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Procedia Manufacturing 44 (2020) 639–646

Procedia MANUFACTURING

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1st International Conference on Optimization-Driven Architectural Design (OPTARCH 2019)

Optimal design algorithm for seismic retrofitting of RC columns with steel jacketing technique

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Abstract

Steel jacketing (SJ) of beams and columns is widely employed as retrofitting technique to provide additional deformation and strength capacity to existing reinforced concrete (RC) frame structures. The latter are many times designed without considering seismic loads, or present inadequate seismic detailing. The use of SJ is generally associated with non-negligible costs depending on the amount of structural work and non-structural manufacturing and materials. Moreover, this kind of intervention results in noticeable downtime for the building. This paper presents a new optimization framework which is aimed at obtaining minimization of retrofitting costs by optimizing the position and the amount of steel jacketing retrofitting. The proposed methodology is applied to the case study of a 3D RC frame realized in OpenSEES and handled within the framework of a genetic algorithm. The algorithm iterates geometric and mechanical parameters configurations, based on the outcomes of static pushover analysis, in order to match the optimal retrofitting solution, intended as the one minimizing the costs and, at the same time, maintaining a specified safety level. Results of the proposed framework will provide optimized location and amount of steel-jacketing reinforcement. It is finally shown that the use of engineering optimization methods can be effectively used to limit retrofitting costs without a substantial modification of structural safety.

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10.1016/j.promfg.2020.02.245

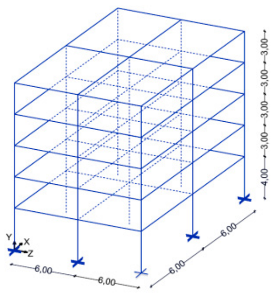
1. Introduction

Steel jacketing is a widely employed technique to improve strength and deformation capacity reinforced concrete (RC) elements presenting critical conditions with respect to seismic and gravity loads condition Steel jacketing of columns is arranged in two possible ways. The first provides a full connection between the steel cage and the slab. In this case, besides the confinement effect, additional flexural strength is provided. For the cases in which full connections are not simple to be realized, steel jacketing is arranged by simply providing the cages. Also in this case a some additional flexural resistance is provided because of friction [1], but the most significant effect is related to the increase of column deformation capacity as consequence of confinement. Experimental and numerical investigations have been carried out by researches for both for the first typology of arrangement (e.g. [2-4]) and for the second one (e.g. [1,6-9]). Despite the effectiveness, it must be also said that steel jacketing is an invasive strengthening technique. In fact, its application to columns provides demolition and reconstitution of portions of masonry infills and plaster. Structural optimization is widely recognized as a valuable computational tool allowing engineers identifying cost-effective design solutions controlling design parameters, and several seismic design optimization applications for steel and RC structures are available in the literature (e.g. [10-17]). At the same time, the issue of the optimization of retrofitting interventions for RC structures has not been investigated many times in the past. Available studies are focused on the optimization of carbon fiber reinforcement of concrete slabs [18] or FRP wrapping [19]. Based on these premises, this paper presents an optimization framework addressing at the individuation of optimal steel jacketing configurations for RC columns in terms of reinforcement location (topological optimization) and spacing between battens. The optimization framework connects Matlab ® genetic algorithm (GA) optimization tool, with a 3D model realized in OpenSEES [20]. The application of the optimization framework will show the minimization of the retrofitting costs, driven by the results by the pushover assessment.

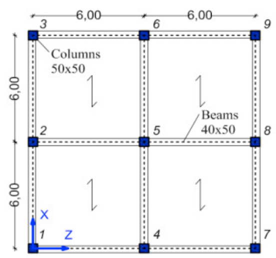
2. Case study

2.1. Overall properties and design details

The case study building is five-storey two-bays RC frame which is not designed to resist seismic loads. The structure (Fig. 1a) is symmetric in plan along the two orthogonal directions. Dimensions in plan are shown in Fig. 1b together with details of beams and columns. It is assumed that the structure is arranged with poor resistance concrete (f_{c0m}=20 MPa), while steel rebars have average nominal yielding strength f_y=455 MPa. Beams are realized with 4+4 ϕ 18, columns are realized with 12 ϕ18 distributed along sides. Stirrup have 6 mm diameter and 200 mm specing. As regards site seismic hazards, the building is supposed to be located in Cosenza (Italy), soil type C. The nominal life (V_N) is 100 years. The resulting return period is T_R=975 years. The RC frame is modelled with distributed plasticity fiber-section elements (beams and columns). Vertical loads are assigned as point loads at the top of columns, depending on the respective tributary areas. The total weight of each floor is 1440 kN. The cross-section fibers are modelled with a "Concrete02" uniaxial material model. For the sake of simplicity, it is supposed that the effect of stirrups on concrete confinement is extended to the whole cross-section. Parameters of concrete confined only by stirrups (f_{c0}, f_{cu}, ε_{c0}, ε_{cu}) are evaluated by using the stress-strain model by Razvi and Saatcioglu (1992) [22, 23]. Steel rebars are modelled using a "Steel02" material with yielding stress f_y=455 MPa. The hardening ratio is set equal to b=0.01 as commonly done in other studies [24,26].



a)



b)

Fig. 1. Geometrical dimensions of the case study structure: (a) 3D frame view; (b) dimensions in plan.

2.2. Modelling of confinement by steel jacketing

It is assuming that steel jacketing of columns is realized without providing moment resisting connection at the top and the bottom of the columns, while frictional effects [1] are neglected. The effect of steel jacketing is then introduced in the retrofitted columns only as confinement, by a simple modification of the stress-strain curve of concrete (Fig. 2a). Concrete02 material model is again used for the concrete fibers involved by steel jacketing confining action. The approach by Montuori and Piluso (2009) [3] combined with the with the expressions provided by Razvi and Saatcioglu (1992) [22] are used to evaluate peak (f_{cc}, ε_{cc}) and ultimate ($f_{ccu}, \varepsilon_{ccu}$) stress and strain values. The model by Montuori and Piluso (2009) which provides a unique stress-strain law for the entire section. The model has been implemented in the TCL OpenSEES script, therefore, any modification of the reinforcement configuration automatically accounted by the Concrete02 uniaxial material during the optimization.

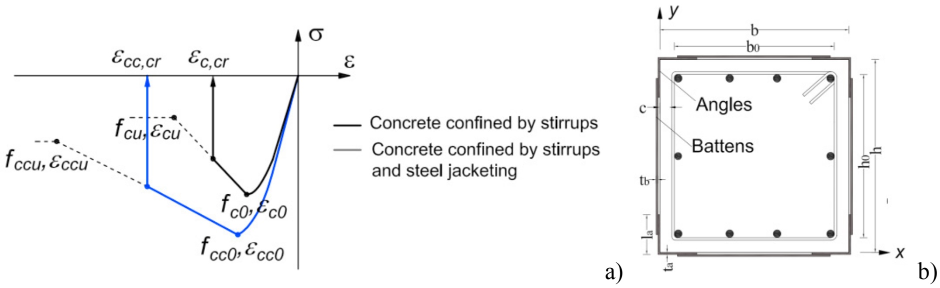


Fig. 2. (a) Confined concrete models for the fiber cross-section with and without steel jacketing reinforcement; (b) Configuration of the cross-section of a column reinforced by steel jacketing.

3. Proposed optimization framework

3.1. Basic principles

In the current study, the Matlab ® genetic algorithm (GA) is used in combination with OpeeSEES to minimize retrofitting costs as a function of the pre-defined design variables associated with the steel jacketing reinforcement. The GA generates a population of individuals [27,28]. Each individual represents a different possible combination of the design variables. The initial population is generated randomly by default. The subsequent generations are generated using the fitness values (evaluating the objective function) of the individuals in the previous generation. The performance of each individual is evaluated by carrying out a pushover analysis [29,30] and computing the ratio between ductility capacity and demand (μ_c/μ_d) and the associated retrofitting cost. The retrofitting cost is eventually incremented by a penalty values if the solution is unfeasible (μ_c/μ_d <1). The GA will combine the individuals presenting the better fitness values for each generation.

3.2. Design optimization variables

For the current case study, the following simplified assumptions are made:

- Retrofitted columns can be only located within the first the second floor.
- A uniform pushover lateral forces profile is applied only in one direction;

Moreover, the following design assumption are given:

- Steel angles are constituted by L-shaped steel profiles having lateral length l_a=100 mm and thickness t_a=5mm.
- The thickness of the battens t_b is 5 mm, the width w_b is 50 mm.
- The minimum and maximum spacings between the battens are 150 and 400 mm respectively.
- The design yielding strength of steel angles and battens is f_{yb}=275 MPa.
- The central columns (position 5 in Fig. 1b) at the first and second floor are always retrofitted.

Based on these assumptions, the design variables are the position of the retrofitted column (within the first two floors) and the spacing between the stirrups. The design vector (***b***) is then defined as follows:

$$\boldsymbol{b} = \begin{pmatrix} s_b \\ \boldsymbol{p} \end{pmatrix} \tag{1}$$

where s_b is a scalar belonging to the interval $S= [140 \;\; 400]$, while ***p*** is a 16x1 vector collecting the positions of the columns at the first two floor (excluding the central ones) having the following form:

$$\boldsymbol{p} = [c_{11} \;\; c_{21} \;\; c_{31} \;\; c_{41} \;\; c_{61} \;\; c_{71} \;\; c_{81} \;\; c_{91} \;\; c_{12} \;\; c_{22} \;\; c_{32} \;\; c_{42} \;\; c_{62} \;\; c_{72} \;\; c_{82} \;\; c_{92}]^T \tag{2}$$

Within the optimization process the GA generates the population of individuals by assigning the elements of the ***b*** vector. This results in a list of data read by the TCL script which builds the model. The pushover analysis is then started. Results are processed as described in the subsequent section.

3.3. Assessment of feasibility through pushover analysis

Pushover curves obtained from each individual are processed in the framework of the N2 method [21] in order to determine the capacity / demand ductility ratios. The following well-known relationships are used to evaluates the ductility demand (μ_d):

$$\begin{cases} \mu_d = (q^* - 1)\dfrac{T_C}{T^*} + 1 & (T^* \le T_C) \\ \mu_d = q^* & (T^* > T_C) \end{cases} \tag{3}$$

in which T^* is the period of the equivalent SDOF system having mass m^* and stiffness k^*. The latter is evaluated from the bilinearized capacity curve, therefore:

$$T^* = 2\pi\sqrt{\frac{m^*}{k^*}} \;; \quad k^* = \frac{F_y^*}{d_y^*} \tag{4}$$

Finally, q^* is the reduction factor, obtained as the ratio between the force requested to the ideally elastic SDOF and the yielding force:

$$q^* = \frac{S_{ae}(T^*)m^*}{F_y^*} \tag{5}$$

On the other hand, the ductility capacity (μ_c) is the ratio between the ultimate displacement capacity and the yielding capacity of the bilinear curve. Hence:

$$\mu_c = \frac{d_u^*}{d_y^*} \tag{6}$$

The capacity / demand ratio (ξ_μ) is finally defined as:

$$\xi_\mu = \frac{\mu_c}{\mu_d} \tag{7}$$

3.4. Objective function and penalty function

The objective function evaluates the retrofitting costs which are intended as the material costs and the manpower costs to realize column steel jacketing (C_{SJ}) and necessary works on plasters and masonry (C_M). The general form of the objective is then:

$$C = C_M + C_{SJ} \tag{8}$$

In the current study C_M has been estimated considering a fixed cost (c_m) of 2000 € per reinforced column, therefore:

$$C_M = n_c c_m \tag{9}$$

where n_c is the number of retrofitted columns. As regards C_{SJ}, this is evaluated as:

$$C_{SJ} = n_c W_{s,T} c_s \tag{10}$$

where W_S is the total weight of steel used to arrange the cage and c_s is the manpower and material cost per unit weight (4.5 €/m^3). The weight of each steel cage is therefore:

$$W_{s,T} = (V_{a,T} + V_{b,T})\gamma_s \tag{11}$$

in which γ_s is the specific weight of steel, $V_{a,T}$ is the total volume of steel angles, and $V_{b,T}$ the total volume of battens, which depends of their spacing as follows:

$$V_{b,T} = 4V_b\left(\frac{l_c}{s_b}\right) \tag{12}$$

In Eq. (12) V_b is the volume of a single batten and l_c is the length of the column. The GA minimizes retrofitting costs operating on the number of retrofitted columns (n_c) and the spacing between the battens (s_b).Within the optimization process, the feasibility of a solution is represented by the capacity / demand ratio (ξ_μ), determined as illustrated in the previous section. In order to introduce feasibility into fitness of a solution, a penalty function is assigned to consider the violation of a constraint. This is simply done by attributing a penalization of the fitness values if a solution is not feasible. This can be done by changing the objective function (C) into the function F as follows:

$$F = C + \Pi \tag{13}$$

where Π is the penalty function assuming the following values:

$$\Pi = \begin{cases} 0 & (\xi_\mu \geq 1) \\ C_{max}\left(\dfrac{1}{\xi_\mu}\right)^3 & (\xi_\mu < 1) \end{cases} \tag{14}$$

where C_{max} is the maximum possible retrofitting cost (reinforcement of all first and second floor columns with s_b=150 mm).

4. Results of the optimization for the case study

4.1. Preliminary investigation

In order to get some reference points with respect to the final solution obtainable by the optimization algorithm, the case study structure has been tested without any retrofit and under different trial retrofitting configuration. The five preliminary tests provided the following retrofitting configurations:

- Test 1: No retrofitting (as built);
- Test 2: Retrofitting of all 1st and 2nd floor column with s_b=150 mm;
- Test 3: Retrofitting of all 1st floor columns and 2nd floor central column with s_b=150 mm;
- Test 4: Retrofitting of all 1st floor and 2nd floor central columns with s_b=250 mm and
- Test 5: Retrofitting of all 1st floor and 2nd floor corner columns and 1st floor and 2nd floor central column with s_b=250 mm.

Results of the tests are illustrated in Fig. 3 in terms of total base shear against top displacement. Results in obtained for the ductility capacity/demand ratio and retrofitting costs are instead listed in Table 1. From the preliminary tests it can be observed that the unreinforced structure (Test 1) has low displacement capacity and suffers a significant load drop (Fig. 3a). The overall retrofitting of the first and second floor (Test 2, Fig. 3b) significantly improved seismic behaviour (ξ_μ = 1.72) but was associated with noticeable retrofitting cost (51,578 €). The reinforcement of all the columns of the first floor (Test 3, Fig. 3c) was not sufficient to pass the verification check. Finally, it was observed that more effective results were found by retrofitting specific columns at the first and the second floor (Tests 4 and 5, Figs. 3d, 4e).

Table 1. Preliminary tests results

Test	μ_d (-)	μ_c (-)	ξ_μ (-)	s_b (mm)	n_c	C (€)	Verif. check
1	3.120	2.470	0.792	-	0	-	No
2	2.450	4.220	1.722	150	18	51,578 €	Yes
3	2.451	2.280	0.931	150	10	28,654 €	No
4	2.815	2.748	0.976	250	10	27,170 €	No
5	3.125	3.220	1.030	250	10	27,170 €	Yes

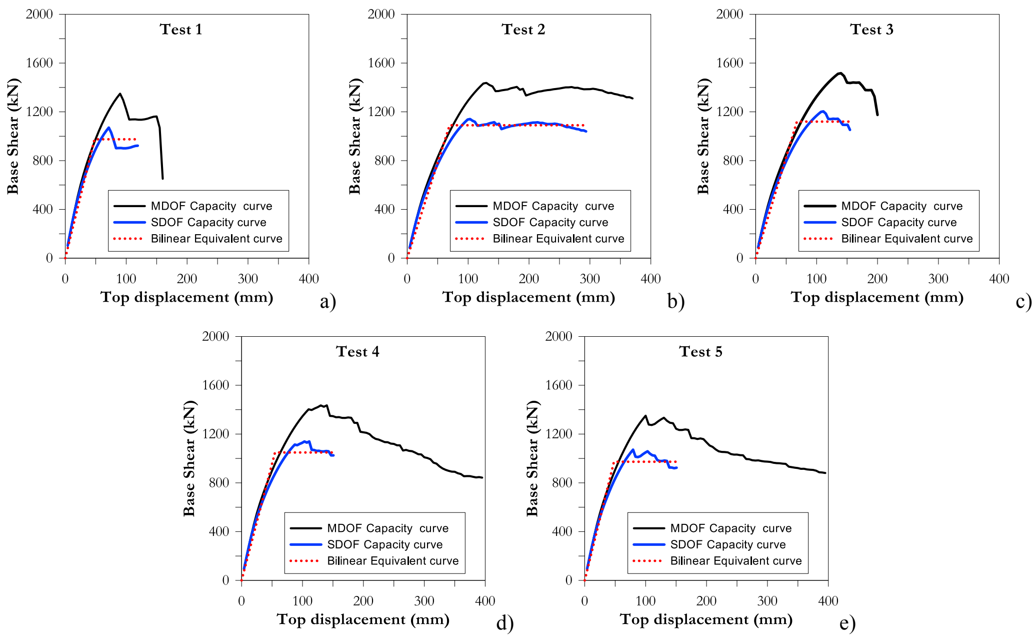


Fig. 3. Preliminary Tests: (a) Test 1; (b) Test (2); (c) Test (3); (d) Test (4); (e) Test (5);

4.2. Results of the optimization

The optimization carried out for the reference case study has shown the convergence history illustrated in Fig. 4a, where iterations (generation) are reported against the fitness value obtained from Eq. 14. It can be observed that the algorithm tends to a stable solution after about 850 generations of individuals. Similarly Fig. 4b shows the history of the capacity / demand ratio (ξ_μ) coefficients over the generations. It can be noted that the GA starts finding feasible solutions (on average) after 600 iterations and also that ξ_μ approaches to values close to 1 by going ahead with the iterations. This indicates that optimized solutions are also associated with a major exploitation of the retrofitting intervention.

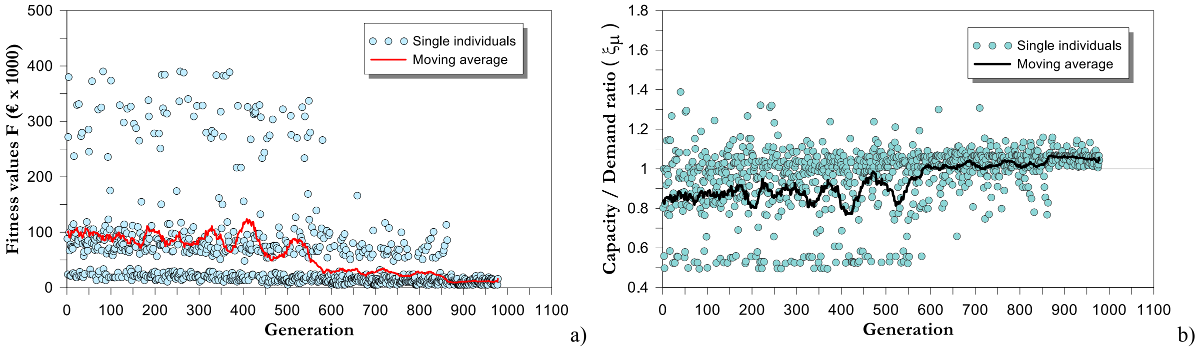


Fig. 4. (a) Convergence history of the cost value on the penalized objective function; (b) History of the capacity / demand ratio (ξ_{μ}) values over the generations.

The optimal solution, found at iteration 821, and provides retrofitting of central columns 2 and 8 **(**Fig. 1b**)** at the first storey (besides the central internal column at the first and the second storey) with a batten spacing of 250 mm. The resulting ξ_{μ} is 1.014. This solution is found considering a pushover force profile acting along *Z* positive direction. Given that the structure has polar symmetry it is simply is supposed to retrofit in the same way column 6 and 4 in order to face seismic demand along *X* direction. The so defined optimal configuration of reinforcement pushover response is shown in Figs. 5a and 5b. The finally obtained capacity demand ratio is ξ_{μ} =1.01, while the overall cost of the intervention is 16,302 €. It should be finally observed that the obtained cost is reduced by 40% with respect to the best solution found in the preliminary tests. However, in the face of this, obtained ξ_{μ} factors remain in the same order of magnitude.

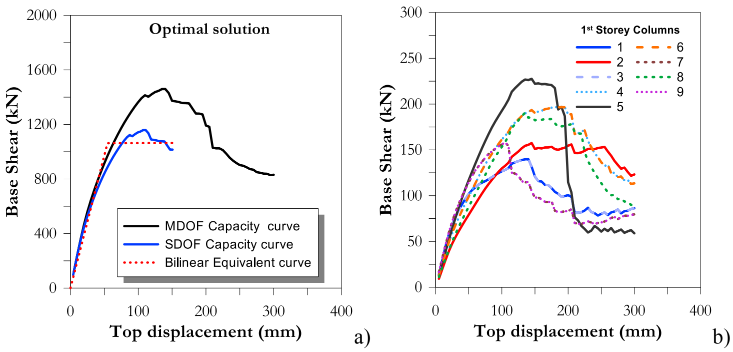


Fig. 5. Optimal solution: (a) MDOF and SDOF capacity curves. (b) First storey columns capacity curves.

4. Conclusions

The paper has presented a new optimization framework aimed at minimizing steel jacketing retrofitting intervention costs for columns of reinforced concrete frame structures. The method is associated with the use of nonlinear static analysis (pushover) as assessment procedure, in combination with N2 method. The optimization strategy used a genetic algorithm to minimize the costs of the intervention, operating on the number of reinforced columns and the spacing of battens. The GA was automatically connected to an interactive 3D fiber-section model of the structure realized in OpenSEES. Results have shown that the effectiveness of the proposed methodology. The optimal solution was characterized by a significant reduction of the retrofitting costs, associated with a capacity / demand ratio close to the unit. The current approach has been tested on a very simple frame structure, however, for larger RC structures having a significant number of columns, it expected to get noticeable advantages in terms of economical of and downtime costs.

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