A soft-computing approach to seismic retrofitting of existing RC structures

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ABSTRACT: This paper proposes a soft-computing approach intended at supporting engineering judgement on seismic retrofitting of existing Reinforced Concrete (RC) frames. It formulates a genetic algorithm aimed at selecting the “fittest” retrofitting solution by combining “member-level” and “structural-level” techniques. In the proposed approach, each “individual’s phenotype” includes a set of member-level interventions, described by the number of Fiber Reinforced Polymers (FRP) layers confining the single columns of the frame, and structure-level information, reporting the profiles possibly adopted in the various bays for realizing a concentric steel bracing system. Hence, a genotypic representation is obtained by adopting conventional binary coding. The proposed genetic algorithm is capable to handle the three main genetic operators (namely, selection, crossover and mutation) that simulate the driving mechanisms of the evolution of species, as figured out by Charles Darwin, and resulting in the “survival of the fittest” rule. In this case, a fitness function based on initial costs and taking into account the technical effectiveness of the retrofitting interventions is considered with the aim to select the most cost-effective solution among the technically sound ones. Finally, a simple application of the proposed procedure is presented.

1 INTRODUCTION

Reinforced Concrete (RC) existing in earthquake-prone areas are often vulnerable to seismic actions due to material aging and inadequate structural detailing. Their vulnerability is generally due to the fact that the original design did not consider Capacity Design rules introduced by the most up-to-date seismic codes, such as EN 1998-1 (CEN, 2005). Reducing land use and environmental impact due to new buildings mainly related to construction and demolition waste (Faella et al., 2016) has led governments to encourage retrofitting and reusing (rather than demolishing) old structures. Therefore, seismic retrofitting of existing structures is nowadays a relevant technical challenge for engineers and a major societal priority (fib, 2003). As matter of fact, retrofitting interventions lead to modify both displacement capacity and demand, making the latter lower than the former and complying with all the performance objectives of relevance for the structure under consideration. Retrofitting solutions aimed at enhancing the capacity of under-designed members, and, as consequence, of the structure as a whole are based on confinement with steel and/or Fiber Reinforced Polymer (FRP) materials, as well as concrete jacketing and are referred as “member-level” (local) techniques within the scientific literature (fib, 2006; Rodriguez and Park, 1991). Conversely, “structure-level” (global) techniques (fib, 2003) refer to all those interventions (introduction of new structural systems such as steel bracing, RC shear walls and so on) that allows to reduce the displacement demand on the existing structure. In principle, the two aforementioned techniques can be used simultaneously with the aim to obtain a synergistic capacity increase and demand reduction on the structure as a whole. Specifically, such a combination is rather common and widely used in practice, but not well defined design rules are nowadays available for supporting engineers in selecting the best combination of member- and structure-level retrofitting interventions related to particular performance objectives. In principle, potentially infinite combinations of member- and structure-level interventions lead to obtain seismic strengthening resulting in different direct costs, life-cycle costs, reliability levels and other quantitative/qualitative parameters describing their "fitness" as a retrofitting solution. In the current of practice, mainly due to the lack of a rational strategy completely accepted by the scientific community, any considerations about "optimisation" are often restricted to "economic" aspects and are left to the designer's judgement. The possibility of combining member- and structure-level techniques for minimising the initial cost of retrofitting is only conceptually explored in the scientific literature (Martinelli et al., 2015). Choosing the "fittest" combination can be regarded as a constrained optimisation problem, which cannot be approached by means of analytical techniques commonly employed in structural engineering, as it depends on the several relevant variables. Conversely, it can properly be approaching by means of meta-heuristic techniques, possibly based on multi-criteria optimization objectives (Caterino et al., 2009). The current version of the genetic algorithm (Holland, 1975), as proposed in this paper, is capable of selecting the "fittest" retrofitting solution (in terms of initial costs) obtained by combining structure-level techniques, based on steel bracing subsystems, and FRP confinement-based member-level ones. Specifically, the paper presents the general procedure inspired to the well-known Darwin's "evolution of species" (1859) and the assumption of the "survival of the fittest" rule. Although recent applications of these techniques are already available in the field of structural engineering, they are mainly restricted to the design of new structures (Fragiadakis et al., 2008). The following sections summarise the main aspects of the proposed genetic algorithm and its application in the rational design of retrofitting interventions. Finally, the last section presents an application of the proposed procedure intended at demonstrating its actual potential.

2 OVERVIEW OF THE PROCEDURE

The conceptual definition of the seismic retrofitting problem is generally stated by following Limit State (LS) function g_{LS}:

$$g_{LS,i} = C_{LS,i} - D_{LS,i} \geq 0 \tag{1}$$

where the capacity $C_{LS,i}$ and demand $D_{LS,i}$ are intended in terms of displacements or forces for ductile and brittle mechanisms, respectively. As a matter of principle, the function g_{LS} is negative for vulnerable structures and retrofitting interventions are needed for complying with the performance objectives at the relevant LSs resulting in positive values of $g_{LS,i}$. The seismic retrofitting can be obtained modifying both capacity and demand by means of infinite combinations of member- and structure-level techniques. The optimal retrofitting solution can be found by solving the following constrained problem:

$$\begin{aligned} \bar{x}_{opt} &= \arg\min_{x}\left[f\left(x\right)\right] \\ g_{LS,i} &\geq 0 \quad \forall i = 1 \ldots n_{LS} \end{aligned} \tag{2}$$

where *f(x)* is the objective function to be minimised and *x* is the vector of design variables defining the generic intervention. In the present paper, the objective function is related to the total direct cost of intervention aiming at choosing the cheapest retrofitting solution. Such a function is reported in Eq. (3) where $C_{loc}(x)$ and $C_{glob}(x)$ refer to the cost of local and global interventions, respectively and take into account both demolition and reconstruction operations needed for realising FRP confinement and installing steel bracings, the latter considering also the connection with the existing RC members through steel jackets:

$$f(x) = \left[C_{loc}(x) + C_{glob}(x) + C_{found}(x) \right] + \Phi_{pen} \left[\min_{i} \left(g_{LS,i} \right) \right] \tag{3}$$

Moreover, *f(x)* also include the costs of interventions at the foundation level $C_{found}(x)$ generally needed as a result of concentrate reaction increments due to structure-level interventions. Finally, a penalty function $\Phi_{pen}(\bullet)$ is introduced in order to increase the cost solutions that do not fit with the retrofitting objectives defined by Eq. (2).

2.1 *Encoding of the generic "individual" intervention*

The conceptual flow-chart shown in Figure 1 depicts the main steps of the proposed procedure.

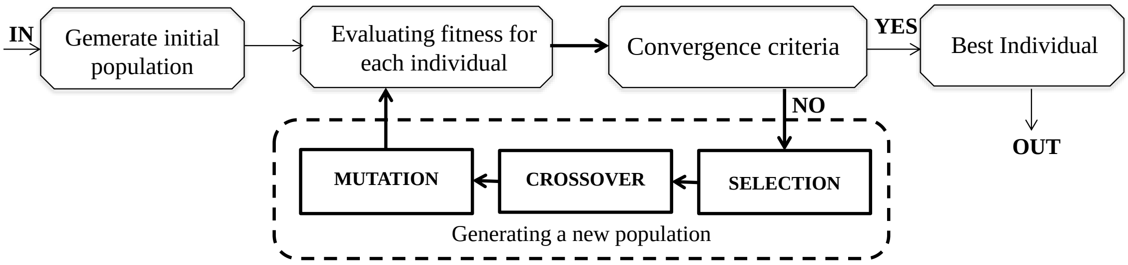

Figure 1. Flow-chart of the optimisation procedure

It starts with a random generation of N_{ind} individuals which represent the first population. Each structure (individual **x**) is encoded by a chromosome-like array of bits. The vector includes variables describing both member- and structure-level techniques. The string representing the binary coding of one individual is structured by concatenating the set of variables (or genes) that represent it (Biondini, 1999). Figure 2 depicts an example of the binary genotype encoding a generic structure with 12 total columns and 4 beams for each floor: the first part of the string describes the member-level techniques (FRP confinement) of columns, whereas the second part describes the structure-level ones related to the bays of the first storey.

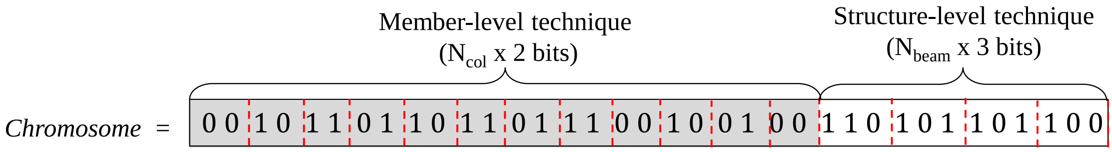

Figure 2. Example of binary genotype for coding a retrofitting intervention

In the first part of the individual encoding, each couple of bits describes the number of FRP layers confining the corresponding column. Hence, a total of $2*N_{col}$ bits is considered, N_{col} being the number of columns in the structural model of the existing frame. In the current implementation, the aforementioned number of confining FRP layers ranges between zero (as-built configuration denoted by the value "00") and three (denoted by "11" through binary coding). The information about FRP confinement are employed for modifying the original (unconfined) mechanical behaviour of concrete. As is well-known, based on the number of layers to be applied for the corresponding column, the original (unconfined) stress-strain relationship is duly modified (Kent and Park, 1971) as schematically described in Figure 3.

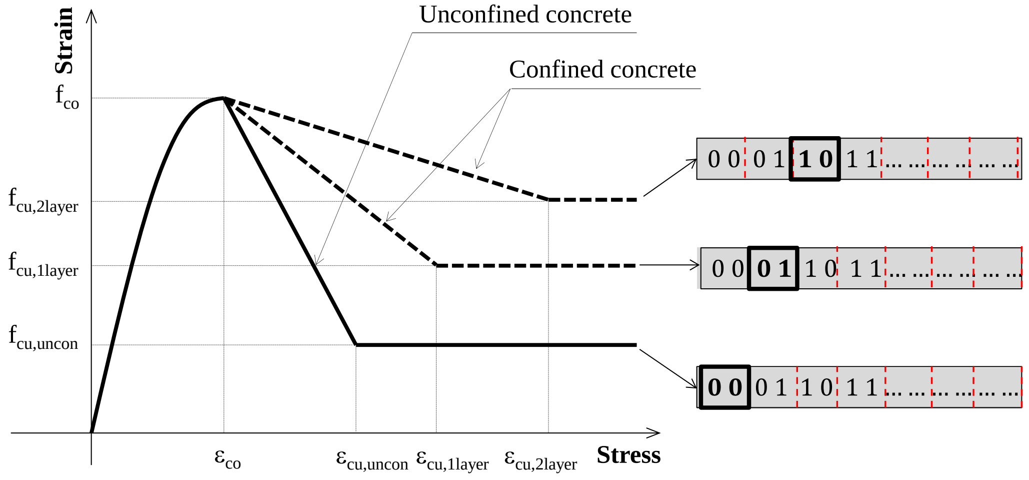

Figure 3. Model by Kent & Park (1971) for confined concrete

The second part of the *x-array* represents the profiles adopted for realizing the first level of concentric steel bracings considered as a structure-level technique. Furthermore, since steel bracings are supposed to be only realised between each couple of columns connected by a beam, the maximum number of bracing systems is equal to the number of beams N_{beams} at the first floor. Three bits are employed for codifying structure-level techniques (Figure 2); consequently, there are only 2^3 possible phenotype solutions, which identify the section of steel bracings at the first level. They can range from “000”, which means absence of bracing system, to “111”, which corresponds to the 7th profile within in a list of steel sections potentially available for the purpose. Considering the inertial nature of the seismic loads, the section of steel members is reduced at upper levels by means of the following relationship:

$$A_{k,des} = \frac{\sum_{j=k}^{n} h_j \cdot W_j}{\sum_{i=1}^{n} h_i \cdot W_i} \cdot A_1 \tag{4}$$

where h_j represents the position in height of the floor with respect to the foundation level, n is the total number of floors, W_j is the seismic mass of the j-th floor. Moreover, A_1 is the area of the cross section of the bracing at the first level and $A_{k,des}$ is the theoretical area of the bracing cross section required at the k-th floor. Finally, the knowledge of theoretical areas allows to select the steel commercial section whose area must be greater than $A_{k,des}$.

2.2 Seismic Analysis and Evolution criteria

Nonlinear Static Analysis are adopted for evaluating the displacement demand. Specifically, four PushOver analyses are performed for simulating the seismic response of the structure in both x and y direction as well as in positive and negative verses. The triangular distribution of lateral loads is taken into account in the current version of the procedure. However, further distributions might be easily implemented for performing analysis according to recent seismic codes (M.II.TT., 2008). The seismic demand is evaluated by applying the N2-Method (Fajfar, 1999), while the capacity models adopted by EN 1998-1 (2005) are considered for determining the capacity $C_{LS,i}$ needed for evaluating the values of function $g_{LS,i}$ according to Eq. (1). Finally, the total cost and the function $g_{LS,i}$ are evaluated for all N_{ind} individuals of the population and the genetic algorithm evolves through three operators until the counter of population reaches a maximum fixed number. Within the present work this threshold value is fixed to 150. The first genetic operator (namely *selection*) is used to select "parents" among a mating pool solution according to their fitness. The fitness function F(x_k) of each individual x_k is defined as follows:

$$F\left(x_k\right)=\frac{\min\limits_{h=1\ldots N_{ind}} f\left(x_h\right)}{f\left(x_h\right)} \tag{4}$$

where N_{ind} is the (invariant) number of individual forming each generation and f(x_k) is the value of the objective function of the k-th individual. The function F "measures" the performance of individual solutions in the problem domain: it represents the ability of the individual to "compete" among the whole population. Each individual "competes" and its probability of survival and reproduction its features in the following generation is defined as a function of its fitness:

$$p\left(x_k\right)=\frac{F\left(x_k\right)}{\sum\limits_{h=1}^{N_{ind}} F\left(x_h\right)} \tag{4}$$

where ΣF(x_h) is the sum of all of the fitnesses of the population. Therefore, the selection procedure is implemented through the so-called "roulette-wheel" rule described in Lipowski and Lipowska (2012). Hence, the string characterised by higher fitness value has a higher probability of being selected and copied into the mating pool for reproducing itself in the next generation. The second operator (*crossover*) combines segments of selected strings chromosome arrays into new "offspring" solutions by exchanging their genetic information ("multi-point" crossover): the influence of the number of crossover points on the resulting efficiency is a key issue, for whose refer to Spears (1992) for further details. In the example shown in Figure 4, crossover operator is applied column-by-column and bay-by-bay, respectively in the first and second part of the genotype.

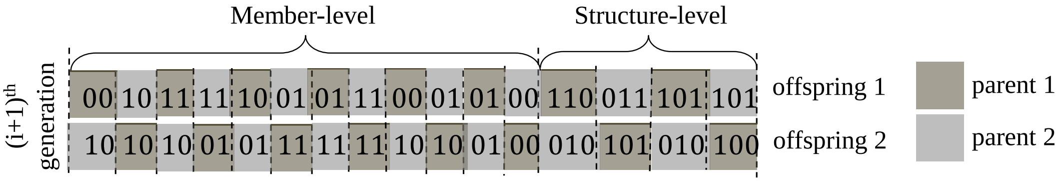

Figure 4. Crossover operator applied to couples of "parent" individuals

In order to preserve some of the fitter individuals, not all selected strings in the mating pool are used in crossover: only N_{ind}*0.95 individuals of the population are used in the crossover. The third operator is *mutation* that introduces diversity in the population whenever the population tends to become homogeneous due to repeated use of selection and crossover operators. Mutation operator allows for the possibility that non-existing features from both parent strings may be created and passed to their children. It helps to avoid getting trapped at local optima. It runs through the string of bits and changes the bit from 0 to 1 or otherwise if a fixed probability test is passed. This probability, called mutation rate p_m, is usually fairly small and, in the present proposal, it is set equal to 0.02. In detail, a "coin-toss" type mechanism is employed: the bit is mutated if a random number between zero and one is less than the aforementioned mutation rate (p_m = 0.02).

3 SAMPLE APPLICATION

The details and the actual potential of the presented optimization procedure can be well outlined considering the sample application reported in this section. For this purpose, a simple 3D three-storey RC frame with three bays in x-direction and one bay along y axis is analysed. Figure 5 depicts its in-plane and three-dimensional configuration.

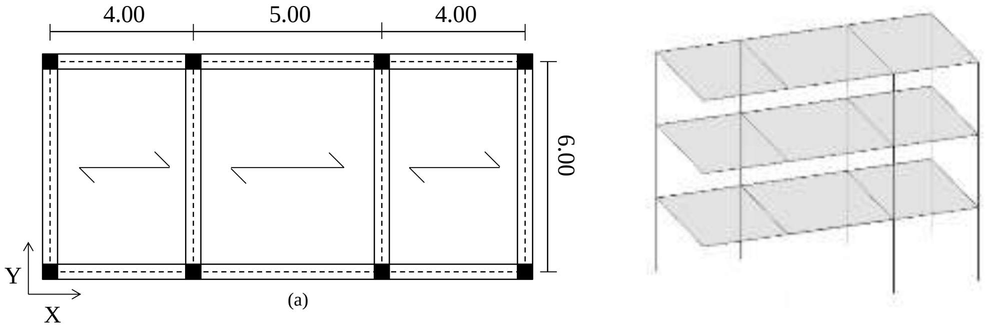

Figure 5. In-plain configuration and 3D view of the considered structure

The cross-sectional area of beams and columns is 30x40 and 30x30 cm^2, respectively. Foundation is not simulated and fixed supports are considered. Rigid joints are used for simulating beam-to-column connections. Each generation includes 50 individuals for each generation and the genetic algorithm stops either after 150 generations or if the objective function results unchanged for 30 consecutive generations. Both the LSs of Life Safety (SLV) and Damage Limitation (SLD) are considered.

A bilinear stress-strain curve with Young modulus equal to 210 GPa and yielding stress f_y= 220 MPa is adopted for describing the elasto-plastic behaviour of steel. The Kent-Scott-Park model (Kent & Park 1971) with degraded linear unloading/reloading stiffness and no tensile strength is used in order to describe the constitutive law of existing concrete. The effects of FRP confinement result in increasing the ductility of concrete according to the model mentioned model mentioned in section 2 (Figure 3). Live loads equal to 2.00 kN/m^2 and the permanent ones equal to 5.00 kN/m^2 are applied on the floors, which are considered as rigid diaphragms and simulated by means of elastic trusses.

A Finite Element model is built in OpenSEES (Mazzoni et al., 2006) for simulating the seismic response of the structure under consideration. The fiber approach is used to take into account mechanical non-linearity modelling either beams, columns or steel bracings with the so-called *“nonlinearbeamcolumn”* element and considering five integration sections (Gauss-Lobatto quadrature points) for each element. Moreover, concentric steel bracings in structure-level interventions are modelled by introducing an accidental eccentricity in the middle of each brace evaluated according to EN 1993-1-1 (2005). Such a simulation allows to properly reproduce the buckling response of the bracing in compression.

Figure 6 depicts the outcome of the proposed algorithm throughout the generations: the objective (initial cost) function starts from 156’481 € and decreases progressively. As expected, the curve shows a very steep slope over the initial generations and a slow reduction, often characterised by a staircase shape, towards the final convergence, which is supposed to be achieved after 150 generations. It is worth to highlight that no further improvements are observed in f(x) over the last 15 iterations.

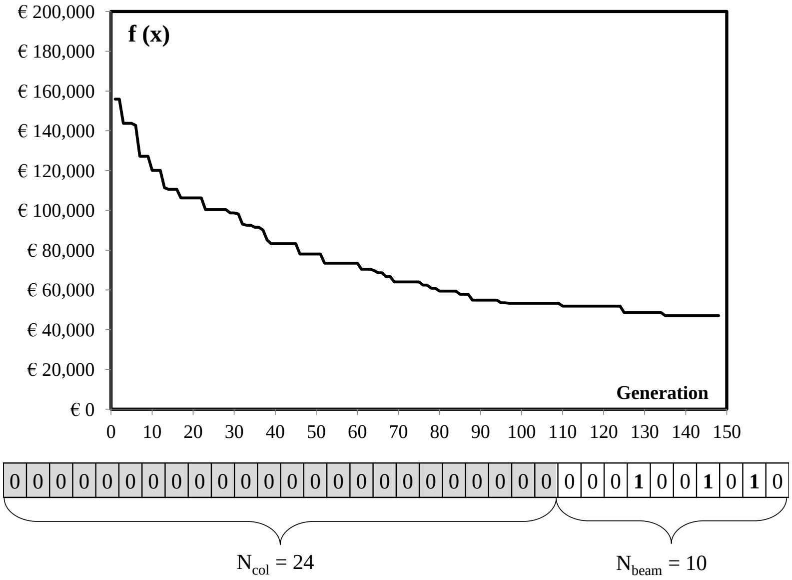

Figure 6. Convergence history and optimal phenotype solution in the last population

Finally, the optimal phenotype selected within the 150th population is characterised by s direct cost of 43’703 €. Specifically, it came up to consist of three concentric steel bracing (one realised in the plain frame along the x-direction and two along the y-direction) and no local FRP interventions (Fig. 7).

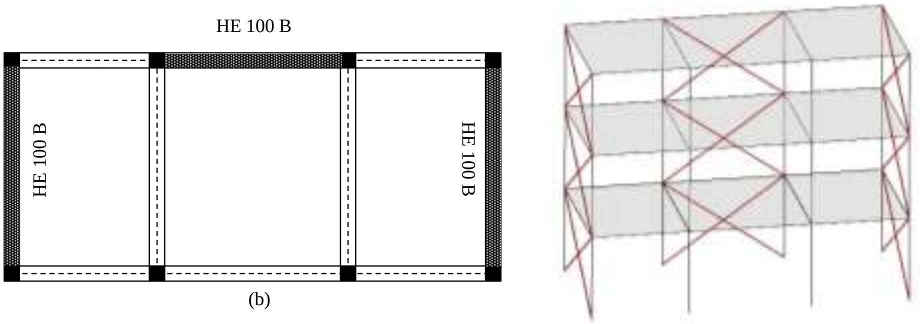

Figure 7. In-plain configuration and 3D view of the optimal retrofitting solution

The optimal section of steel members for the first level of the bracing system is HE 100 B along both x and y-direction. Such a section is the smaller one included within the list of steel sections implemented in the procedure and potentially available for designing retrofitting interventions.

4 CONCLUSIONS

This paper has outlined a general procedure based on a genetic algorithm intended at optimising seismic retrofitting of existing structures by combining member- and structure-level techniques. The proposed genetic algorithm has the potential to support engineering judgement (being far from the ambition to replace it) in determining the “fittest” seismic retrofitting solution for RC frames. The sample application herein reported demonstrates that the implemented procedure is capable of finding a solution characterised by a cost significantly lower than the initially assumed trial solution. Nevertheless, the implementation of this numerical model is still under development taking into account the following final remarks:

- the GA parameters should be tuned according the problem under consideration;
- the optimal retrofitting solution could be different if other aspects are considered;
- the influence of seismic safety and actual cost of intervention on the final practioner’s decision could be handled by Analytic Hierarchy Process;
- the computational time cost is one of the critical issues and mainly depends on the accuracy of seismic analysis.

Therefore, current commitments are also aimed at enhancing the computational efficiency of the computer procedure to be actually feasible in real applications.

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