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A novel genetic algorithm-based optimization framework for minimizing seismic retrofitting interventions costs in existing masonry structures

Fabio Di Trapani[a,*], Antonio P. Sberna[a], Giuseppe C. Marano[a]

[a]*Politecnico di Torino – Department of Structural, Building and Geotechnical Engineering, Corso Duca degli Abruzzi 24, 10126, Turin, Italy*

Abstract

The pressing necessity of enhancing the seismic safety of existing masonry structures in earthquake-prone areas has led, in recent years, the research to propose a vast amount of new retrofitting techniques. However, retrofitting interventions are generally associated with important costs. Currently, there are no formal methods to optimize these interventions thus, their design is entrusted only to engineers' intuition. This paper presents a novel optimization framework aimed at the minimization of seismic retrofitting-related costs by an optimal placement (topological optimization) of reinforced plasters in masonry structures. In the proposed framework a 3D equivalent masonry model implemented in OpenSees is handled by a genetic algorithm developed in MATLAB® routine that iterates reinforcement configurations to match the optimal solution. The feasibility of each solution is controlled by the outcomes of a seismic static equivalent analysis by controlling the safety check of masonry walls with respect to both flexural and shear collapse. It is also shown, through a case study, that the proposed approach is efficient to pinpoint optimal retrofitting configurations, significantly reducing invasiveness and downtime.

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Keywords: structural optimization; seismic retrofitting; masonry structures; FRCM; genetic algorithm

1. Introduction

Currently, a vast variety of effective retrofitting techniques are accessible but there are no formal engineering methods to assist practitioners in designing these types of interventions. This process is mainly based on an

* Corresponding author.
E-mail address: fabio.ditrapani@polito.it

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engineer's intuition and experience. This may lead to an over-estimation of retrofitting interventions amount, associated with an increase in related economical costs and downtimes.

Over the years, the capability offered by artificial intelligence has been widely employed to solve different structural engineering problems allowing to obtain noteworthy results Quaranta et al. (2020). The topic of the optimization of strengthening and retrofitting interventions for reinforced concrete structural elements has not been investigated many times in the past and available studies are restricted to the optimization of carbon fibre reinforcement of concrete slabs Chaves and Cunha (2014) or FRP jackets Seo et al. (2018).

More recent studies focused on the topic of the optimization of seismic retrofitting costs. Among them, Papavasileiou et al. (2020) implemented a genetic algorithm (GA)-based optimization framework for encased steel-concrete composite columns through three different retrofitting techniques. Falcone et al. (2019) proposed a framework for the optimization of the costs for FRP jacketing and steel bracings of existing reinforced concrete structures. Di Trapani et al. (2020, 2021) implemented a new framework aimed at minimizing steel jacketing retrofitting costs for RC structures. Minafò and Camarda (2022) proposed a genetic algorithm for the minimization of costs of buckling-restrained braces on reinforced concrete 2D frames. Ultimately, Di Trapani et al. (2022) provided a new GA-based optimization procedure for optimize two different retrofitting techniques (FRP wrapping of columns and steel braces) in RC frame structures controlling indirectly the associated annual loss of economic value in its reference service-life considering the associated seismic risk by evaluating the expected annual loss.

As it can be noted, the major scientific interest in this topic mostly addressed frame structures, leaving an evident lack concerning masonry structures. However, the design of retrofitting interventions in masonry structures is not straightforward, as the reinforcement techniques can modify both strength, stiffness and mass, leading to recursive design issues. Based on these considerations, the present paper proposes a novel framework based on a genetic algorithm seeking at supporting the design of optimal seismic reinforcements for existing masonry structures. The algorithm aims at minimizing an objective function that evaluates the intervention cost. The final output of the framework is the optimal retrofitting arrangement, namely the position of the retrofitted walls in the structure.

The optimization procedure is carried out by connecting the GA routine developed in MATLAB® with an equivalent 3D frame elastic model analysed through the OpenSees software platform (McKenna et al. (2000)). The performance of each tentative solution (in terms of safety checks) is assessed by an equivalent linear static seismic analysis combined with flexural and shear safety checks provided for all the masonry walls.

The proposed framework is finally tested on a 2-storey masonry building, showing that the resulting retrofitting optimization allows noticeable cost-saving associated with a significant invasiveness reduction.

2. Optimization framework

The optimization procedure herein proposed is based on the genetic algorithm metaheuristic technique. This class of artificial intelligence algorithm analyze the research space by point through the handling of a set of variables that are gathered in a so-called design vector. The algorithm starts generating a random initial population of design vectors (tentative solutions) and evaluating the objective function corresponding to them. Each tentative solution represents a possible retrofitting configuration (Fig. 1). The considered retrofitting technique is the application of a reinforced plaster to both sides of a masonry wall. The procedure performed by the algorithm is schematically represented in Figure 1.

The pursuit of the research space minima is achieved by selecting the best tentative solutions and mixing their design vector (namely genome) through crossover and mutation genetic operators. The first one combines the genomes of tentative solutions, the second introduces some randomness to prevent the algorithm stuck into local minima. The selection of the best parents from whose genome the offspring will be made is exerted by tournament selection.

The decision variables, namely the parameters to optimize, are defined at the beginning of the procedure. For each candidate solution, the algorithm provides the analysis, the assessment, and the evaluation of the cost. The routine is stopped when the cost is minimized, namely when no further cost reductions are obtained from the subsequent generations.

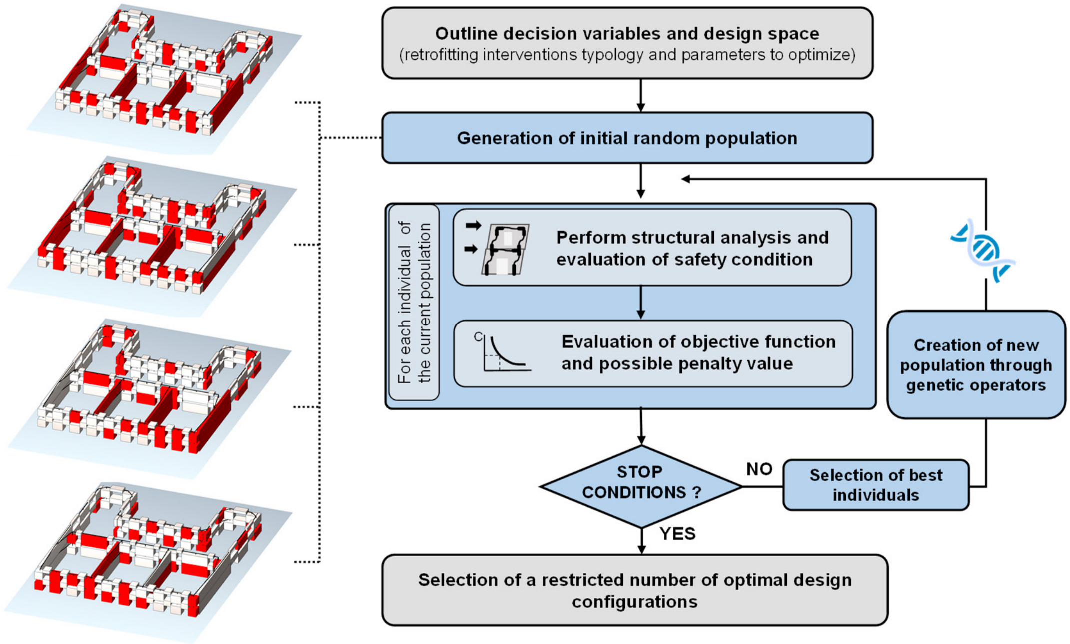


Fig. 1. Flowchart of the genetic algorithm optimization process

2.1. Design vector encoding

The main aim of the optimization algorithm is to pinpoint the position of the reinforced plasters so that the retrofitting cost is minimized. The topological optimization is performed by using binary variables to encode the presence or not of the reinforcement on each wall. All the decision variables are gathered in the design vector b so defined:

$$\mathbf{b} = \begin{bmatrix} \dots & c_{ij} & \dots \end{bmatrix}^T \tag{1}$$

where c_{ij} is the Boolean variable assuming the value 1 if the wall is retrofitted and 0 if not. The subscript i indicates the position of the wall in-plan, and j the story. The considered reinforcement technique entails the application of a glass fiber reinforced polymer (GFRP) net embedded in a layer of special mortar of specified thickness applied to both sides of the wall. To reduce the dimension of the research space, and reduce the computation burden required for the analysis, each Boolean variable can represent a cluster of adjoining walls.

According to the Italian Technical Code (2018), the effect of reinforced plasters on masonry walls can be simply considered as incrementing the mechanical properties of the material by the coefficient α_R ($\geq$1). In this way, if the Boolean variable associated with a wall is 1, the mechanical properties of the masonry are multiplied by α_R, so that:

$$\overline{f}_d = \alpha_R \cdot f_d; \qquad \overline{\tau}_{0d} = \alpha_R \cdot \tau_{0d}; \qquad \overline{E}_m = \alpha_R \cdot E_m; \qquad \overline{G}_m = \alpha_R \cdot G_m \tag{2}$$

The reinforce mechanical properties in Eq. (2) are then assumed as the new ones for the wall.

2.2. Objective function

The objective function (OF) is aimed at evaluating the costs associated with the implementation of the retrofitting intervention. To take into consideration the feasibility of each solution (namely if all the safety checks are verified for an individual), the fitness function involves a penalty function, that fictitiously increases the fitness value for unfeasible individuals, as:

$$F = C + \Pi \tag{3}$$

where C is the cost function and Π the penalty function. In particular, considering that the cost per surface area of reinforced plasters is a constant, this can be calculated as the area (in m^2) of reinforced plasters intervention, so that:

$$C = \sum_{i=1}^{n_{rp}} A_{rp,i} \tag{4}$$

where $A_{rp,i}$ is the area of the *i-th* reinforced wall. It is noteworthy observing that for each wall, the area is computed twice, as the GFRP plaster is applied on both sides. The penalty function is instead defined as:

$$\Pi = p \cdot \left(\sum_{j=1}^{n_{wf}} A_{wf,j} \sum_{k=1}^{n_{ws}} A_{ws,k} \right) \tag{5}$$

where p is a magnification coefficient fictitiously increasing the weight, in terms of retrofitting costs of the walls that don't achieve flexural and shear safety checks. In Eq. (5) $A_{wf,j}$ and $A_{ws,k}$ represent the areas of walls having a strength capacity/demand ratio lower than the one with respect to flexure and shear respectively.

3. Analysis and post-processing of results

3.1. Seismic analysis and safety checks

The feasibility of each tentative retrofitting configuration is assessed by performing an equivalent static seismic analysis. According to Eurocode 8, and Italian NTC 2018, the equivalent horizontal seismic load is evaluated as:

$$F_b = S_d(T_1) \cdot (W / g) \cdot \lambda \tag{6}$$

where $S_d(T_1)$ is the design spectral acceleration, W is the total weight of the structure, g is the gravitational acceleration, and λ is a corrective factor that is 0.85 if $T_1 \leq 2 \cdot T_c$ and the structure has more than two stories, or 1 otherwise, while the fundamental period (T_1) is estimated as $T_1 = 0.05 \cdot H^{3/4}$, where H is the total height of the building. The combination of seismic forces simultaneously acting in the two horizontal orthogonal directions (X and Z) is considered by performing 8 analyses, where the forces are applied alternatively as 100% in one direction and 30% in the perpendicular one.

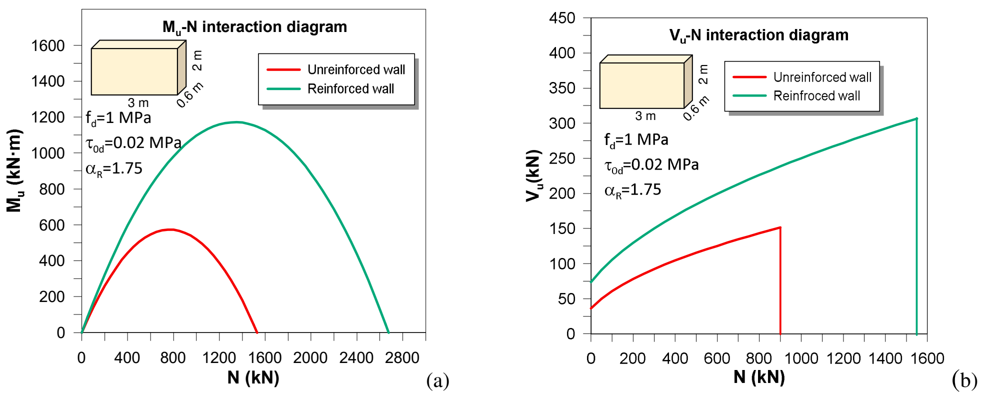


Fig. 2 – Unreinforced and reinforced interaction diagrams for a sample wall: (a) Mu-N; b) Vu-N.

Safety checks of each masonry wall are carried out with regard to both flexural (Eurocode 8) and in-plane shear collapse according to model proposed by Turnšek and Čačovič (1971). A comparison of the resulting flexural and shear unreinforced and reinforced M_u-N and V_u-N interaction diagrams by Eqs. (8) and (9) are reported in Fig. 2 for a sample masonry wall.

4. Case study test

4.1. Seismic analysis and safety checks

The case study structure consists of a two-storey masonry structure with a total height of *8 m* and a C-shape floor plane, whose maximum dimensions area of *27.80 x 12.5 m* (Fig. 3). Masonry elements are supposed to be made of squared stone masonry with good texture.

Mechanical properties of the unreinforced masonry are reported in Table 1 as well as those resulting from the application of Eq. (2) with an increment coefficient $\alpha_R=1.7$, as provided by NTC 2018. The building is supposed to be located in Cosenza (Italy), soil type C. The reference nominal life (VN) is of 100 years. The resulting return period is $T_R=975$ *years*. The fundamental vibration period of the analysed structure is $T_1=0.23$ *sec*. According to Italian NTC 2018, the behaviour factor is set as 3.

Table 1. Mechanical properties of masonry for the case-study structures

	f_d (MPa)	τ_{0d} (MPa)	E_m (MPa)	G_m (MPa)	Unit weight w (kN/m^3)
as-built	3.2	0.065	1750	575	21
reinforced	5.4	0.11	2975	977	

A confidence factor $CF=1.2$ and a partial safety factor $\gamma_m=2$ are applied to the material resistance values reported in Table 1. It is assumed that the reinforced plasters are implemented with a thickness of 5 cm for each side of retrofitted walls. Vertical loads are modelled as point loads applied to the top node of each vertical beam as a function of the respective tributary areas in the plan. In seismic combination, it is assumed a unit load respectively for the slab and the roof of $q_{slab}=5.6\ kN/m^2$ and $q_{roof}=5\ kN/m^2$. The total seismic weight of the structure is *9504 kN*.

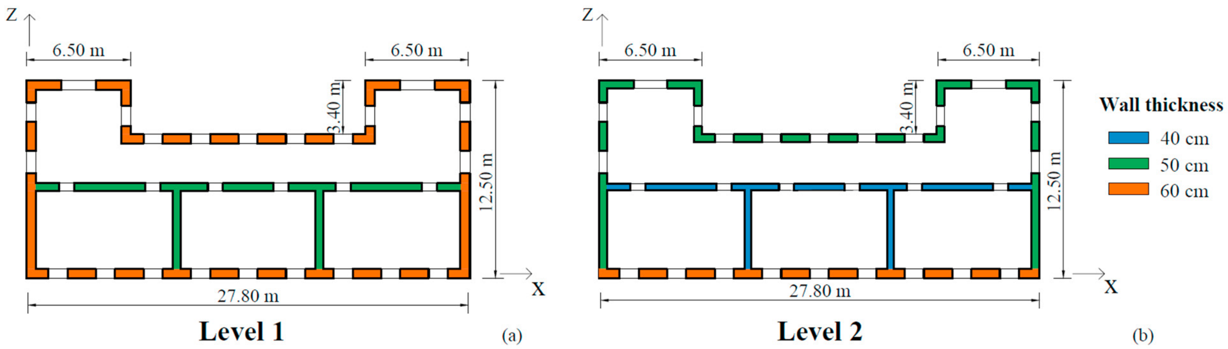


Fig. 3. In-plane geometrical dimensions of the reference structural model: (a) Level 1; (b) Level 2.

A 3D model of the structure is realized in OpenSees (McKenna et al. (2000)) using the Equivalent Frame Method, according to which the structure is modelled in masonry panels, spandrels, and rigid offsets. The effective length of the panel deformable portions is evaluated according to Braga and Dolce (1982). The elastic portion of masonry walls and spandrels are modelled using *ElasticTimoshenkoBeam* elements implemented in OpenSees. In this way, alto the tangential stiffness is considered. Floors are supposed to have rigid diaphragm behaviour by imposing diaphragm constraints at the nodes.

4.2. Assessment of the as-built structure and first retrofitting solution

Seismic analyses are carried out according to what is defined in Section 3.1. The reference elastic and design spectra are illustrated in Fig. 4a. The preliminary assessment of the as-built structure is carried out to individuate the walls that are not satisfying safety checks under the reference seismic demand. In Fig. 4b, a schematic representation of safety checks for the as-built structure is depicted, highlighting walls undergoing shear and/or flexural demand exceedance. Results of safety checks for the walls are quantitatively illustrated in Table 2. Overall, 18 over 72 walls (25%) failed shear and or flexural verifications.

Table 2. Results of the as-built and retrofitted structure safety assessment.

Structural model	Walls failing flexure safety check (#)	Walls failing flexure safety check (#)	Walls failing flexure+shear safety check (#)	Total surface (both sides) of walls failing safety checks (m^2)	Total surface of GFRP reinforced plaster (m^2)
As-built	4	6	8	349.7	-
Non-opt. Retrofit	0	0	0	-	349.7

Safety checks were repeated by applying the GFRP reinforcement to the total area of the walls missing safety checks (*349.7 m^2* considering both the sides of the walls). In this case, all the walls passed safety checks, however, the feasible solution found is not optimized. Assuming a retrofitting cost of 200 €/m^2, the retrofitting cost was in this case 69540 €.

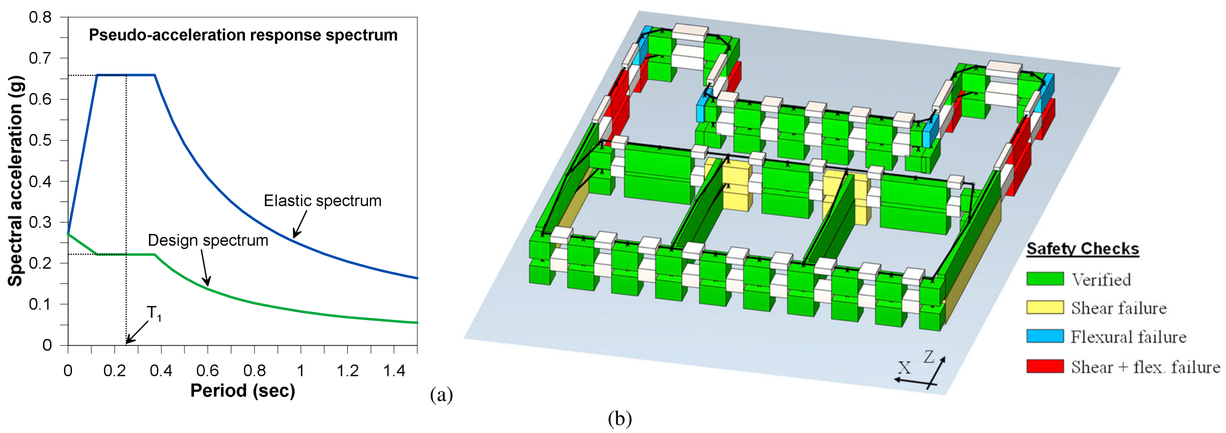


Fig. 4. Assessment of the as-built structure: (a) Elastic and design spectra; (b) Safety checks of the walls on the structural model.

4.3. Optimization results

The proposed optimization framework has been tested with the case study structure above described. To avoid unpractical retrofitting configurations and to reduce the dimension of research space, it was assumed that reinforcement interventions could be implemented for clusters of adjoining walls. A sample of the clustering procedure is shown in Figure 5 for the ground floor walls.

The analyses have been carried out using an initial population (P) of 200 tentative randomly generated solutions. The algorithm proceeds by generating 100 new children every generation through the previously described routine, involving parent selection, crossover and mutation.

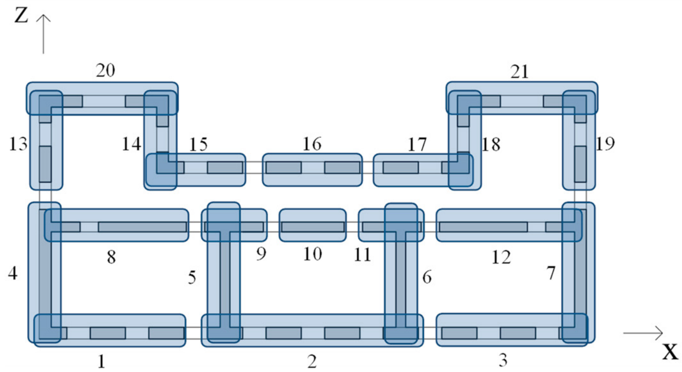


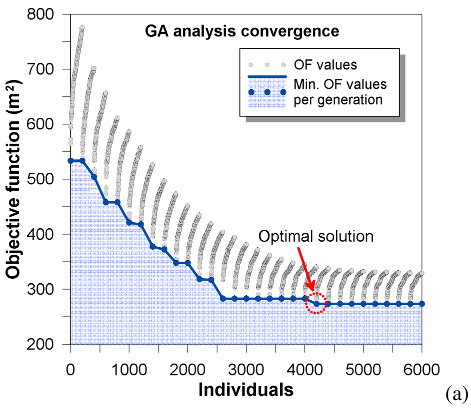
Fig. 5. Sample of clusters subdivision of the ground floor walls.

A tournament size $k=3$ is used for the parent selection operator. Stopping criteria have been set to a maximum of 25 generations (G_{max}) and a stall of 10 generations (S_{max}), representing the maximum number of generations in which the algorithm does not improve the optimal solution. The magnification for the penalty function inside the evaluation of fitness, for the reasons discussed in the previous sections, was set as $p=5$. GA parameters set up to accomplish the analysis are summarized in Table 3.

Table 3. GA setup parameters

Dimension of the design vector ***dim(b)***	Population size ***P***	Number of offspring ***O***	Tournament size ***k***	Mutation probability P_m	Max generations G_{max}	Max stall S_{max}
42	200	200	3	10%	30	10

The convergence history of the optimization carried out with the proposed GA routine is shown in Fig. 6. The optimal solution consists of reinforcing only 8 (out of 42) wall clusters. Of these, 5 clusters are located on the ground floor (6 walls for a total GFRP reinforced plaster area of 170 m^2) and 3 on the first floor (6 walls for a total GFRP reinforced plaster area of 103.6 m^2). The total surface of GFRP reinforced plaster is finally 273.6 m^2.



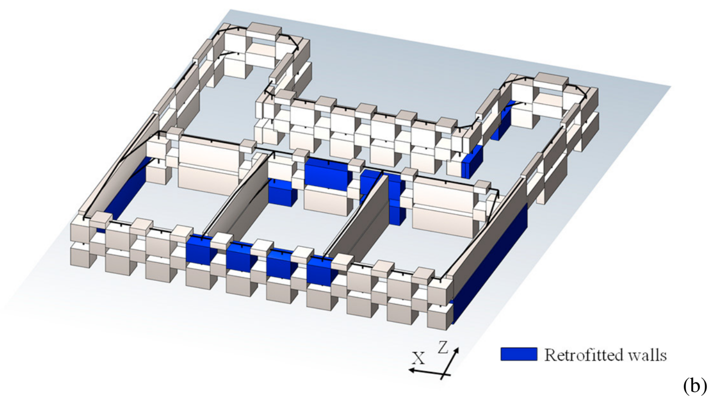


Fig. 6. GA optimization result: (a) Retrofitted clusters over the individuals; (b) Optimal retrofitting arrangement

By comparing the optimal solution found with the non-optimized retrofitting solution previously found (consisting of the reinforcement of all the walls that were not passing safety checks), a reduction of 27.7% of the surface of the walls undergoing GFRP reinforced plaster retrofitting, and a reduction of the retrofitted walls (from 18 to 12) is observed.

5. Conclusions

The paper has presented a novel optimization framework aiming at the topological optimization of GFRP reinforced plaster reinforcement interventions in existing masonry structures subjected to seismic loads. The framework is based on a genetic algorithm developed in MATLAB®, which is connected to a FE model developed in OpenSees. The main target of the algorithm is to provide the retrofitting arrangement required to achieve structural safety requirements minimizing the extension of the interventions in terms of square meters of reinforced plasters and consequently reducing the cost. The performance of each tentative solution is evaluated starting from the results of the equivalent elastic analysis. This type of analysis is chosen to reduce the computational effort of the optimization procedure, but the obtained outcomes can be eventually validate using a more refined structural analysis method (e.g., non-linear static analysis). Through a case study implementation, it has been proved that the proposed framework can efficiently pinpoint the optimal retrofitting configuration with a significant reduction of intervention costs, and invasiveness. The outcomes of this kind of optimization algorithms should be intended as a preliminary design tool to assist practitioners in individuating cost-effective configurations of retrofitting interventions even for complex structures. Finally, it should highlight that, even if artificial intelligence guided design could represent an attractive and effective tool the final engineering decisions have still to remain up on the designer who is the only one able to discern between the analysis outcomes and the real boundary conditions.

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