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GENETIC OPTIMIZATION FOR THE DESIGN OF SEISMIC RETROFITTING OF PLANE RC FRAMES WITH BUCKLING RESTRAINED BRACES (BRBS)

Giovanni Minafò, Gaetano Camarda

Università degli Studi di Palermo, Dipartimento di Ingegneria
Viale delle Scienze, 90128 Palermo (Italy)

giovanni.minafo@unipa.it
gaetano.camarda@unipa.it

Abstract

The increasing development of computational power in modern digital devices has spread the use of structural optimization in design applications of different fields of engineering problems. This approach exposes engineers to challenging design procedures aimed to optimize all variables to satisfy the imposed requirements, finding the "optimal" solution. Despite this wide use, the application of optimization algorithms for the design of seismic retrofitting strategies becomes tougher, due to the difficulties in finding a mathematical expression which includes and combines all the key variables (i.e., cost, safety, sustainability, design) and the nonlinearity of the analysis. In this paper, the Genetic Algorithm search method (GA) has been used to optimize the retrofitting, using Buckling-Restrained Braces (BRBs), of a three-storeys RC structure designed to resist only gravity loads. The optimization aims to ensure the safety level required, minimizing intervention costs and use of materials, particularly finding the best topology solution for BRB positioning. To this purpose, an objective function has been applied to the model to minimize retrofit costs intervention using GA. The procedure has been implemented in Python Programming Language. In particular non-linear static analysis has been run using OpenSeesPy framework to evaluate the seismic required safety level at each simulation, while GA has been carried out with a custom design code to provide the best topology position of BRBs to minimize costs and consequently the use of materials. The method brought out the real possibility to ensure the required seismic safety level while reducing intervention cost and use of materials with an optimized and structured BRB positioning.

Keywords: Structural optimiziation, Genetic Algorithm, Retrofitting, BRB.

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1 INTRODUCTION

Soft-computing techniques are becoming increasingly common in the field of civil engineering for structural optimization. These methods are widely used for sizing, topology optimization, and form-finding of new structures and infrastructures [1], but structural optimization is less commonly used for structural retrofitting of existing structures. Despite the growing interest in retrofit of existing framed RC structures, it is difficult to find procedures to define the optimal parameters for intervention design. It is also important to note that the displacement demand on existing structures depends on the stiffness, the mass of the structure and the dynamic characteristics of the system. The introduction of new lateral-resisting components, such as braces, shear walls, or stiffening frames, alters the force-displacement demands, and the design of the retrofit cannot be achieved in a closed-form. As a result, retrofitting applications are often designed without an "engineered process", and often lead to an overestimated retrofit solution. The scientific community has only recently begun to address this issue, and some innovative applications using soft-computing techniques and artificial intelligence have recently been proposed [2]. In this field, Genetic Algorithms (GAs) have shown to be especially useful for optimizing design processes. GA is a meta-heuristic algorithm built on Darwin's "evolution of species" [3], that has been commonly used for optimization problems [4, 5], but only a few recent applications are available for structural retrofitting. Di Trapani et al. [6] presented a GA model for designing steel jacket confinement of columns in 3D structures with a typical gravity load configuration. In the present paper a GA implementation, for structural optimization of seismic retrofitting interventions in 2D RC frames with BRBs, is presented. The aim is to use the GA approach to design BRB configurations that provide the necessary level of safety while minimizing costs. The RC frames are modeled using fiber section beam elements with force formulation and plastic hinge regions at the extremities, implemented using OpenSeesPy framework [7]. The GA was implemented using a custom code written in Python programming language [8], where a boolean integer design vector is used to assigns the position of the BRB and its orientation. For each configuration, the algorithm performs a modal and a non-linear static analysis to check the safety level of the frame according to N2 verification [9]. The fitness of the solution is evaluated at each iteration combining the retrofit cost and a penalty factor, implemented to penalize infeasible solutions in terms of seismic safety. The opensource environment here proposed (Python-OpenSeesPy) allows finding the optimum BRB configuration for the frame to retrofit, ensuring seismic safety and minimizing the retrofit cost.

2 CASE OF STUDY AND NUMERICAL MODELLING

A case of study of 2D RC frame retrofitted with BRB elements is here presented, Figure 1. The chosen case of study replicates a typical situation of framed structures designed in the early 1980s in Europe. The frame has 5 storeys and 4 bays with a rectangular section for all elements, in particular, some columns are disposed to be stressed on their weak inertia axis and others are oriented on their principal strong inertia axis.

The design of reinforcing steel of the section was evaluated using elastic calculations, as usually assumed in old designs approaches, particularly a set of static lateral load was assumed as a fraction of the axial forces in the columns for each storey. The latter was a usual assumption in design process according to old codes in Italy during the 1970s.

A process of calculation of uniformly distributed load was done before the implementation of the model in the algorithm, as result the assumed load on the beams was 33.64 kN/m at first storey, 32.89 kN/m at intermediate storeys and 15.79 kN/m at last storey. The load value here assumed are calculated as a combination of seismic loads-i.e. as the sum of dead gravity loads and a fraction of the live load.

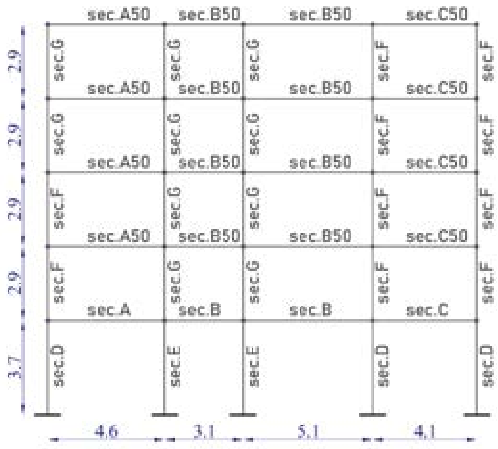

Figure 1: Studied frame geometry and sections.

The materials properties, Figure 2, of the concrete and the reinforcing steel used for the model design are reported in Table 1. The steel model used, take into account isotropic hardening of the material and needs the tangent at initial strain hardening (E_{sh}) as parameters. As regards the concrete material, it was modeled without taking into account the tensile strength. The depth of the concrete cover was set for all the sections to 25mm.

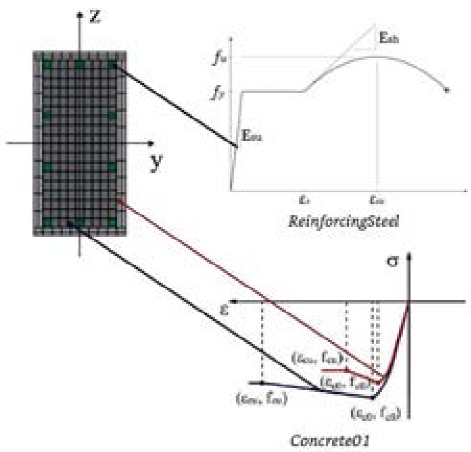

Figure 2: Fiber section discretization and materials behavior.

Steel	Unconf. Concrete	Conf. Concrete
f_y = 319 MPa	f_c = 18.4 MPa	f_c = 18.4 MPa
f_{su} = 365 MPa	f_{cu} = 18.4 MPa	f_{cu} = 20.26 MPa
E_{su} = 210000 MPa	E_c = 29444 MPa	E_c = 32544 MPa
E_{sh} = 31500 MPa	ε_o = 0.002	ε_o = 0.0035
ε_{su} = 0.06	ε_u = 0.0035	ε_u = 0.005

Table 1: Materials properties.

With regards to the elements section indicated in Figure 1, the geometry details are reported in the following Table 2.

Section	Dimensions	Top reinf.	Bottom reinf.
A	600x300 mm	3ϕ16	2ϕ16
B	600x300 mm	4ϕ16	2ϕ16
C	600x300 mm	6ϕ16	2ϕ16
D	300x600 mm	3ϕ16	3ϕ16
E	600x300 mm	4ϕ16	4ϕ16
F	300x500 mm	3ϕ16	3ϕ16
G	500x300 mm	4ϕ16	4ϕ16
A50	500x300 mm	3ϕ16	2ϕ16
B50	500x300 mm	4ϕ16	2ϕ16
C50	500x300 mm	6ϕ16	6ϕ16

Table 2: Sections and reinforcement adopted.

2.1 Modelling

As mentioned before, the numerical implementation of the considered frame was done using OpenSeesPy framework, in particular using for RC beams and columns the force-based elements with flexibility formulation. A "BeamWithHinge" element, based on plastic hinge integration [10], was used for the implementation of the beams and columns with a plastic hinge length equal to half the depth of the section for the columns and the depth of the section for the beams. The element state is determined using a total of six integration points (two for each hinge and two for the interior). Two different fiber sections are assigned for each element, one for the two plastic hinge regions and one for the remaining region of the element. The confined and unconfined concrete were modeled using Concrete01 uniaxial material, while the constitutive law for the bars was implemented using the ReinforcingSteel uniaxial material (Fig. 2).

As regards the BRB, it is well known that it usually exhibits good capacity in tension and compression. During compression phase the core plate starts to buckle, but the phenomena is prevented by the reinforcing case (usually filled with concrete). The constitutive law of the element was implemented following the model suggested by Upadhyay et al. [11]. The model adopted used Steel02 material for the steel core and in order to take into account tension and compression a Pinching4 material is added in parallel to Steel02. At this point, the material model adopted was calibrated by comparing the results achieved with the experimental data available in Xu and Pantelides [12], the calibration results are presented in Figure 3. A corotational element truss formulation is used to implement the BRB in the structural model.

The design of BRB features was executed before the implementation in the nonlinear models of the frame. The dissipative length (Lc) and the elastic end length were calculated following Gelfi et al. [13] relationship:

$$Lc = \frac{\Delta_{bm}}{\varepsilon_{cu}} = L_b\left(\frac{d_r}{h}\sin\beta\cos\beta\right) \quad (1)$$

Where Δ_{bm} is the elongation of BRB, ε_{cu} is the plastic strain, d_r is the storey displacement, L_b is the overall diagonal length of the BRB, β is the inclination of the brace and h is the height of the considered storey. Two area parameters are set for the BRB and they are fixed in all the elements: A_c = 5000 mm^2 for the core area, while in the elastic zone the section area is equal to A_e = 64500 mm$^{2.}$

The design length core, length end, diagonal length, inclination of the brace and the elastic modulus of the BRB vary on the basis of the considered bay.

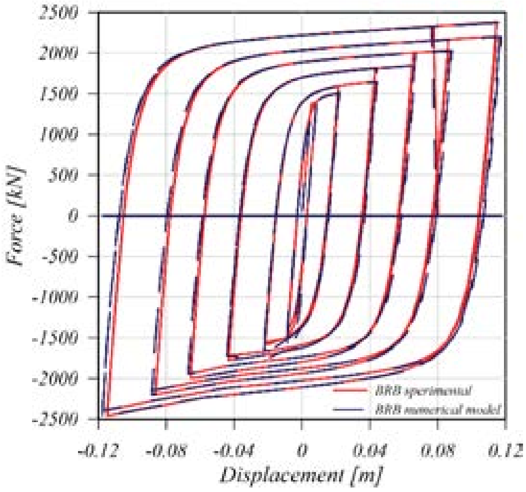

Figure 3: Calibration of BRB constitutive model.

2.2 Analyses and structural safety

The implemented environment provides a modal dynamic and a static non-linear analysis for each analyzed configuration. Modal analysis was performed to identify the lateral load profile to be applied to the structural nodes, while the NL analysis was performed to evaluate the capacity curve (force-displacement) of the analyzed configuration. The latter analysis was performed under displacement control with incremental steps of 0.05mm and load profile proportional to the first modal shape. The maximum displacement of 200mm was imposed on all analyses and the Newton-Raphson algorithm was used with a norm displacement increment check with tolerance equal to 10^{-6}.

The required seismic action was estimated based on the elastic response spectrum reported in Figure 4, assuming a high seismicity zone (type 1) and design spectral parameters ground acceleration on rock soil ag = 0.286g, soil factor S=1.332 and damping correction factor η=1 (corresponding to 5% damping).

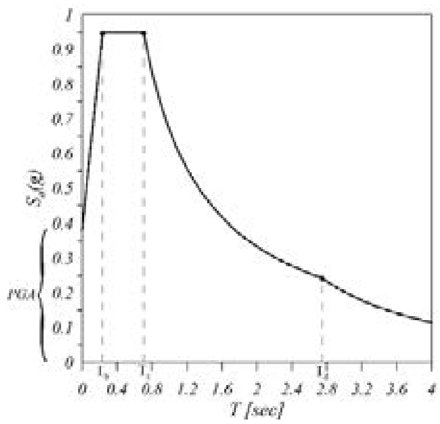

Figure 4: Pseudo acceleration response spectrum.

The safety of the structure was checked in compliance with Eurocode 8 [14] by comparing the required displacement demand with the capacity of the equivalent Single Degree of Freedom (SDOF) system, as expected in N2 method [15]. The SDOF capacity curve was linearized with elastoplastic behavior, by the equivalent energy rule, and the seismic safety was evaluated by comparing the linearized SDOF response with the Acceleration-Displacement format (ADRS). Finally, structural safety index was evaluated as the ratio between the displacement capacity and the required displacement $\zeta = d_u^*/d_{r,max}^*$.

3 IMPLEMENTATION OF THE GA FRAMEWORK

The Genetic Algorithm is a meta-heuristic search method for optimization, based on evolutionary processes in which the algorithm simulates biological mechanisms. The aim of the GA is to find the optimal solution of a predefined objective function using the solution's fitness value. In the present work, the fitness of a solution depends on retrofit cost and structural safety, in particular, retrofit cost has to be minimized.

As mentioned before the environment was implemented on custom code written in Python programming language, while for the analysis the OpenSeesPy library has been used, so that all the processes were implemented in one code using *opensource* tools only.

The first step of the procedure begins generating an initial random population of individuals ($p_{size} = 5$ in the present work), where an individual defines the location and orientation of the BRB across the frame. Each individual of the population is identified by a design vector V_d , Figure 5, with 1 row and a number of columns depending on the number of the bays of the frame. An integer encoding type is used to enable BRB retrofit using boolean parameters from 0 to 2, where 0 means bare frame, 1 means bay retrofitted with a BRB in the tensile direction and 2 means bays retrofitted with BRB in compression.

$$V_d = [\underset{0}{1}\ \underset{1}{0}\ \underset{2}{0}\ \underset{3}{0}\ \underset{4}{0}\ \underset{5}{2}\ \underset{6}{0}\ \underset{7}{0}\ \underset{8}{0}]_{1x9}$$

Figure 5: Example of design vector.

Each design vector is decoded in a retrofit BRB topology configuration for the structural analysis to be executed. At the end of population analysis, the safety index (ζ), retrofit cost and fitness of individuals are calculated. The retrofit cost is obtained through the objective function, while the fitness value of the configuration is calculated as follows:

$$f = \frac{C+\delta}{100} \tag{2}$$

Where C represents the retrofit cost, while δ is a contribute that penalizes the solution if the safety index is less than 1. In particular, the latter coefficient is implemented as follows:

$$\delta(\zeta) = \begin{cases} 0, \ \zeta \geq 1 \\ C_{max} + C \cdot e^{\zeta}, \ \zeta < 1 \end{cases} \tag{3}$$

Where C_{max} is the maximum retrofit cost if all the bays of the frame were reinforced using BRB. The cost function, hence the objective function to minimize, is calculated as the sum of two main contributions:

$$C = C_m + C_s \tag{4}$$

C_m is the manpower and safety cost for each BRB (increased with the BRB number), while C_s is the cost that takes into account the scaffolding cost, demolition and rebuilding cost of infill walls and the cost of BRB. Is important to notice that C_s not only depends on the BRB geometrical properties but it is strictly related also to the geometrical parameters of the bay's walls.

For each population, that identify a generation, a *Tournament selection* (Fig. 6) is applied to selects 2 parents individuals used to generate a new possible solution (offspring). This selection method runs a series of tournaments inside the population pool, where individuals are randomly selected and the winner is chosen by its fitness value; in the present work lower the fitness and better is the solution.

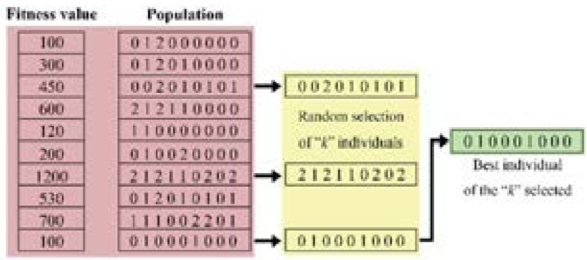

Figure 6: Example of tournament selection implemented.

The selected parents are then coupled using the *Crossover operator,* which is used to generate new offspring that will improve the exploration of the search space. In particular, *Single-point crossover* is implemented, where a random point is evaluated to cut in half the two parents and the offspring are generated cross-merging the pieces of the two individuals. At this point, the new offspring could be modified using the *Mutation operator,* which will randomly change an integer inside the design vector. In particular, if the chosen position has a value equal to 1, it can be changed in a random value inside the list (0, 2), and so on for the other cases. The mutation will happen depending on a mutation rate parameter (m_r = 0.2 in this work) defined by the user.

Is important to notice that the number of offspring is generally higher than population size (p_{size}), hence before the process could proceed a *Survival selection* is applied to resize the offspring individuals to the population size. The survival selection will select the first p_{size} individuals with the best fitness to move forward to the next generation and repeat the process, but before that, a convergence check is executed to evaluate if the optimal solution has been reached. In this work the convergence is reached when there is no difference between old and new populations for a certain number of generations, depending on the number of bays and storeys of the frame.

4 RESULTS AND DISCUSSION

Figure 7 shows the optimal retrofit configuration achieved by the Genetic Algorithm. Four BRB are needed to secure the frame, one per storey disposed along the tensile direction at the three bottom storeys and along the compressive direction for the fourth storey.

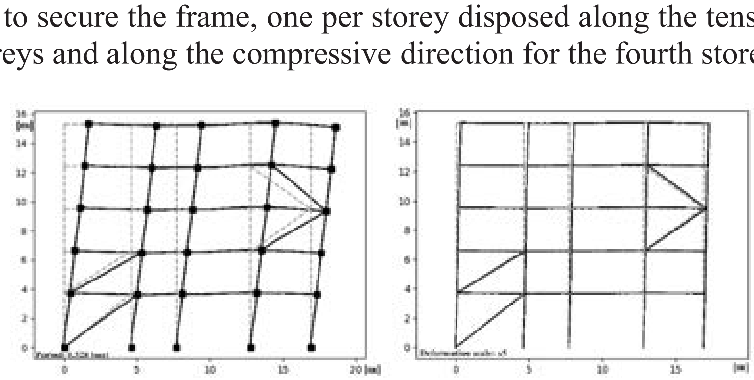

Figure 7: First modal shape and last step of static non-linear analysis of the retrofitted frame.

The optimal solution is achieved by the algorithm with a safety index $\zeta = 1.17$ and a retrofit cost of 28753€, while the total retrofit cost for all the bays of the frame with BRB is estimated to be 136597€, this means a saving cost of about 79%.

Finally, Figure 8 and 9 shows the verification of the displacement demand on the considered frame for both the bare (Fig. 8) and retrofitted (Fig. 9) configuration.

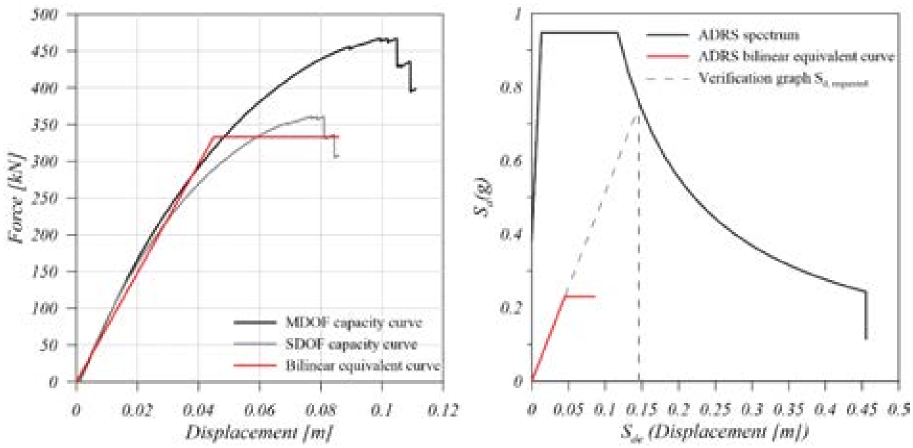

Figure 8: N2 verification of bare frame.

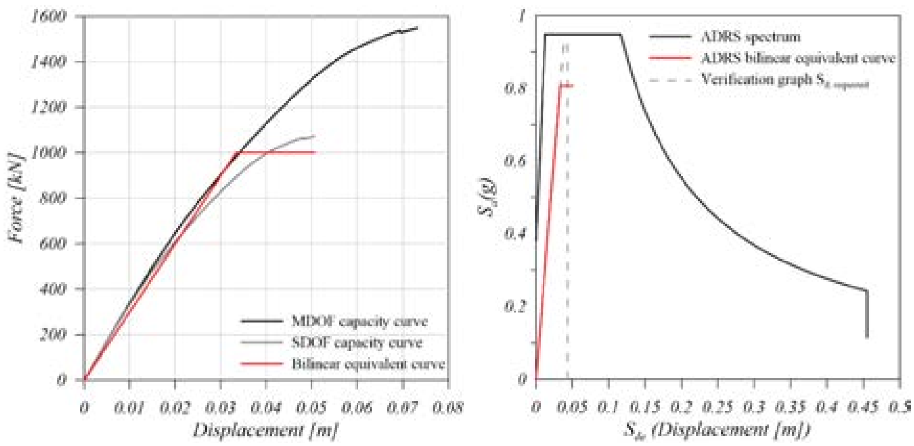

Figure 9: N2 verification of retrofitted frame.

As regards the implemented GA, the best fitness values of each generation are plotted in Figure 10(b), or for each analyzed individual in Figure 10(c), while the color of the points depends on the value of the safety index. It is observed that the solution comes after 50 generations of 5 individuals and a stable convergence is achieved with a constant value of fitness.

It is also worth noting that the solution cannot be improved, meaning that the number and disposal of braces is the minimum for ensuring the safety level. Figure 10(d) shows the best individual fitness of each generation.

Furthermore, the number of unfeasible solutions is a limited part of all the generated configurations (Fig. 10(c)), which confirms that the GA tends to select only possible solutions within the search space. The convergence of the procedure is reached after 20 generations with 5 individuals, meaning that 100 modal and pushover analyses are needing, as shown in Figure 10(d).

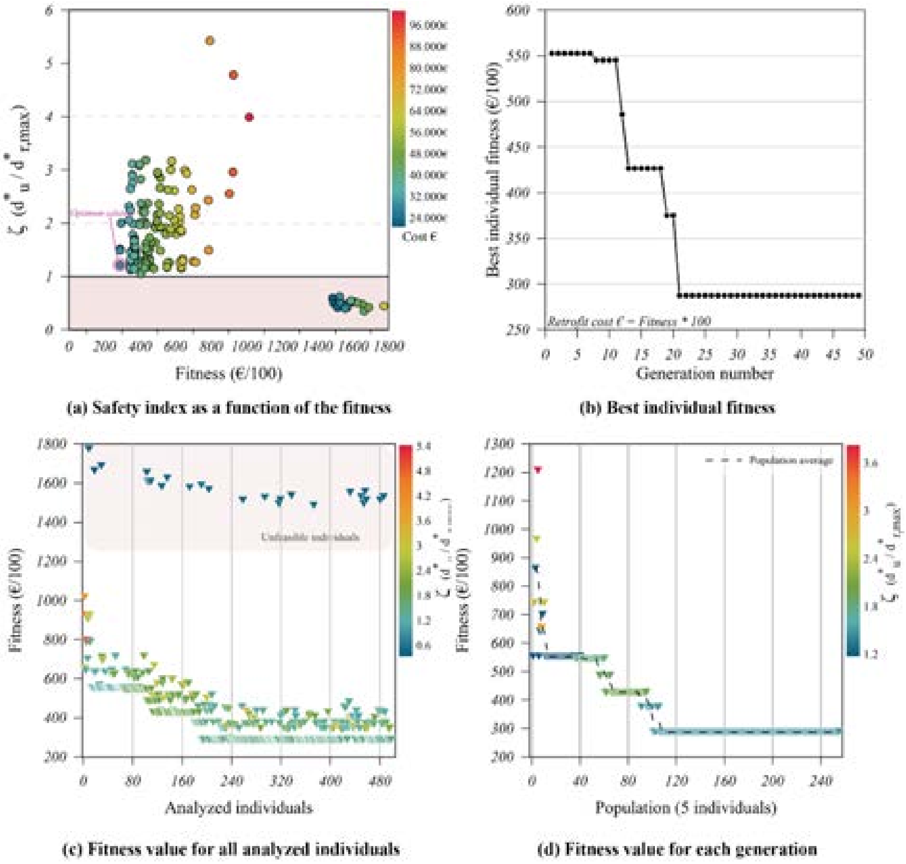

Figure 10: Results of the proposed procedure for the studied frame.

The efficacy and the stability of the proposed algorithm were assessed by comparing the results with those of multiple simulations carried out with a Monte Carlo (MC) approach. A comparison between GA retrofitted configuration, MC configuration and the bare frame is reported in Table 3.

Configuration	Period T[s]	ζ	Cost [€]	d_u^*[m]	$d_{r,max}^*$[m]
Bare frame	1.002	0.585	-	0.09	0.146
Retrofitted (GA)	0.53	1.168	28753	0.05	0.043
Retrofitted (MC)	0.44	1.294	40439	0.04	0.0287

Table 3: Results comparison between the bare frame, retrofitted (GA) and retrofitted (MC) analysis.

The same number of analyses as GA individuals number was performed on frames with randomly disposed BRBs. In particular, the design vector was composed by generating a pseudorandom integer number in the range 0 to 2 for each bay with equal probability. The number of generated configurations was selected to keep the same computational effort in comparison with the GA and having the same number of overall structural analyses (500 simulations).

Figure 11 shows the comparison between the results obtained through the MC simulation with those achieved with the proposed GA approach. The graphs show the cost (Figures 11(a) and 11(b)) and the safety index (Figures 11(c) and 11(d)) associated with each generated configuration, while the red line indicates the moving average for each 5 individuals. It is evident that the GA quickly converges down to a minimum value of the cost of about 29000€, while the distribution of the cost for the MC approach follows the "white noise" distribution, keeping the average cost on the starting value.

A similar consideration can be made in terms of safety index, which is almost kept constant by the GA, searching smartly the best configuration on a limited range around 1. It is also observed as the Coefficient of Variation associated with the distributions of the GA is significantly lower concerning that of the MC analysis, due to the capability of the algorithm in improving the solution progressively.

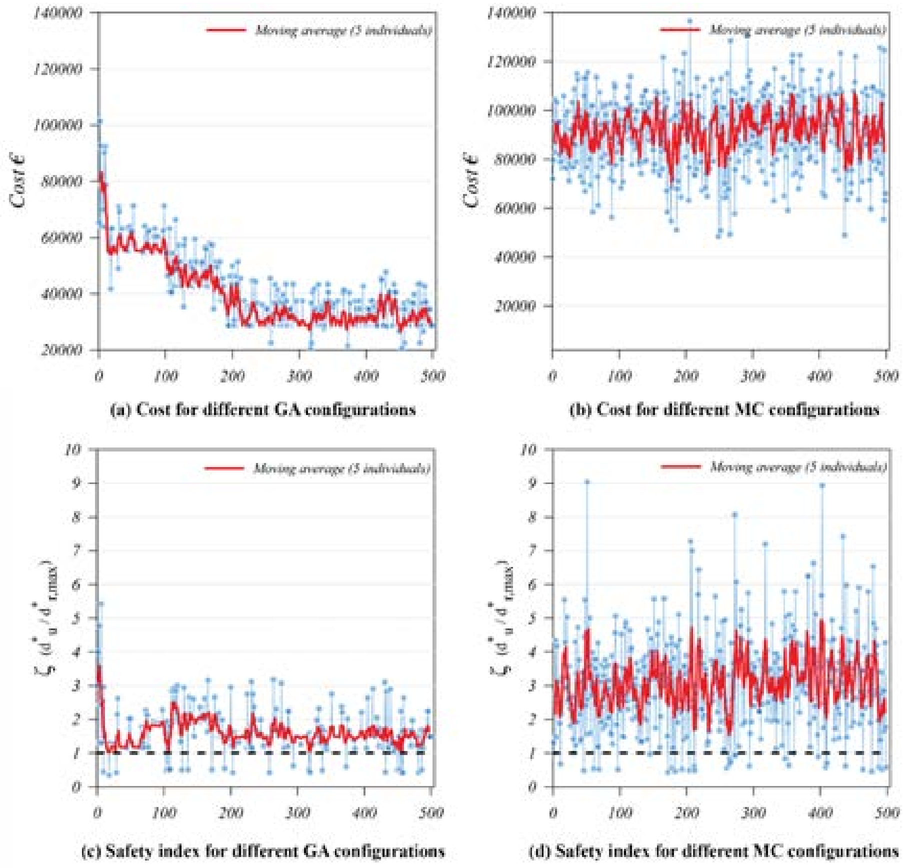

Figure 11: Comparisons between GA and Monte Carlo simulations.

It is evident that the GA allows achieving safe results with the cheapest solution. It is also to note that with the same number of analyses, hence the same computational time, the best solution of the MC simulation is more expensive than the solution found by GA of approximately 40.64% with an almost equal safety index.

5 CONCLUSIONS

This paper presented the proposal of a GA framework for designing the optimal configuration of BRBs for the seismic upgrading of plane RC frames. The algorithm allows varying the position and the direction of the braces, while the mutation and generation operations search for the most suitable configuration of the retrofitted frame. The GA was implemented in a Python environment while the OpenSeesPy library was adopted for modelling and analyzing the frames, making up a unique open-source framework for analysis and optimization.

Based on the obtained results and for the range of analyzed variables, the following conclusions can be drawn:

- the algorithm proved to be stable, finding the optimal configuration after a number of generations depending on the deformability of the structure;
- the solutions achieved for all the cases ensured the required safety level and proved to minimize the cost, on the basis of the selected features of the BRB;
- the penalty function implemented ensured the safety of the structure while the algorithm minimizes the cost;
- comparison with Monte Carlo simulations has shown the intelligence of the Genetic Algorithm in using previous information data to improve the search inside the solution space;

Further analysis has to be done to assess the algorithm behavior of the algorithm implementing 3D structural analysis and taking into account the possible shear increment at beam-column nodes.

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