described in §2.1, the critical parameters for every retrofit alternative studied should be initially defined, consisting the design variables (*x*) of the optimization process (e.g., the jacket thickness, reinforcement, material properties, etc.). Parameters that are related to the retrofit efficiency (i.e., strength and/or ductility enhancement) should be explicitly met to define a retrofit target and are therefore set as constraints (*c(x)*) within the optimization problem. Criteria related to performance, cost, and sustainability are defined as objective functions (*f(x)*) to be minimized/maximized in order to obtain an optimum solution.

$$\left.\begin{array}{l}
\text{Problem Statement} \\
\min \quad \begin{bmatrix} f_1(\mathbf{x}) \\ f_2(\mathbf{x}) \\ f_3(\mathbf{x}) \\ f_4(\mathbf{x}) \end{bmatrix} \quad \text{(objective functions)} \\
\textit{Subjected to} \\
\qquad c_i(\mathbf{x}) \leq 0 \quad \text{(inequality constraints)} \\
\qquad \mathbf{x}_{lb} \leq \mathbf{x} \leq \mathbf{x}_{ub} \quad \text{(bound constraints)} \\
\qquad \mathbf{x} \in \mathbb{N}
\end{array}\right\} \qquad (1)$$

In order to solve the optimization problem described above, the genetic algorithm is applied. This algorithm class starts with an initial population and creates the next generation through elitism, crossover, and mutation. Special steps and modifications are applied for the incorporation of constraints. The algorithm stops when one of the stopping criteria is met, i.e., if max generations are met or relatively small changes are observed in the objective functions. Contrary to singleobjective optimization, which tries to find one optimal solution, the multi-objective optimization applied herein results in a set of possible solutions (design variables). A decision-making procedure is applied at a second step to select the optimum solution of the set. The methodology is uniform, and no information is lost before the decision-making application since all the Pareto front is available. This posterior methodology provides a basis for the appropriate selection and evaluation of the decision-maker. In this work, the multi-criteria decision-making method BWM (best-worst method) is utilized. This method derives the weights (w_i) of the individual criteria based on a pairwise comparison of the best and worst with the others. A scale 1 to 9 is selected for the pairwise comparisons. In the first step, the scale of the best to the others and others to the worst is defined, and each criterion's weight is computed (Σw_i=1.0). The consistency ratio ξ characterizes the derived weights; specifically, larger values indicate a less reliable comparison. If the consistency ratio is not acceptable, then modified values for the pairwise comparisons should be provided. Finally, this methodology yields a reliable and consistent comparison matrix. Based on these weights, the score of each solution at the Pareto front is calculated (V_p), and the best alternative is identified (Eq.2)

$$V_p = \sum_{i=1}^{n} w_i V_{pi} \qquad (2)$$

2.3 Parameters affecting the retrofit efficiency in terms of strength and ductility for piers retrofitted with RC and FRP jackets

In line with the above, the rapid, first-stage selection of the optimum retrofit measure for bridge piers is, practically, the estimation of the design variables (i.e., the retrofit measure's parameters) that optimize the objective functions (cost, performance and sustainability criteria) satisfying specific constraints that are related to the anticipated performance level. Since the objective functions are not optimized simultaneously for the same design variable values, a multi-objective optimization technque (as described in §2.2) should be applied for the selection of the optimum retrofit measure for bridge piers.

For the case of bridge pier retrofit, the *design variables* are defined as the parameters of the retrofit measure selected, (i.e., the jacket thickness, material properties, reinforcement ratio, etc.) and the *objective functions* as the cost, CO_2 emissions and ductility for selected performance levels (i.e., available displacement ductility for moderate and major limit states). The *constraints* are defined as the targeted strength and ductility values that are set by the user, e.g., 20% increase of the ultimate moment strength (M_u) and 10% increase of the displacement ductility ($\mu_\delta = \delta_u/\delta_y$ or δ_4/δ_1) of the retrofitted section, compared to the as built one. In particular, the targeted strength and ductility enhancement of the retrofitted section (or member) is defined as the increase of the ultimate flexural strength ($M_{u,jacket}/M_{u,core}$) and the increase of the displacement ductility μ_δ ($\mu_{\delta,jacket}/\mu_{\delta,core}$, $\mu_\delta = \delta_u/\delta_y$ or δ_4/δ_1). It should be outlined that RC and FRP jackets are the most widely used retrofit measures applied to bridge piers for strength and ductility enhancement; RC jackets result in both strength and ductility enhancement, while FRP jackets are mainly related to ductility enhancement.

Therefore, to apply the optimization techniques, the relationship between the design variables and the objective functions should be available, i.e., the equations relating the retrofit measure's parameters to moment strength and ductility. As already presented in [8], the strength and ductility of the as-built and retrofitted bridge piers depend on the parameters related to the geometry, material properties, reinforcement ratios, etc., of the core and the jacket. The closed-form relationships proposed in [8] for the estimation of the ultimate moment strength ratio of the retrofitted to the as-built section ($M_{u,jacket}/M_{u,core}$) and the relevant for the estimation of the retrofitted to the as-built yield and ultimate displacement (necessary to calculate $\mu_{\delta,jacket}/\mu_{\delta,core}$) are shown in Tables 1 and 2 below for the case of cylindrical piers. Relevant closed-form relationships are available for the case of retrofitted piers with FRP jackets.

Table 1. Empirical relationships for the estimation of ultimate moment strength of the retrofitted with RC jacket section, related to the as built.

Cylindrical Piers (RC Jacket)

$$M_{RCj} \big/ M_{core} = \beta_0 + \beta_1 \cdot (D_{RCj} / D_{core}) + \beta_2 \cdot (\rho_{l,RCj} / \rho_{l,\mathrm{core}}) + \beta_3 \cdot (\rho_{\mathrm{w},RCj} / \rho_{\mathrm{w,core}})$$
$$+ \beta_4 \cdot (f_{c,RCj} / f_{c,\mathrm{core}}) + \beta_5 \cdot (f_{\mathrm{y},RCj} / f_{\mathrm{y},core})]$$

	β_0	β_1	β_2	β_3	β_4	β_5
$M_{\mathrm{u},RCj} \big/ M_{u,\mathrm{core}}$	-4.257	+4.727	+0.284	-0.056	+0.065	+0.237

Table 2. Empirical relationships for the estimation of d_1 (d_y) and d_4 (d_u) of the retrofitted with RC jacket section, related to the as built.

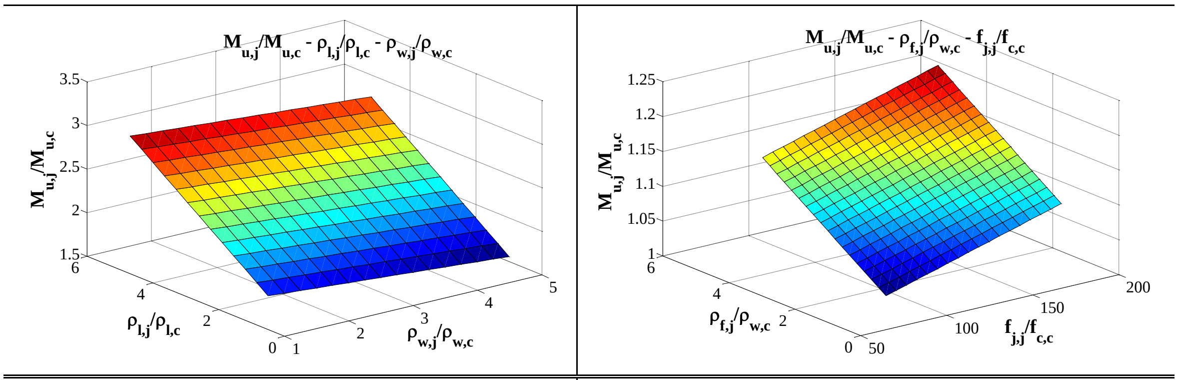
Cylindrical Piers (RC Jacket)

$$(d_{RCj} / \mathrm{H}) \big/ (d_{core} / \mathrm{H}) = \beta_0 + \beta_1 \cdot (D_{RCj} / D_{core}) + \beta_2 \cdot (\rho_{l,RCj} / \rho_{l,\mathrm{core}}) + \beta_3 \cdot (\rho_{\mathrm{w},RCj} / \rho_{w,core})$$
$$+ \beta_4 \cdot (f_{c,RCj} / f_{c,core}) + \beta_5 \cdot (f_{\mathrm{y},RCj} / f_{\mathrm{y},core})]$$

	β_0	β_1	β_2	β_3	β_4	β_5
$(d_{1,RCj} / \mathrm{H}) \big/ (d_{1,core} / \mathrm{H})$	+0.566	+0.059	+0.129	+0.016	-0.169	+0.399
$(d_{4,RCj} / \mathrm{H}) \big/ (d_{4,core} / \mathrm{H})$	+1.094	-0.274	+0.003	+0.124	-0.334	+0.388

The relationships proposed in [8] are based on an extensive parametric study considering a wide range of as-built and retrofitted pier properties, including geometry parameters (diameter of the core (D_c) and the retrofitted (D_j) section), reinforcement ratios (longitudinal (ρ_l) and transverse (ρ_w) reinforcement ratios) and material properties (concrete (f_c) and steel (f_y) strength, FRP flexural strength (f_j) and modulus of elasticity (E_f)) for the estimation of curvature, moment and displacement capacity values. In particular, as built and retrofitted cross sections were set up combining the parameters considered, section analyses were performed to obtain the ultimate moment strength and the moment -curvature (M-φ) curve. The latter was used as input for the inelastic pushover analysis of the pier member, providing relationships for the estimation of yield and ultimate displacement at the control point of the pier. Based on regression analysis of the results, the closed-form relationships were formed.

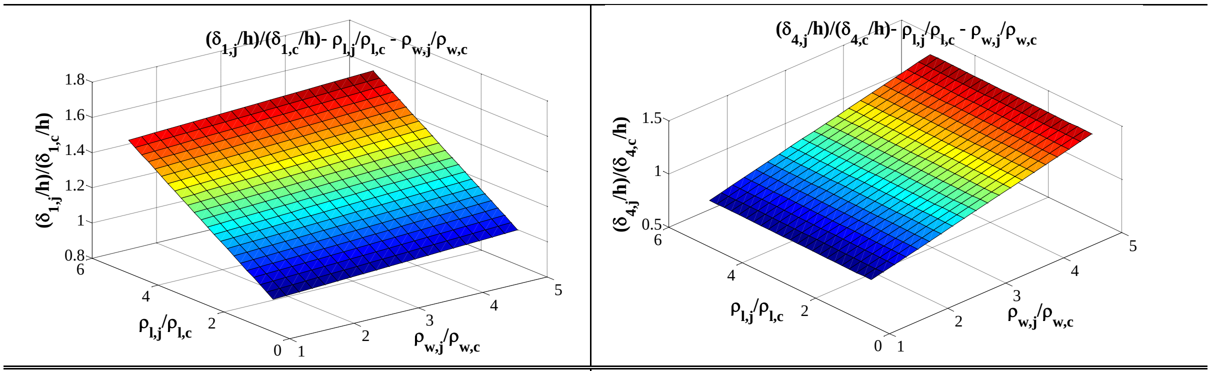
Based on the above one can practically implement the suggested relationships and estimate the moment strength (M_u) and displacement ductility (μ_δ) considering the selected parameters of the core section and the properties for the retrofit measure. The relationships were implemented for selected core and retrofit measure properties for both cases of RC and FRP jackets, and the results are shown in Fig.2 to Fig.8, highlighting the contradictory effect of each parameter on the estimated ultimate moment, yield and ultimate displacement values.



D_j=2.4 (m) , D_c=2.0 (m) , $f_{c,j}$= 38 (MPa), $f_{c,c}$= 28 (MPa), $f_{y,j}$= 550 (MPa), $f_{y,c}$= 440 (MPa)	D_j=2.001 (m), D_c=2.0 (m), $E_{f,j}$=225000 (MPa), $f_{c,c}$=28 (MPa)

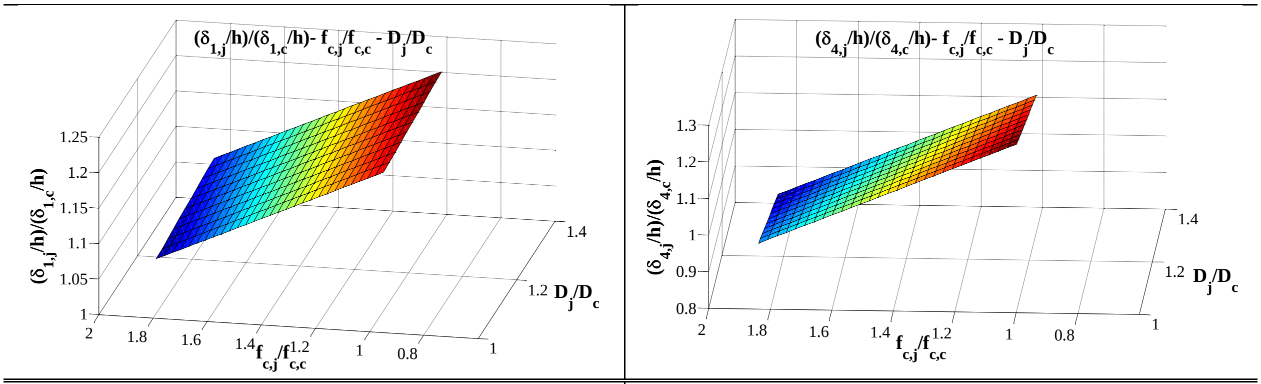
Figure 2. Retrofitted to as-built ratios of the ultimate moment (M_u) values for cylindrical piers versus material (f_c, f_l) and reinforcement (ρ_l, ρ_w, ρ_l) properties for the case of RC (left) and FRP (right) jacket.

As shown in Fig.2 (left), the effect of increasing the RC jacket to core longitudinal and transverse reinforcement ratios ($\rho_{l,j}/\rho_{l,c}$ and $\rho_{w,j}/\rho_{w,c}$) on the ultimate moment strength is not the same. It is evident that for the case of RC jackets, the effect of the increase of the jacket to core longitudinal reinforcement on the ultimate moment strength ratio is greater compared to the relevant when the transverse reinforcement ratio is increased. Additionally, as shown in Fig.2 (right) for the case of FRP jacket, both the increase of the jacket to core reinforcement and material strength ratio, result in an increase of the ultimate jacket to core moment strength ratio.



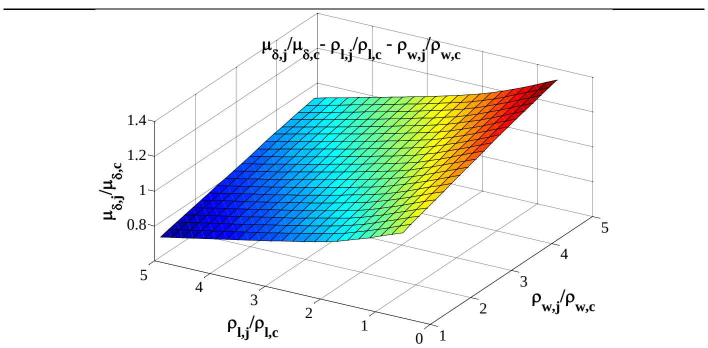
D_j=2.4 (m) , D_c=2.0 (m) , $f_{c,j}$= 38 (MPa), $f_{c,c}$= 28 (MPa), $f_{y,j}$= 550 (MPa), $f_{y,c}$= 440 (MPa)	D_j=2.4 (m) , D_c=2.0 (m) , $f_{c,j}$= 38 (MPa), $f_{c,c}$= 28 (MPa), $f_{y,j}$= 550 (MPa), $f_{y,c}$= 440 (MPa)

Figure 3. Retrofitted to as-built ratios of the yield (d_1) and ultimate (d_4) displacement versus relevant reinforcement ratios (ρ_l, ρ_w) for the case of cylindrical piers retrofitted with RC jackets.



$\rho_{l,j}$= 0.015 , $\rho_{l,c}$= 0.010 , $\rho_{w,j}$= 0.015 , $\rho_{w,c}$= 0.01 , $f_{y,j}$= 550 (MPa), $f_{y,c}$= 440 (MPa)	H=10 (m), D=2.0 (m) , f_c= 33 (MPa), f_y= 550 (MPa), v=0.20

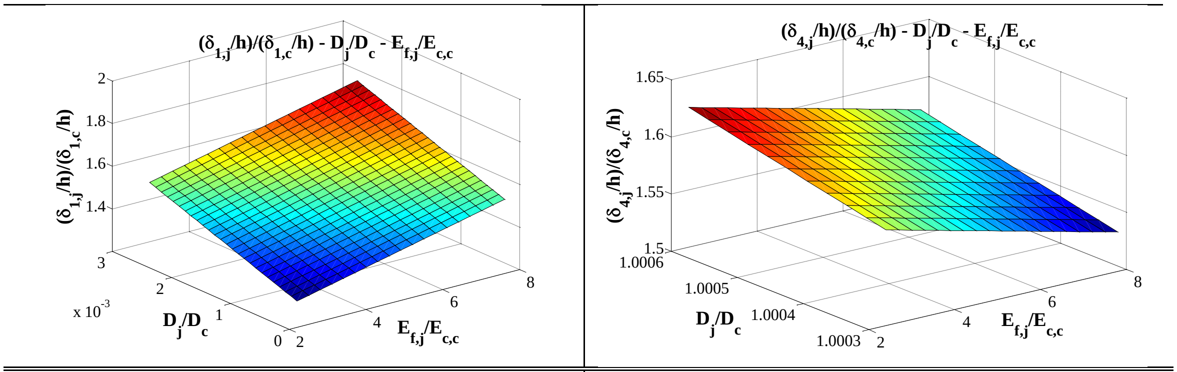
Figure 4. Retrofitted to as-built ratios of the yield (d_1) and ultimate (d_4) displacement at pier top versus relevant material strength (f_c) and diameter (jacketed to as built) ratios for the case of cylindrical piers retrofitted with RC jackets.



D_j=2.4 (m) , D_c=2.0 (m) , $f_{c,j}$= 38 (MPa), $f_{c,c}$= 28 (MPa), $f_{y,j}$= 550 (MPa), $f_{y,c}$= 440 (MPa)

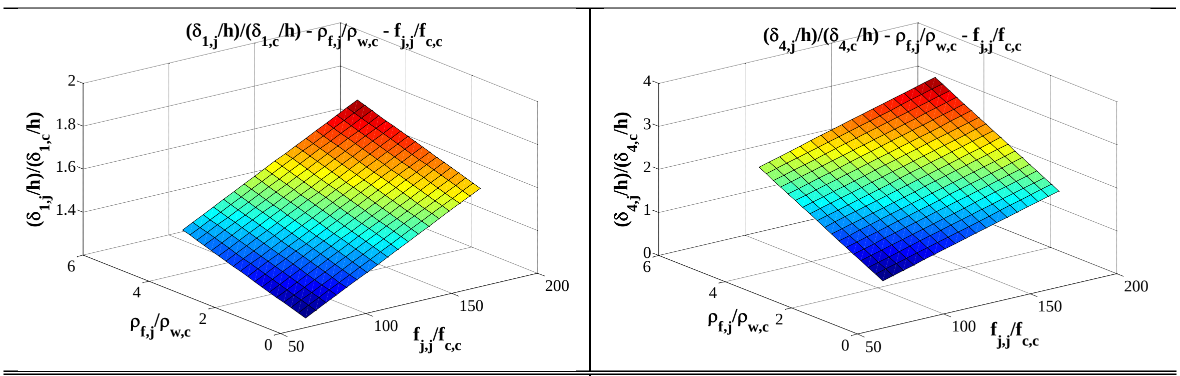
Figure 5. Retrofitted to as-built ratios of the displacement ductility (μ_δ) versus relevant reinforcement ratios (ρ_l, ρ_w) for the case of cylindrical piers retrofitted with RC jackets.

The effect of varying parameters on the yield and ultimate displacements (δ_1 and δ_4) is, eventually reflected in the displacement ductility ($\mu_\delta=\delta_4/\delta_1$). From Fig.5, it is obvious that when the longitudinal and the transverse reinforcement ratios are increased for the case of RC jacket, the displacement ductility increases as well, however not at the same rate.



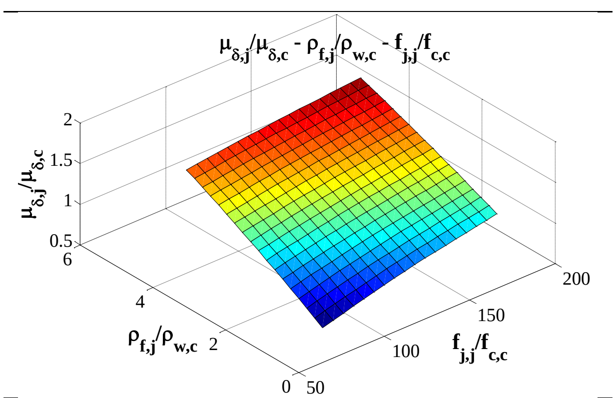
$f_{f,j}$= 4150 (MPa), $f_{c,c}$= 28 (MPa) , $\rho_{f,j}$= 0.001 , $\rho_{w,c}$= 0.005	$f_{f,j}$= 4150 (MPa), $f_{c,c}$= 28 (MPa) , $\rho_{f,j}$= 0.001 , $\rho_{w,c}$= 0.005

Figure 6. Retrofitted to as-built ratios of the yield (d_1) and ultimate (d_4) displacement versus modulus of elasticity and diameter (jacketed to as built) ratios for the case of cylindrical piers retrofitted with FRP jackets.



D_j=2.001 (m), D_c=2.0 (m), $E_{f,j}$=225000 (MPa), $f_{c,c}$=28 (MPa)	D_j=2.001 (m), D_c=2.0 (m), $E_{f,j}$=225000 (MPa), $f_{c,c}$=28 (MPa)

Figure 7. Retrofitted to as-built ratios of the yield (d_1) and ultimate (d_4) displacement versus relevant material (f_j,f_c) and reinforcement ratios (ρ_l, ρ_w) for the case of cylindrical piers retrofitted with FRP jackets



D_j=2.001 (m), D_c=2.0 (m), $E_{f,j}$=225000 (MPa), $f_{c,c}$=28 (MPa)

Figure 8. Retrofitted to as-built ratios of the displacement ductility (μ_δ) versus relevant material and reinforcement ratios for the case of cylindrical piers retrofitted with FRP jackets.

The relevant relationships for the retrofitted piers with FRP jackets are applied, and the results are shown in Fig. 6 to Fig. 8. Both the ultimate and the yield displacements of the FRP-jacketed piers increase when the jacket to core thickness, material strength, and reinforcement ratios increase (Fig. 6 and Fig.7), however with varying rate. Therefore, there is a relevant increase of displacement ductility, which is greater in the case of the reinforcement ratio increase, as shown in Fig. 8.

Based on the above, it is obvious that the effect of different retrofitting measure parameters on the seismic performance of the retrofitted pier varies; therefore, the application of muli-objective optimization measure is necessary in order to derive and propose the optimum set of thickness reinforcement and material properties to achieve the targeted performance.

3 Framework proposed for the selection of optimum parameters of different retrofit measures

The proposed framework in order to define the optimum measure and parameters for bridge pier retrofit considering user defined cost, sustainability and performance criteria is outlined in four distinct steps presented in Fig.9. The first step is related to the selection of the retrofit measure (i.e., RC or FRP jacket) and the definition of the critical parameters of the jacketed pier section that should be considered as design variables within the optimization procedure. In the second step, cost, sustainability, and performance criteria are defined in terms of closed-form relationships (objective functions) relating the design variables to the criteria set in monetary, CO2 emission, and displacement ductility terms. Furthermore, the retrofit targets (constraints) are also defined and related to the design variables. In the third step, the multiobjective optimization measures using genetic (evolutionary) algorithms are applied, and the Pareto front for the performance, cost, and sustainability criteria is estimated. Finally, within step 4, a multi-criteria method (BWM) is applied, selecting weights for the correlation of best and worst parameters. The weighting procedure results in the estimation of the optimum solution from the Pareto front and the relevant properties for each retrofit measure considered.

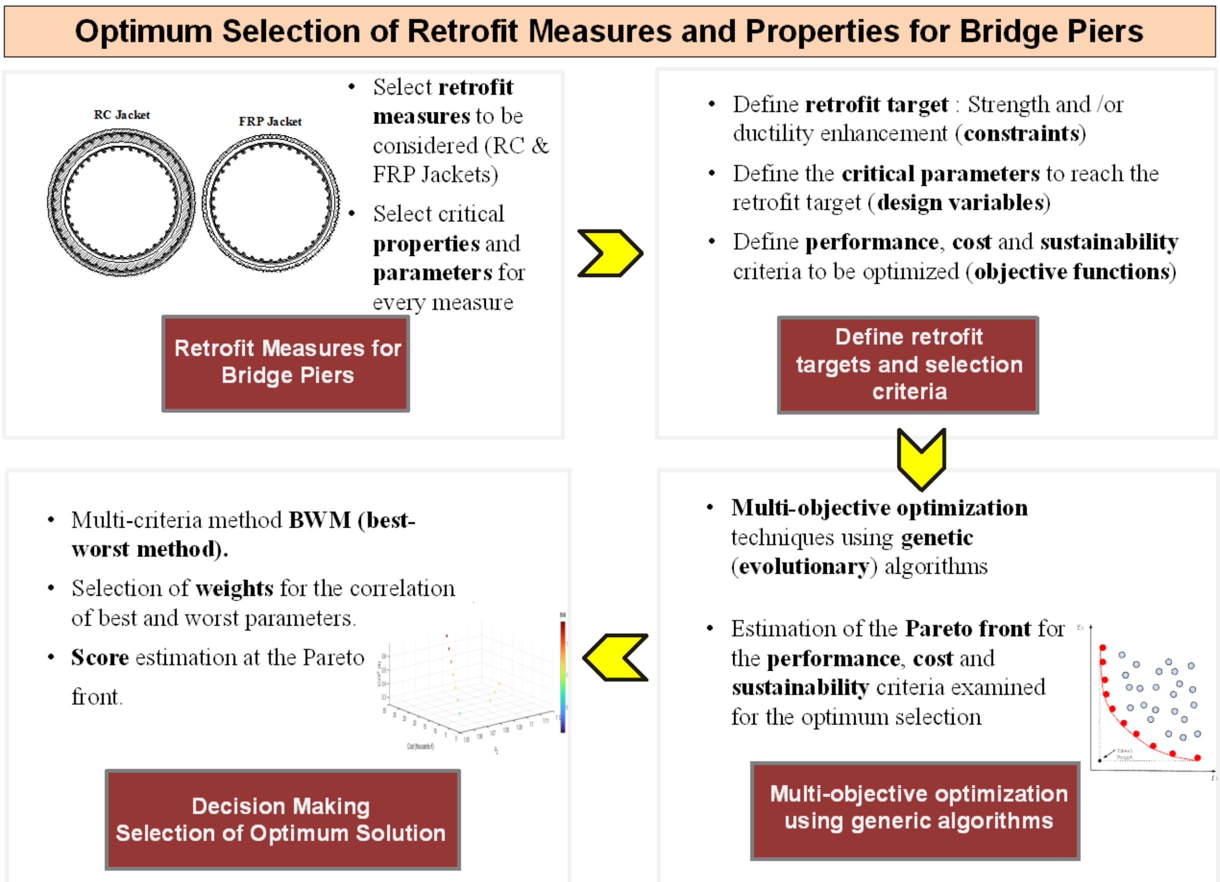


Figure 9. The steps of the proposed framework for the optimum retrofit measure and properties selection

The main steps of the herein proposed framework are described in detail below:

- **Step 1:** Selection of the retrofit measures (RC and FRP jackets) and the design variables that affect the efficiency of each measure.

  The most popular and frequently proposed in literature retrofit measures for strength and ductility enhancement of bridge piers are initially selected. For the measures selected (i.e., RC and FRP jackets), the parameters that mostly affect the effectiveness of each measure are defined. The latter is based on an extensive parametric study that highlights the variation of moment strength and displacement ductility with variable geometry, material, and reinforcement properties.

- **Step 2:** Definition of design variables, objective functions, and constraints

During the second step, the objective functions that should be optimized are defined along with the constraints, i.e., the retrofit targets. The objective functions are related to performance, sustainability, and cost criteria. Regarding the performance criteria, they are related to displacement ductilities for selected performance levels. The closed form relationships that are available in [8] for $\mu_{\delta 2,jacket}/\mu_{\delta 2,core} = (\delta_{2,jacket}/\delta_{1,jacket})/(\delta_{2,core}/\delta 1_{2,core})$ and $\mu_{\delta 3,jacket}/\mu_{\delta 3,core} = (\delta_{3,jacket}/\delta_{1,jacket})/(\delta_{3,core}/\delta_{1,core})$, corresponding to minor and moderate damage, are proposed as objective functions herein (Table 1). It is outlined that δ_1 is the yield displacement, δ_2 the displacement threshold for minor damage and δ_3 the displacement threshold for moderate damage. Regarding the sustainability criteria the CO_2 emissions of each retrofit measure are estimated. According to [20] and [21] the CO_2 emissions considered herein are equal to 0.12 kgCO_2/kg for the concrete, 0.684 kgCO_2e/kg for the steel reinforcement and 4.97 (~5.0) kgCO_2e/kg for the FRP. Finally, regarding the cost criteria, the cost for each retrofit measure is estimated considering 800€/m^3 for the RC jacket (considering the total construction cost), 1100€/tn for the steel reinforcement, and 400-600€/m^3 for the two cases of FRP jacket. It is outlined that all the values mentioned above are indicative and can be modified within the source code available. The retrofit targets (constraints) considered herein are the following: 20% increase of the ultimate flexural strength (M_u) and 10% increase of the displacement ductility (μ_δ) for the case of RC jackets and 10% increase of the displacement ductility ($\mu_{\delta u}$) for the case of FRP jackets. Based on Step 1, the design variables selected for RC jackets are the jacket thickness, the longitudinal reinforcement ratio, and the transverse reinforcement ratio. For the case of FRP jackets the design variables are the FRP type (two different FRP types are considered, $E_{j,FRP}$=210GPa & $f_{j,FRP}$=3.00GPa or $E_{j,FRP}$=225GPa & $f_{j,FRP}$= 3.50GPa) and the jacket thickness. Regarding the FRP thickness, it is outlined that two different thickness values are considered (0.169mm and 0.333mm jacket thickness for each FRP type respectively), considering the number of layers varying. The objective functions and the constraints related to the performance to be optimized and to the targeted retrofit performance respectively are shown in Table 3 for the case of RC jackets and in Table 4 for the case of FRP jackets (also included in the source code available in Github).

Table 3. Objective functions and constraint functions for the case of RC jacket

Objective functions	$\frac{\mu_{\delta 2,RCj}}{\mu_{\delta 1,core}} = \frac{\delta_{2,RCj} / \delta_{2,core}}{\delta_{1,RCj} / \delta_{1,core}} = \frac{1.167 - 0.353 \cdot (D_{RCj} / D_{core}) + 0.012 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.007 \cdot (\rho_{w,RCj} / \rho_{w,core}) + 0.002 \cdot (f_{c,RCj} / f_{c,core}) + 0.164 \cdot (f_{y,RCj} / f_{y,core})}{0.566 + 0.059 \cdot (D_{RCj} / D_{core}) + 0.129 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.016 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.169 \cdot (f_{c,RCj} / f_{c,core}) + 0.399 \cdot (f_{y,RCj} / f_{y,core})}$
	$\frac{\mu_{\delta 2,RCj}}{\mu_{\delta 1,core}} = \frac{\delta_{3,RCj} / \delta_{3,core}}{\delta_{1,RCj} / \delta_{1,core}} = \frac{0.802 - 0.212 \cdot (D_{RCj} / D_{core}) - 0.013 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.219 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.324 \cdot (f_{c,RCj} / f_{c,core}) + 0.528 \cdot (f_{y,RCj} / f_{y,core})}{0.566 + 0.059 \cdot (D_{RCj} / D_{core}) + 0.129 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.016 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.169 \cdot (f_{c,RCj} / f_{c,core}) + 0.399 \cdot (f_{y,RCj} / f_{y,core})}$
Constraints	$M_{u,RCj} / M_{u,core} = -3.45 + 4.649 \cdot (D_{RCj} / D_{core}) + 0.210 \cdot (\rho_{l,RCj} / \rho_{l,core}) - 0.049 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.074 \cdot (f_{c,RCj} / f_{c,core}) - 0.286 \cdot (f_{y,RCj} / f_{y,core})]$
	$\frac{\mu_{\delta 4,RCj}}{\mu_{\delta 1,core}} = \frac{\delta_{4,RCj} / \delta_{4,core}}{\delta_{1,RCj} / \delta_{1,core}} = \frac{1.094 - 0.274 \cdot (D_{RCj} / D_{core}) + 0.003 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.124 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.334 \cdot (f_{c,RCj} / f_{c,core}) + 0.388 \cdot (f_{y,RCj} / f_{y,core})}{0.566 + 0.059 \cdot (D_{RCj} / D_{core}) + 0.129 \cdot (\rho_{l,RCj} / \rho_{l,core}) + 0.016 \cdot (\rho_{w,RCj} / \rho_{w,core}) - 0.169 \cdot (f_{c,RCj} / f_{c,core}) + 0.399 \cdot (f_{y,RCj} / f_{y,core})}$

Table 4. Objective functions and constraint functions for the case of FRP jacket

Objective functions	$\frac{\mu_{\delta 2,FRPj}}{\mu_{\delta 1,core}} = \frac{\delta_{2,FRPj} / \delta_{2,core}}{\delta_{1,FRPj} / \delta_{1,core}} = \frac{-7.61 + 8.58 \cdot (D_{FRP,j} / D_{core}) + 2.67e^{-03} \cdot (E_{FRP,j} / E_{c,core}) + 4.49e^{-04} \cdot (f_{jFRP,j} / f_{c,core}) + 2.91e^{-02} \cdot (\rho_{fFRP,j} / \rho_{w,core})}{-1.27e^{-02} + 1.28e^{+02} \cdot (D_{FRP,j} / D_{core}) - 9.14e^{-03} \cdot (E_{FRP,j} / E_{c,core}) + 4.06e^{-03} \cdot (f_{jFRP,j} / f_{c,core}) + 4.89e^{-02} \cdot (\rho_{fFRP,j} / \rho_{w,core})}$
	$\frac{\mu_{\delta 3,FRPj}}{\mu_{\delta 1,core}} = \frac{\delta_{3,FRPj} / \delta_{3,core}}{\delta_{1,FRPj} / \delta_{1,core}} = \frac{+9.02e^{+01} - 8.96e^{+01} \cdot (D_{FRP,j} / D_{core}) - 1.07e^{-01} \cdot (E_{FRP,j} / E_{c,core}) + 1.40e^{-02} \cdot (f_{jFRP,j} / f_{c,core}) + 4.71e^{-01} \cdot (\rho_{fFRP,j} / \rho_{w,core})}{-1.27e^{-02} + 1.28e^{+02} \cdot (D_{FRP,j} / D_{core}) - 9.14e^{-03} \cdot (E_{FRP,j} / E_{c,core}) + 4.06e^{-03} \cdot (f_{jFRP,j} / f_{c,core}) + 4.89e^{-02} \cdot (\rho_{fFRP,j} / \rho_{w,core})}$
Constraints	$M_{u,FRPj} / M_{u,core} = -3.91e^{+01} + 4.01e^{+01} \cdot (t_{FRP,j} / D_{core}) + 2.36e^{-02} \cdot (E_{FRP,j} / E_{c,core}) - 1.51e^{-03} \cdot (f_{jFRP,j} / f_{c,core}) - 1.54e^{-02} \cdot (\rho_{fFRP,j} / \rho_{w,core})$
	$\frac{\mu_{\delta 3,FRPj}}{\mu_{\delta 1,core}} = \frac{\delta_{4,FRPj} / \delta_{4,core}}{\delta_{1,FRPj} / \delta_{1,core}} = \frac{+7.56e^{+01} - 7.49e^{+01} \cdot (D_{FRP,j} / D_{core}) - 7.61e^{-02} \cdot (E_{FRP,j} / E_{c,core}) + 1.11e^{-02} \cdot (f_{jFRP,j} / f_{c,core}) + 4.02e^{-01} \cdot (\rho_{fFRP,j} / \rho_{w,core})}{-1.27e^{-02} + 1.28e^{+02} \cdot (D_{FRP,j} / D_{core}) - 9.14e^{-03} \cdot (E_{FRP,j} / E_{c,core}) + 4.06e^{-03} \cdot (f_{jFRP,j} / f_{c,core}) + 4.89e^{-02} \cdot (\rho_{fFRP,j} / \rho_{w,core})}$

- **Step 3:** Multi-objective optimization using genetic (evolutionary) algorithms. Estimation of the Pareto front.

Genetic algorithms are applied to solve the multi-objective optimization problem. The solution is practically a set of points defining the Pareto front. The algorithm stops when one of the constraints are met or when minor differences are observed at the objective functions among iterations.

- **Step 4:** Decision-making method to define the optimum solution (function and the relevant design variables- parameters for each retrofit measure considered).

A decision-making procedure is applied within Step 4 to select the optimum solution of the Pareto set. It is outlined that the optimum solution is estimated for every different retrofit measure studied. A multi-criteria decision-making method BWM (best-worst method, as described in [22]) is applied, estimating the weights of all the criteria considered based on the user-based correlation estimation. Within the proposed framework, the best criterion (i.e., the most important) considered is the cost, and the less important is the performance for minor damage. The correlation of the best and the worst parameter with the other parameters is shown in Table 4. The weighting factors among the criteria considered (cost, CO_2, $\mu_{2jacket}$/ μ_{2core}, $\mu_{3jacket}$/ μ_{3core}) are computed according to [22] for each retrofit solution, highlighting the optimum solution. The score of each solution is quantified, indicating the best alternative of the Pareto front (Table 5).

Table 4. Correlation factors derived from BWM

Best to others	**Cost**	**CO_2 emissions**	**$\mu_{\delta2,jacket}/\mu_{\delta2,core}$**	**$\mu_{\delta3,jacket}/\mu_{\delta3,core}$**
Cost	1	3	9	4
Others to worst	**Cost**	**CO_2 emissions**	**$\mu_{\delta2,jacket}/\mu_{\delta2,core}$**	**$\mu_{\delta3,jacket}/\mu_{\delta3,core}$**
$\mu_{\delta2,jacket}/\mu_{\delta2,core}$	9	6	1	5

Table 5. Weights for derived from BWM

Criteria	Cost	CO_2 emissions	$\mu_{\delta2,jacket}/\mu_{\delta2,core}$	$\mu_{\delta3,jacket}/\mu_{\delta3,core}$
Weights	0.564	0.219	0.052	0.164

4 Application of the proposed framework to a bridge pier retrofitted with RC and FRP jackets

The framework proposed is applied for the selection of the optimum retrofit measure of a case study bridge pier. The scope is to select the most efficient retrofit measure and its properties, considering cost (€/m), sustainability (kgCO2e/kg) and performance (targeted ultimate strength and displacement ductility) criteria. The as-built section of the bridge pier studied is cylindrical with a diameter of 1.6m, concrete C16/20 (mean value f_{cm}=24MPa), steel S400 (mean value f_{ym}=440MPa), longitudinal reinforcement ratio ρ_l=0.008 and transverse reinforcement ratio ρ_w=0.075. The steps of §3 are applied to define the optimium retrofit measure for this case study bridge, in particular :

Step 1 : Two alternative retrofit measures, namely RC and FRP jackets are selected for the bridge pier, since they are the most common measures used for strength and ductility enchancement. The parameters that mostly affect the retrofit effectiveness considered are both geometry and reinforcement parameters, i.e. the jacket thickness, FRP layers, material properties, reinforcement ratios.

Step 2 : The design variables, the objective functions, and the retrofit targets are defined within this step. For the RC jacket the design variables selected are the jacket thickness (*t*) (as a multiple of 2cm) , the longitudinal reinforcement, i.e., the number of bars considering fixed bar diameter (Φ22), and the transverse reinforcement, i.e., the distance (*s*) of the transverse reinforcement considering fixed bar diameter (Φ16). Concrete C25/30 and S500b are considered for RC jacket and steel reinforcement material, respectively. For the case of FRP jacket the design variables selected are the FRP type (two different FRP types are considered, $E_{j,FRP}$=210GPa & $f_{j,FRP}$=3.00GPa or $E_{j,FRP}$=225GPa & $f_{j,FRP}$= 3.50GP) and the thickness, i.e., the number of layers for 0.169mm and 0.333mm thickness according to the FRP type selected. Four objective functions for RC and FRP jackets are considered, i.e. the functions related to cost and CO_2 emissions (considering the €/m^3 ,€/tn and kgCO_2e/kg values mentioned in §3) and the functions related to displacement ductility for minor ($\mu_{\delta2,jacket}/\mu_{\delta2,core}$) and moderate ($\mu_{\delta3,jacket}/\mu_{\delta3,core}$) damage, as presented in Table 3, for the case of RC jackets, and Table 4, for the case of FRP jackets. Regarding the retrofit targets (constraints), a 10% increase of the displacement ductility is the target of both retrofit measures.

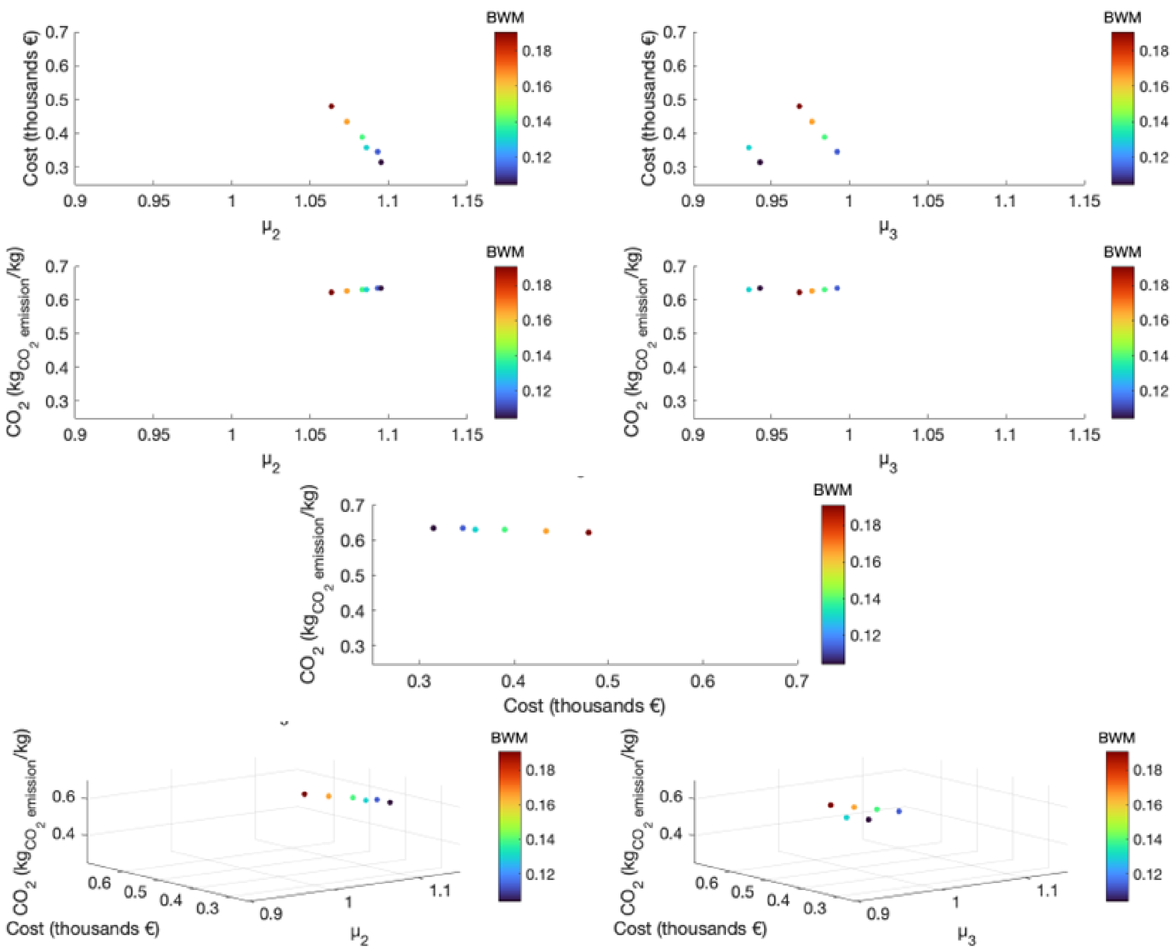


Figure10. Optimum retrofit values for the case of RC Jacket

Step 3 : The multi-objective optimization problem is solved applying the genetic algorithms and the source code provided. The objective functions are optimised and the Pareto front is defined. It is outlined that the cost and CO_2 emissions were scaled (cost/1000 and CO_2 emissions/1000) in ordert o have parameters with the same value range.

Step 4 : The BWM method is applied considering the weighting factors of Table 5.

Applying the steps 1 to 4, the optimum retrofit solution is estimated for each measure, along with the design variables, i.e., the jacket thickness, material, and reinforcement properties, related to the retrofit measure selected. The solution that results in the minimum cost and CO_2 emissions, maximizing at the same time the displacement ductility for the minor (μ_2) and moderate (μ_3) damage state, also accounting for the retrofit target (10% increase of the displacement ductility) is shown in Table 6 and Fig.10&11 for the cases of RC and FRP jacket respectively.

Table 6. Criteria values for the optimum solution for every retrofit measure

	Cost *(€/m)*	**CO_2 emissions** *(kgCO2e/kg)*	**$\mu_{\delta2,jacket}/\mu_{\delta2,core}$**	**$\mu_{\delta3,jacket}/\mu_{\delta3,core}$**
RC Jacket	0.316 (×1000)	0.634	1.095	~1.00
FRP Jacket	2.210 (×1000)	0.336	1.050	1.59

The design variables, i.e. the jacket properties that result in the optimum results of Table 4, are 8cm jacket thickness, longitudinal reinforcement 18Φ22 and transverse reinforcement Φ16/100 for the case of RC jacket and one layer of FRP jacket (t=0.169mm) with material properties equal to $E_{j,FRP}$=210GPa & $f_{j,FRP}$=3.00GPa.

Based on Table 6 and Fig.10&11 it is obvious that for the same retrofit target, the selection of the RC jacket may be more efficient in financial terms, however, the selection of FRP jacket is more efficient in sustainability terms (less CO_2 emissions). It is also highlighted that FRP jacket is more efficient for the displacement ductility enchacement corresponding to demands related to the performance level of moderate damage.

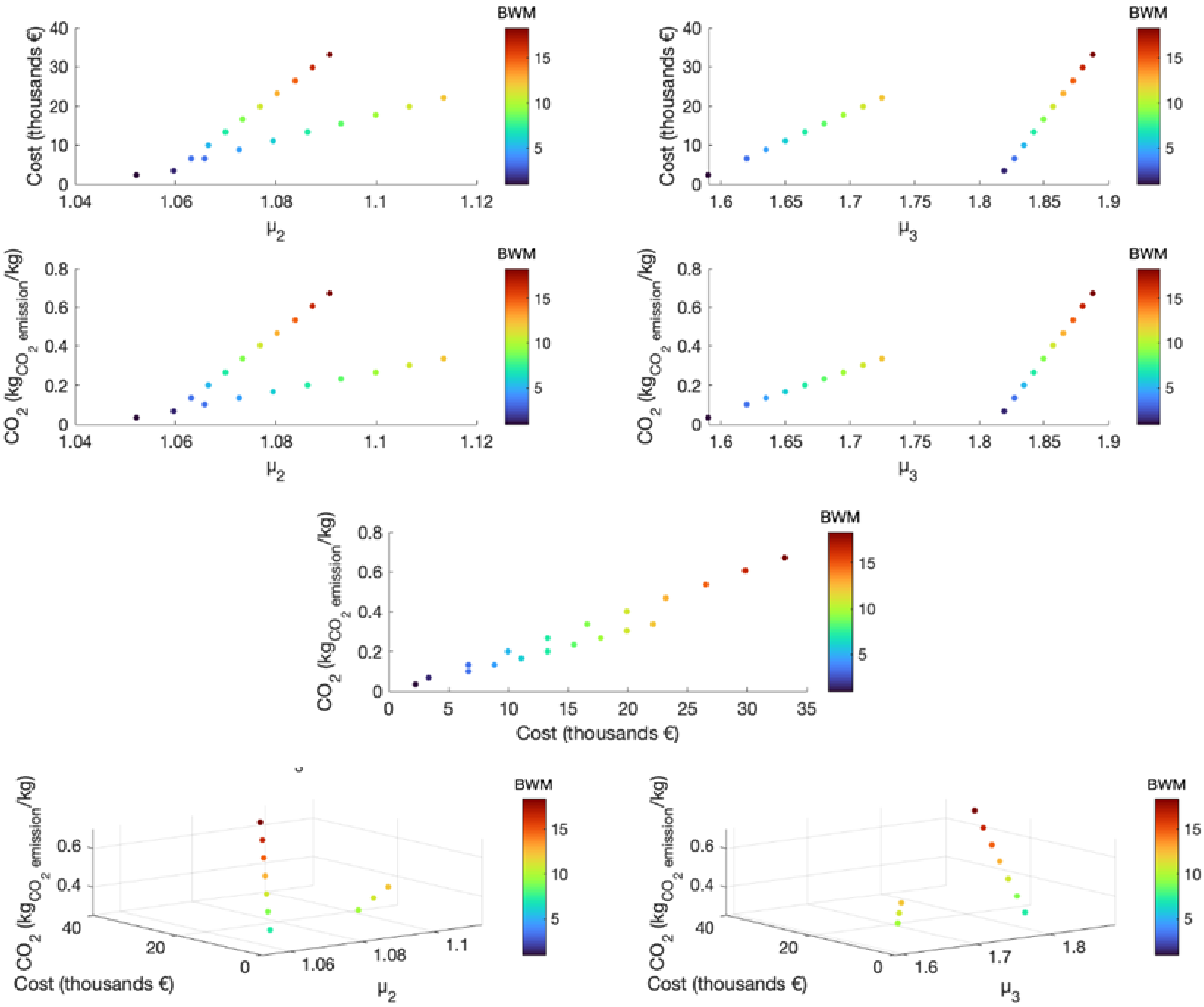


Figure11. Optimum retrofit values for the case of FRP Jacket

Therefore, the jacket properties for a first-stage selection of the optimum retrofit measure have been performed, considering critical criteria and specific retrofit targets. Using the source code provided herein in python, one can easily change the criteria and the retrofit target to estimate the relevant optimum parameters without performing analysis.

5 Conclusions

A holistic approach based on multi-objective optimization algorithms has been proposed herein for the optimum selection of bridge pier retrofit measure properties considering performance, cost and sustainability criteria. The critical criteria and retrofit targets are defined for various retrofit measures, also accounting for a refined decision-making procedure, defining scores (weighting factors) for each criterion. On this basis, the different retrofit measures can be compared in terms of effectiveness, also providing the jacket properties that result in the optimum solution and consisting a first-stage selection or jacket type and propeties. A source code has been developed in GitHub and is available herein, in order to to apply the methodology proposed. The methodology is applied to a case study bridge pier, estimating the optimum retrofit measure among RC and FRP jackets and their properties. The results are discussed, focusing on the effectiveness of the methods and the need for a first-stage jacket properties selection.

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Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Dr. Sotiria Stefanidou