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Genetic algorithm-based optimization procedure for the seismic retrofitting of existing masonry structures

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Abstract

The design of seismic retrofitting of existing masonry structures mainly concerns the determination of the position and the arrangement of reinforcements. The implementation of these interventions is generally associated with noticeable costs, significant downtime, and relevant invasiveness. Despite the vast variety of efficient retrofitting interventions available, the design of retrofitting interventions in masonry structures is not straightforward, as the reinforcement techniques can significantly change strength but also stiffness, and masses. This can lead to recursive design issues that are mainly tackled with several trial-and-error attempts and engineers' intuition.

This paper presents a novel optimization framework aimed at the minimization of seismic retrofitting-related costs by pinpointing the optimal position (topological optimization) of glass-fibers (GFRP) reinforced plasters in masonry structures. In the proposed framework a 3D masonry model implemented in OpenSees is handled by the proposed genetic algorithm developed in MATLAB®. The metaheuristic procedure allows obtaining the optimal solution without the need of evaluating all the possible solutions that could involve huge computational effort. The characteristics of each tentative solution are encoded on a design vector of Booleans representing the position of reinforced walls inside the structure. The fitness of each solution is evaluated through an objective function that estimates the intervention costs indirectly calculating the area of GFRP implemented. The optimal solution is searched by selecting the best individuals of each generation through a tournament selection and mixing their design vector with the crossover genetic operator. In order to prevent stacks into local minima, the mutation operator is involved to introduce modest

random alterations of the genes. The feasibility of each configuration is controlled by flexural and shear safety checks of masonry walls. The possible unfeasibilities are taken into account in the procedure with a penalty function that increases fictitiously the fitness according to the size of walls that do not achieve the safety checks. The routine is stopped when the cost is minimized, namely when no further cost reductions are obtained from subsequent generations.

The framework is tested with a real case study structure, showing the suitability of the algorithm to provide cost-effective retrofitting solutions. The proposed algorithm can be an efficient support to engineers in the preliminary design of seismic retrofitting, allowing effortless identification of optimal solutions with a significant reduction in implementation costs that allows better management of funds allocated in seismic retrofitting of earthquake-prone areas building heritage.

Keywords: genetic algorithm, structural optimization, seismic retrofitting, masonry structures, GFRP, reinforced plasters.

1 Introduction

A large number of buildings in earthquake-prone areas are masonry structures designed prior to the entry into force of seismic guidelines. The seismic risk associated with these structures is significant because of their low lateral load-carrying capacity. Although, a vast range of effective retrofitting techniques are available, currently, this design practice is mainly based on trial-and-error attempts and engineers' experience, without a formal implementation of cost/performance optimization. However, retrofitting interventions are generally associated with relevant costs, significant invasiveness, and noticeable downtime.

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. [1]. Only recently, few studies focused on the topic of the optimization of seismic retrofitting on existing structures. Among them, Papavasileiou et al. [2] implemented a genetic algorithm (GA)-based optimization framework for encased steel-concrete composite columns through three different retrofitting techniques. Falcone et al. [3] proposed a framework for the optimization of the costs for FRP jacketing and steel bracings of reinforced concrete frame structures. In a similar way, Di Trapani et al. ([4] - [5]) implemented a novel framework aimed at minimizing steel jacketing retrofitting costs for RC structures. Lastly, Minafò and Camarda [6] proposed a GA-based optimization procedure for the minimization of costs of buckling-restrained braces on reinforced concrete 2D frames.

As it can be noted, the major scientific interest in this topic mostly addressed frame structures, leaving an evident lack with respect to 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, this paper proposes a new framework based on an artificial intelligence algorithm aiming at supporting the design of seismic reinforcements for existing masonry structures by minimizing their cost. The algorithm minimizes an objective function that evaluates the intervention cost as the area of walls where reinforced plasters are implemented. The final output of the framework is the optimal retrofitting configuration, namely the position of the retrofitted walls for the structure. The optimization procedure is carried out by linking a GA optimization routine developed in MATLAB® with an equivalent 3D frame elastic model analysed through the OpenSees software platform. The proposed framework is finally tested on a 2-storey masonry building, showing the suitability of the algorithm to provide cost-effective retrofitting.

2 Methods

The optimization procedure herein proposed is based on the genetic algorithm, a class of artificial intelligence metaheuristic technique that proceeds in the optimization procedure through the handling of the set of variables that are gathered in a design vector representing an individual.

The algorithm starts generating an initial population of tentative solutions and evaluating their related objective function value representing the fitness of the solution. Each individual represents one possible retrofitting configuration (Figure 1). The research of minima is exerted by selecting the best tentative solutions and mixing their design vector through crossover and mutation. For each candidate solution, the algorithm provides the analysis, the assessment, and the evaluation of the cost.

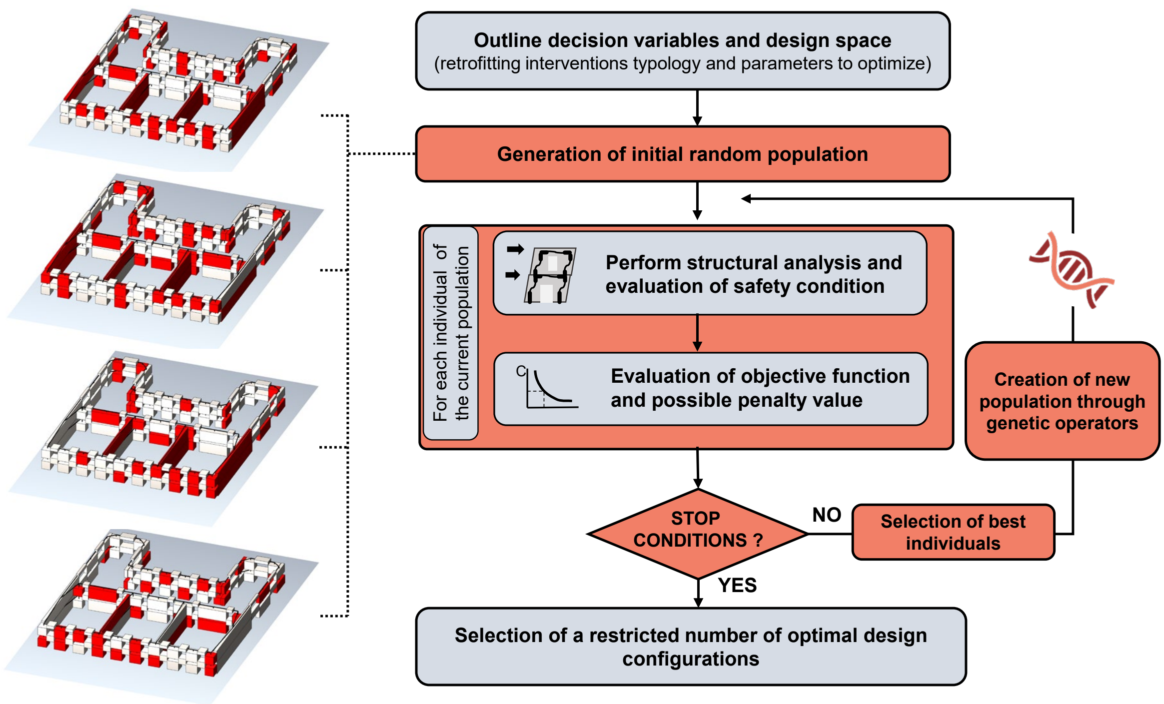


Figure 1: Genetic algorithm optimization procedure flowchart

The considered retrofitting technique is the application of glass fibers reinforced polymer (GFRP) net embedded in layers of special mortar to both sides of masonry walls. The definition of each tentative solution is performed by using a vector of binary variables to encode the presence or not of the reinforcement on each wall 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.
To reduce the dimension of the research space dimension, each Boolean variable can represent a cluster of adjoining walls. This can also be helpful to define some architectonical restraints, to which the intervention must comply.

The performance of each tentative solution is assessed by an equivalent linear static seismic analysis combined with safety checks provided for all the masonry walls. These are carried concerning both flexural (Eurocode 8 [7]) and in-plane shear collapse (Turnšek and Čačovič [8]).

The objective function (F) is aimed at evaluating the costs associated with the implementation of the retrofitting intervention. To consider the feasibility of each solution (namely if all the safety checks are verified), the fitness function involves a penalty that fictitiously increase the cost value in the cases of unfeasible individuals. Since the cost per surface area of reinforced plasters is a constant, the fitness function can appraise the total surface of reinforced plasters (in m^2) as:

$$F = \sum_{i=1}^{n_{rp}} A_{rp,i} + p \cdot \left(\sum_{j=1}^{n_{wf}} A_{wf,j} \sum_{k=1}^{n_{ws}} A_{ws,k} \right) \tag{2}$$

where $A_{rp,i}$ is the area of the i-th reinforced wall, p is a magnification coefficient fictitiously increasing the weight, in terms of retrofitting costs (area in m^2) of walls that do not achieve flexural ($A_{wf,j}$) and shear ($A_{ws,k}$) safety checks.

3 Results

The proposed optimization framework is tested with the case study of a 3D masonry building consisting of a two-storey structure with a total height of 8m and a C-shape floor plane (Figure 2). Masonry elements are supposed to be made of squared stone masonry with good texture.

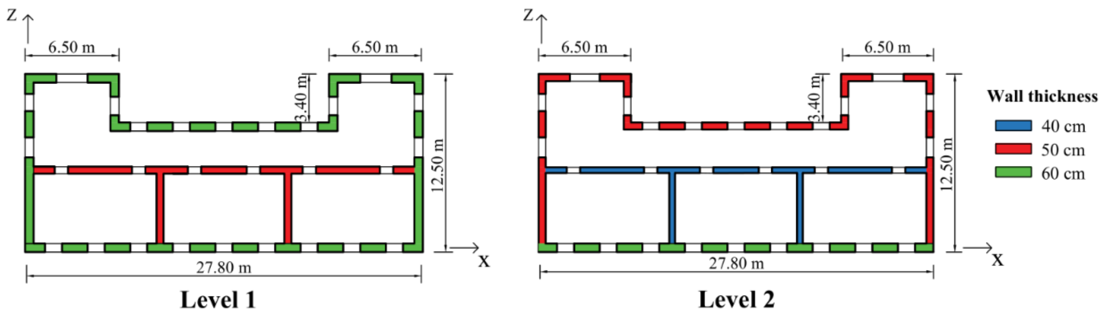


Figure 2: Reference structural model in-plane geometrical dimensions

The building is supposed to be in Cosenza (Italy), soil type C. The fundamental vibration period of the analysed structure is $T_1 = 0.23$ sec. 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.

	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	

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

A 3D model of the structure is realized in OpenSees (McKenna et al. [9]) using the Equivalent Frame Method, according to which the structure is modelled in masonry panels, spandrels, and rigid offsets.

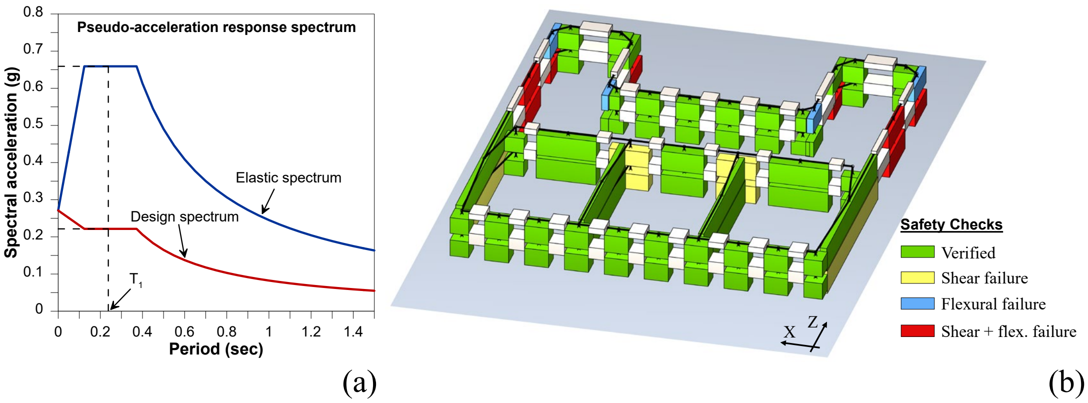


Figure 3: Assessment of the as-built structure: (a) Elastic and design spectra; (b) Safety checks of walls.

In Figure 3, a schematic representation of the preliminary safety checks for the as-built structure is depicted, highlighting walls undergoing shear and/or flexural demand exceedance together with reference spectra.

Model	Walls failing flexure safety check (#)	Walls failing shear safety check (#)	Walls failing flexure+shear safety check (#)	Total surface of walls failing safety checks (m^2)
As-built	4	6	8	349.7
Non-opt. Retrofit	0	0	0	-

Table 2: As-built and retrofitted structure safety assessment results

Results of safety checks for the walls are reported in Table 2. Safety checks were repeated by applying the GFRP reinforcement to the walls missing safety checks (349.7 m^2). This last solution is feasible although it is not optimized; assuming a retrofitting cost of 200€/m^2 the intervention cost is €69540.

The cluster subdivision of adjoining walls is depicted in Figure 4, the 78 walls were converted into 42 clusters of walls.

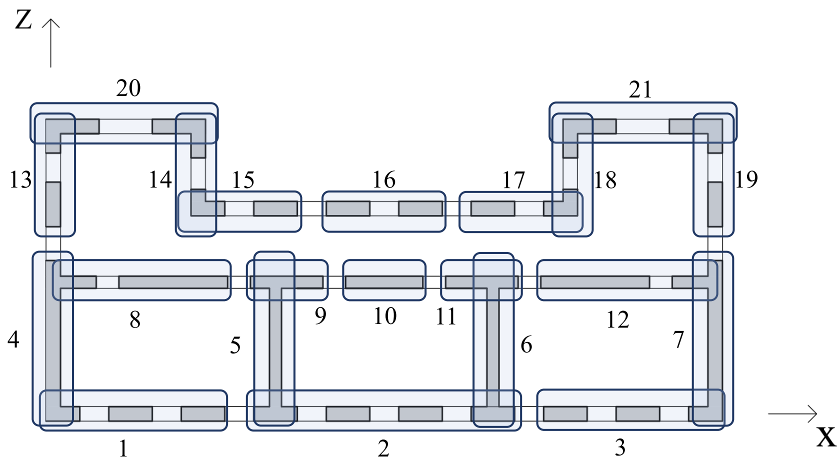


Figure 4: Clusters subdivision of ground floor walls.

The optimal solution (Figure 5) has been found in the 23rd generation and consists of reinforcing only 8 (out of 42) wall clusters, 5 are located on ground floor (6 walls, total area 170 m^2) and 3 on the first floor (6 walls, total area 103.6 m^2). The total surface of GFRP reinforced plaster is 273.6 m^2.

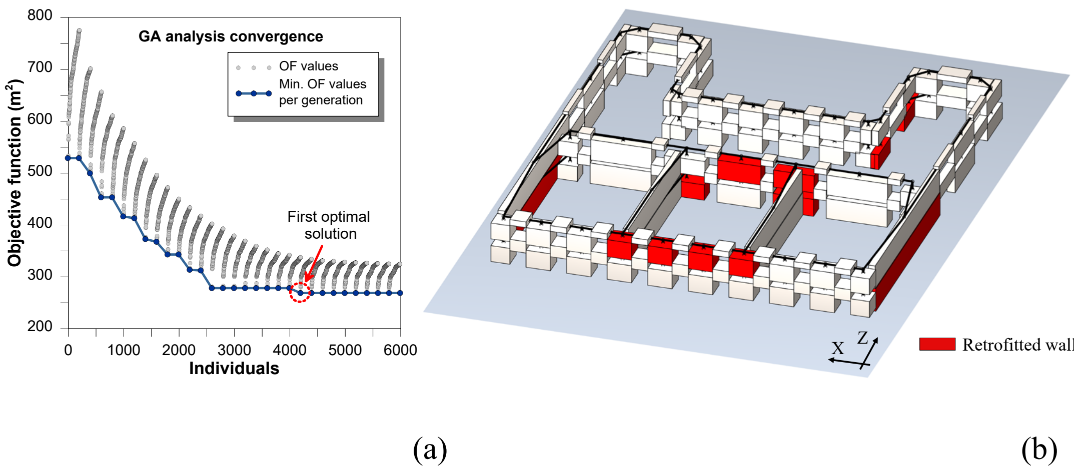


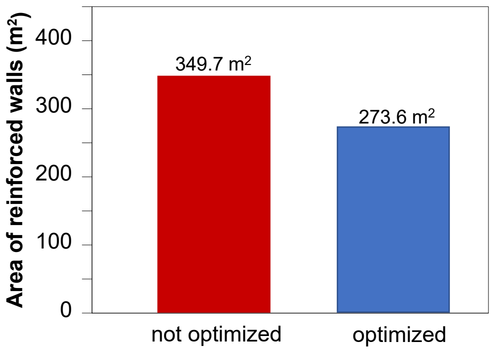
Figure 5: Optimization result: (a) Convergence history (b) Retrofitting configuration

4 Conclusions and Contributions

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 validated 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.

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 (Figure 6), and a reduction of the retrofitted walls (from 18 to 12) is observed. Still assuming the unitary cost of 200 €/m^2 (also including the demolition and reconstruction of plasters), the optimal solution is associated with a retrofitting cost of 54 720 € instead of 69 940 € found for the non-optimized solution.



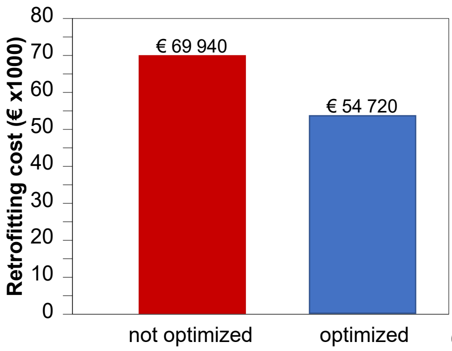


Figure 6: Non-optimized and GA optimized retrofitting solution comparisons: a) area of reinforced walls; b) retrofitting intervention costs.

The outcomes of this kind of optimization algorithm 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 remained up to the designer who is the only one able to discern between the analysis outcomes and the real boundary conditions.

This is the first application of optimization procedures developed to pinpoint retrofitting interventions on existing masonry structures. Extensive usage of the framework will improve the management of the funds allocated to seismic retrofitting of existing structures, enhancing the overall structural safety of building heritage.

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