Comparison of optimization methods for retrofit placement in a non-code conforming reinforce-concrete structure

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SUMMARY:
This paper discusses the suitability of two optimization methods for use in seismic retrofit location selection. The structure for analysis is modelled after a seven story RC structure in California, USA, built according to 1964 Los Angeles City Building Code. The OpenSees parallel computing software package is used to model the dynamic behaviour of a test structure. Past earthquake records are scaled to a seismic hazard level appropriate for the site. MATLAB is used to interface the optimization methods with the model. The optimization methods applied and compared are genetic algorithm and sequential search method. The objective function used accounts for performance-based principles, measured with inter-story drift, and cost, measured by the number of retrofits applied. Results of the optimization methods are compared and discussed with regard to the quality of the solution and the number of simulations required.

Keywords: Seismic retrofit, optimization, performance

1. INTRODUCTION

The 2010 Haiti earthquake has resulted in billions of dollars of economic losses, millions of people displaced and thousands of lives lost (Cavallo, 2010). The 2010 Chilean earthquake, while resulting in large economic losses, had significantly fewer casualties (EERI, 2010). These earthquakes highlight the improvements of modern seismic design over past practices. While the improved standards apply to new structures, many structures built to previous standards are vulnerable to heavy damage or collapse during a seismic event. In some rare cases, a complete tear-down of the structure may be necessary. Much more often, due to cost or cultural considerations, a seismic retrofit is a more suitable option. Many retrofitting techniques have been studied in literature (e.g. FEMA 356; Housner, 1997; Thermou & Elnashi, 2006). Most conventional methods of retrofit add to the lateral strength of the structure (e.g. Steel braces) or improve the ductility of the existing elements (e.g. FRP wrap). More advanced methods seek to dynamically modify the frequency and energy dissipation property of the structure (e.g. mass, viscous, and friction dampers).

The resources available to apply the required retrofits are often limited, especially with a large scale building or city wide retrofit plan. Thus, it is useful to determine the retrofit locations that would provide the most improvement to the structure at the least cost, while still satisfying any minimum performance requirements. Traditionally, engineering judgement has been used to develop a retrofit scheme that is then tested in a simulation or through experiments to determine the effect on the structure. If the performance of the scheme is insufficient, a new scheme is developed and the process is repeated. With improvements in simulation software and computing power, simulations are now performed fast enough such that advanced optimization methods are practically applied to structural problems (Vanderplaats, 1981; Thanedar & Vanderplaats, 1995).

Burns (2002) provides extensive discussion on different types of problems in structural optimization and a number of optimization methods appropriate for each case. For the case of seismic retrofitting of structures, a number of possibilities are eliminated. The non-linear nature of structure response during an earthquake eliminates any methods that rely on the linearity of the problem. Due to the complex nature of the structural response, obtaining a derivative of the function is not possible, thus eliminating another set of optimization methods. For some structural optimization problems, such as member size or material strength, the variables are continuous but seismic retrofit is generally a discrete optimization problem. Additionally, the discrete variables are not defined outside of the feasible solutions; the retrofit is either applied to a location or not, this is contrary to problems such as where a steel plate of 10mm or 15mm is available but using 11mm in the simulation will still provide a solution. Due to the nature of seismic retrofit location optimization, the appropriate solution algorithms are limited. A review of methods that have been applied to structure and retrofit optimization is presented in the following paragraph.

Agrawal & Yang (1999) applied three search methods to a problem of passive damper placement for seismic and wind loads. A number of different objective equations (including terms for energy, damping ratio, and inter story drift) were used to generate optimized damper locations. Ganzerli et al. (2000) included the concepts of performance-based design in the optimization of a simplified structure subject to earthquake loading. Abdullah et al. (2001) used GAs to select placement of sensor/actuator pairs in a 40-story elastic structure with three input earthquake records. Yan & Yam (2002) applied GAs to select actuator locations in a 72-bar space truss for vibration control. Martinez-Rodrigo & Romero (2003) developed performance indices to be used to evaluate viscous damper retrofit strategies and select the best strategy. Dargush & Sant (2005) presented a GA for optimizing retrofitting type and location for structures with vertical stiffness irregularities. Lavan & Levy (2005) used a gradient based method to determine the optimized damping coefficients of a 10-story elastic structure with dampers placed on every floor. Perez & Behdinan (2007) applied a particle swarm optimization method to three benchmark truss design problems. Apostolakis & Dargush (2009) used a GA to select placement of passive dampers in a non-linear three-story steel moment-resisting frame structure subject to seismic time-history analysis. Sung & Su (2010) augmented the GA method with the use of fuzzy logic control to adapt the GA. Bigdeli et al. (2011) applied a variety of optimization methods to select optimal damper locations for the pounding problem in two adjacent structures.

In this paper, a combination of simulation and optimization is used to compare the suitability of two optimization methods (GA and sequential search) for application in retrofit location selection. A seismically deficient structure is simulated in the OpenSees software platform and the optimization methods are used to generate optimized retrofit schemes. The effectiveness of the two methods in generating a successful retrofit scheme, both in terms of calculation time and structure performance, will be discussed.

2. OPTIMIZATION

An optimization problem entails consideration of objective functions and constraints. The general form of an optimization problem is shown in Eqn. 2.1. The objective function, f, measures the quality of the solution and is generally minimized. Constraints can also be applied to the optimization definition with defined functions that disallow certain solutions or with softer, influencing parameters that penalize undesired solutions. When applied to structural performance problems, the objective function often acts more as a black box function; the input parameters are given to the simulation system and some output vales are used to calculate the objective value. It is important to select the output data that is appropriate for the case that is being tested.

$$\min F = f\left(x_1, x_{2,} ..., x_n\right) \tag{2.1}$$

For this paper, two optimization algorithms, GA and sequential search, will be used for optimizing seismic retrofit. The proposed procedure is shown in Figure 1.

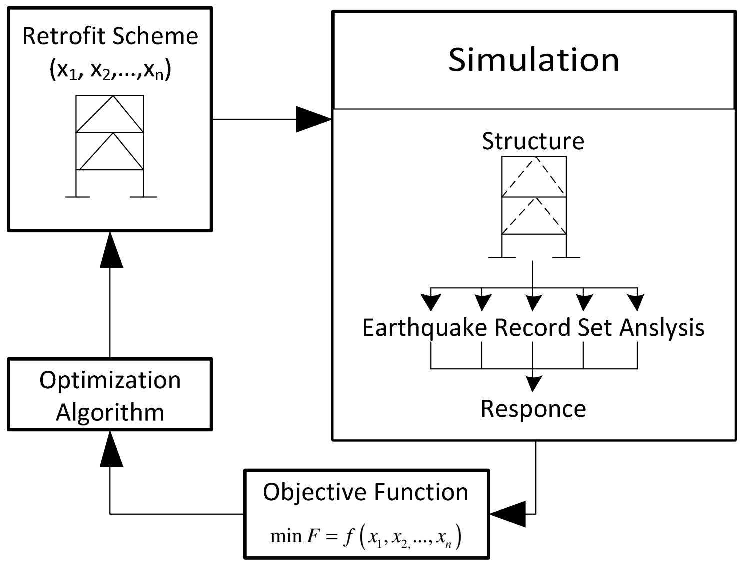

Figure 1: Optimization process

2.1. Genetic Algorithm

GAs are a commonly used optimization technique used to solve a wide variety of engineering problems (e.g. Rajeev & Krishnamoorthy, 1992; Abdullah et al. 2001; Burns 2002; Yan & Yam 2002; Apostolakis & Dargush 2009). This method is based on the behaviour of natural evolution. A general description of GA is given below:

- Randomly generate an initial set of possible solutions.
- Test each solution determine the objective function score.
- Rank solutions based on score.
- Combine and modify the most successful solutions in a semi-random manner to create a new set of solutions.
- Test the new set of solutions repeat the process.

This method has been used, partly, because of its ability to provide an optimized solution in a relatively short computational time. Due to the randomized nature of the GA, there is no guarantee that a global, or even local, optimum solution will ever be found (Burns 2002). While GAs are not guaranteed to find an optimum, the ability to provide a much improved solution in a reasonable amount of time is the main benefit of the GA. For the problem of retrofit location, the possible locations can be coded into a binary string with each variable in the string representing a single location.

GAs have many parameters that must be selected such as population size, generation size, mutation probability, and combination and generation methods. Goldberg et al. (1991) and Burns (2002) provide discussion on the appropriate population and generation sizes. The choice of parameters greatly impacts the number of simulations required and how quickly an optimal solution is selected.

2.2. Sequential Search

The sequential search method is a type of greedy algorithm that makes the locally optimal decision at any given step. This method has been has been used for simplified systems similar to retrofit location selection problems (Agrawal & Yang, 1999; Bigdeli et al. 2011). Due to the nature of the algorithm, a global optimum solution is not guaranteed but the solution will be locally optimal. This is partly due to the more structured approach of this algorithm and less randomness in the generation of potential solutions.

For the specific retrofit location optimization problem, with n retrofit locations and n_r maximum retrofits, a sequential search would proceed as follows:

- Given the base test structure, the n locations are tested with a single retrofit in each.
- The best location of those tested is selected and a retrofit is placed there.
- The remaining (n-1) locations are tested by adding a single retrofit to each.
- The best location of those remaining is selected.
- The process is repeated until all of the retrofits have been placed, or adding more retrofits will not improve the objective function.

This method provides a much more systematic approach to finding an optimised solution. Another advantage of a sequential search is that, in the simplest case, there are no optimization method parameters to select or adjust. Due to the structured nature of this method, the number of simulations required can be determined. The number of required simulations can be calculated as shown in Eqn. 2.2.

$$\begin{aligned} N &= n + (n-1) + \ldots + (n - (n_r - 1)) \\ &= nn_r + n_r - \left(\frac{n_r^2 + n_r}{2} \right) \end{aligned} \tag{2.2}$$

3. STRUCTURE AND SIMULATION

The optimization method will be illustrated with an RC building reported in Krawinkler (2005). This structure is a seven story hotel built in Van Nuys, California, USA. This building was constructed in 1965 according to the 1964 Los Angeles City Building Code. The building is 7 storeys, 8 bays by 3 bays, RC moment resisting frame. The report includes many of the design and material properties of the building such as reinforcement detailing and concrete strength. This building is useful because it represented current practise at the time of construction and is seismically deficient according to current design codes.

The simulation of the Van Nuys hotel was completed in the OpenSees software platform[1]. This open source software is supported by the Pacific Earthquake Engineering Research Center (PEER) and the George E. Brown, Jr. Network for Earthquake Engineering Simulation (NEES) and is designed specifically to model a structure's performance during an earthquake and provide meaningful results (McKenna et al. 2006). The structural elements were modelled as lumped plasticity elements.

One of the reasons this software was chosen was its ability to interact with other programs. The software is able to read from input files to change the structure depending on what is required. Also, the results of the simulation are easily exported to files that can be accessed by other programs and used for further calculation. This level of available communication allows the OpenSees platform to be used as a black-box system allowing different optimization methods to be applied to the same simulation structure without significant one-off development. Additionally, once a preferred optimization method is selected, different structures and retrofit techniques can be optimized through a similar framework.

To improve the overall calculation time of the simulation, a parallel computing version of the

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[1] http://opensees.berkeley.edu

OpenSees software was used (McKenna & Fenves, 2006, 2008). The non-parallel software performs the analysis of the structure with each earthquake record and resetting the state of the structure before applying the next earthquake record. The parallel version of the software allows several instances of the structure to be generated and different earthquake records are applied to each instance simultaneously. Modern computer hardware with multiple available CPU cores is needed to accomplish this parallelization.

To determine the performance of a seismic retrofit scheme, it is necessary to test the structure against earthquake ground motions. The test set of ground motions need to accurately represent the risk level and motion properties for a given location. Due to the large number of available ground motion records, FEMA P695 provides a set of twenty-two ground motions that represent a wide variety of fault types and seismic properties. The ground motion records applied to the structure model were based on the FEMA P695 record set and scaled to the USGS UHS for California using SeismoMatch software[2]. To illustrate the damage vulnerability in the test structure, a hazard level of 10%/50 years probability of exceedence was chosen (see Figure 2). This lower hazard level was selected due to the vulnerability of the test structure; a higher intensity level would have required extensive retrofit for even relatively low performance objectives. The lower intensity level results in a severely damaged structure, but one that allows for some variability in the location and extent of the retrofits selected.

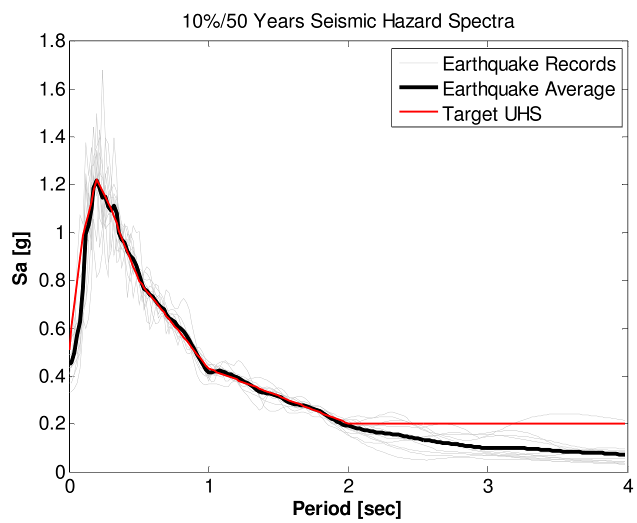

Figure 2: Ground motion records scaled to the target UHS

3.1. Objective function

For this problem, an objective function was selected that incorporated both the performance of the structure and a retrofit cost parameter. The objective function (see Eqn. 3.3) quantifies the performance by including the maximum inter-story drift ratio (MISDR), d_{max} (%). The performance is averaged over a set of earthquake records selected from FEMA P695 that are numbered from 1 to n_{EQ}. The number of applied retrofits, (n_r), is used as a proportional cost measure. The penalty factors (P_{LS}, P_{CP}) shown in Eqns. 3.4, and 3.5 were selected based on the FEMA 356 performance-based design principles. The 'life safety' and 'collapse prevention' performance levels correspond to a MISDR of 1.5% and 2.5%, respectively, and if the drift is beyond these limits, the objective function is penalized.

[2] http://www.seismosoft.com

$$\min F = \left(\frac{\left(\frac{\sum_{i=1}^{n_{EQ}} d_{\max,i}}{n_{EQ}} \right)}{2.5} + \frac{n_r}{56} \right) \cdot p_{LS} \cdot p_{CP} \tag{3.1}$$

$$p_{LS} = \begin{cases} 1, & \text{if } d_{\max} < 1.5 \\ 1.5, & \text{if } d_{\max} >= 1.5 \end{cases} \tag{3.2}$$

$$p_{CP} = \begin{cases} 1, & \text{if } d_{\max} < 2.5 \\ 2, & \text{if } d_{\max} >= 2.5 \end{cases} \tag{3.3}$$

4. RESULTS

As a baseline study, the base structure with no retrofits resulted in an objective function value F = 3.40 and a MISDR = 2.8%. The structure is clearly deficient and in need of retrofitting. These numbers are provided as a means of comparison to the following results.

Initially, the sequential search algorithm completed with only two retrofits placed in the structure, resulting in an objective function value F = 1.40 and a MISDR = 2.25%. Upon investigation, it was clear the algorithm had stopped at a local minimum. The algorithm was changed to allow it to continue and possibly find a better solution with subsequent retrofit placements. The algorithm was allowed to proceed to 10 placed retrofits (515 function evaluations) and provided the solution shown in Fig. 4 resulting in an objective function value F = 0.747 and a MISDR = 1.42%. Compared to the base structure, this is a significant improvement as it was able to bring the structure below the life safety performance limit. Figure 3(b) shows the improvement of the algorithm as subsequent retrofits are placed. There was no improvement in the best solution for a number of placements after the second retrofit.

Implementing a simple algorithm like the sequential search has a drawback of also having simple stopping cases. In this case, the algorithm initially stopped after it failed to find any immediate improvement. Additional retrofits did not improve the objective function for a number of retrofit applications but resulted in an improved scheme with a larger number of applications. The basic sequential search algorithm needs improvements in its ability to find solutions outside of local optima.

The optimized solution produced by the GA is shown in Fig. 4. This solution contains 23 retrofitted locations, significantly more than the sequential search algorithm but this also required the maximum number of 900 (30 individuals over 30 generations) function evaluations during the course of the GA. This solution resulted in an objective function value of 0.56 corresponding to a MISDR of 0.39%. While the final optimized solution of the GA required the maximum number of generation, it is also interesting to note the rate of improvement throughout the whole optimization method. Figure 3(a) presents the objective function value of the best solution for each generation. The improvement profile is similar to most GA results; there is significant improvement in early generations followed by much slower, but still steady progress. In this case there were also some large improvements in two of the later generations.

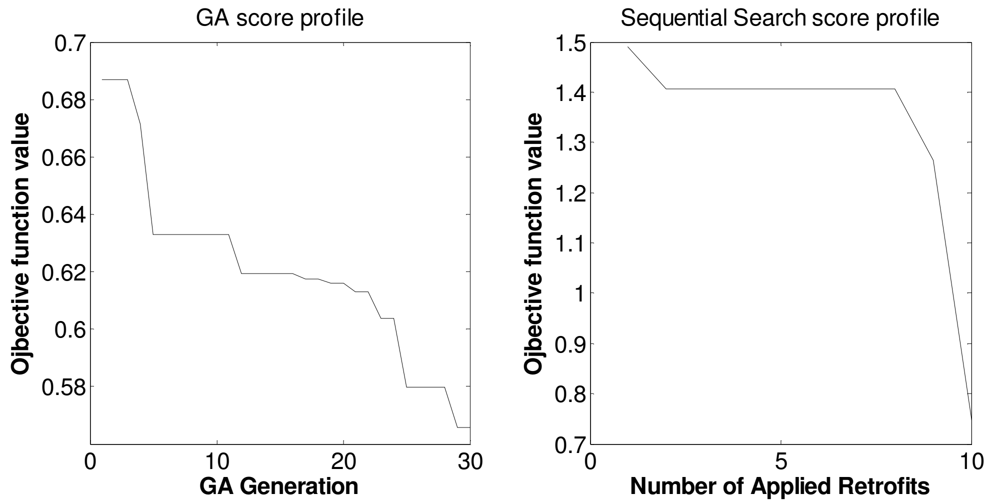

Figure 3: (a) Genetic Algorithm and (b) Sequential Search improvement at each iteration, note the separate vertical axes

It is interesting to note some of the behaviour of the genetic algorithm and how that corresponds to established engineering knowledge. In the second bay from the left of Fig. 4, the applied retrofits are vertically continuous; this matches the idea that vertically continuous retrofits limit any stiffness irregularities and reduces the vulnerability of the structure (FEMA 356). Also, far fewer retrofits are applied to the top story of the structure, matching with the understanding that the upper stories of structure are generally less vulnerable in an earthquake. Increasing the number of generations in the algorithm would increase the chance that these complex factors accounted for in the final solution.

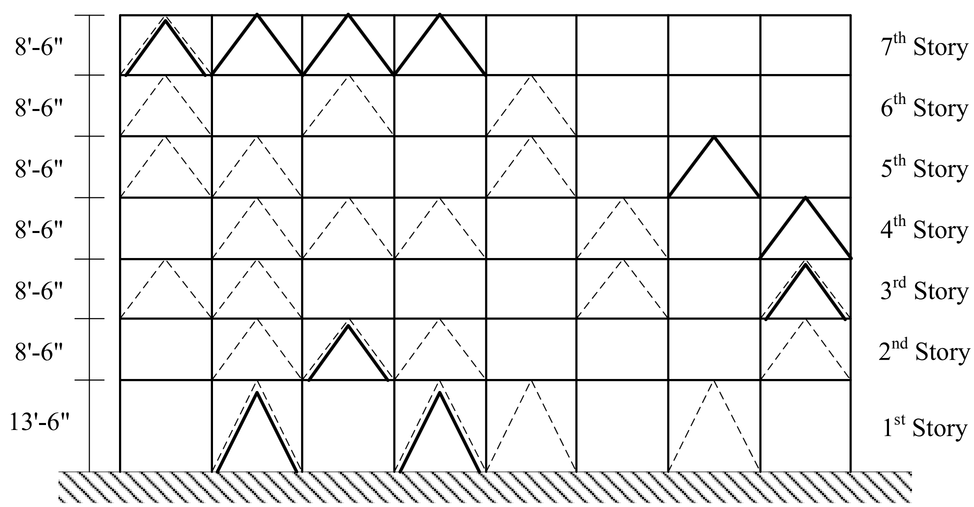

Figure 4: Van Nuys Hotel schematic with Sequential Search (Solid Lines) and Genetic Algorithm (Dashed Lines) optimized retrofit schemes

The GA solution can be compared to some standard retrofit schemes to see the impact of using this particular algorithm. The retrofit schemes and the result are shown in Fig. 5. The figure shows the MISDR for all earthquake records and the objective function value for each retrofit configuration. The central bay retrofit scheme provides strong improvement over the base structure, reducing the drift to meet the life safety performance objective and this scheme has the lowest objective function value because it uses the fewest number of retrofits of the schemes. The exterior bay retrofit scheme provided much improvement over the central bay scheme but required twice as many retrofits to do so.

This resulted in a lower MISDR for most of the earthquake records but a slightly higher objective function. A retrofit scheme was also applied that combined the central and exterior bay schemes, resulting in a structure that is almost entirely retrofitted. This full retrofit scheme resulted is significantly reduced MISDR for all earthquake records and nearly reaching the 'fully operational' performance objective. Due to the large number of retrofits required to reach this level of performance, the objective function value is the highest of the four schemes shown. The scheme generated by the GA shows some improvement over the other schemes. The MISDR is significantly reduced, reaching the 'immediate occupancy' performance objective with fewer retrofit locations than the exterior bay retrofit scheme, resulting in an objective function value that nearly matches the central bay scheme. The GA scheme dominates the exterior bay scheme with better performance and fewer retrofits while still remaining competitive with the other retrofit options.

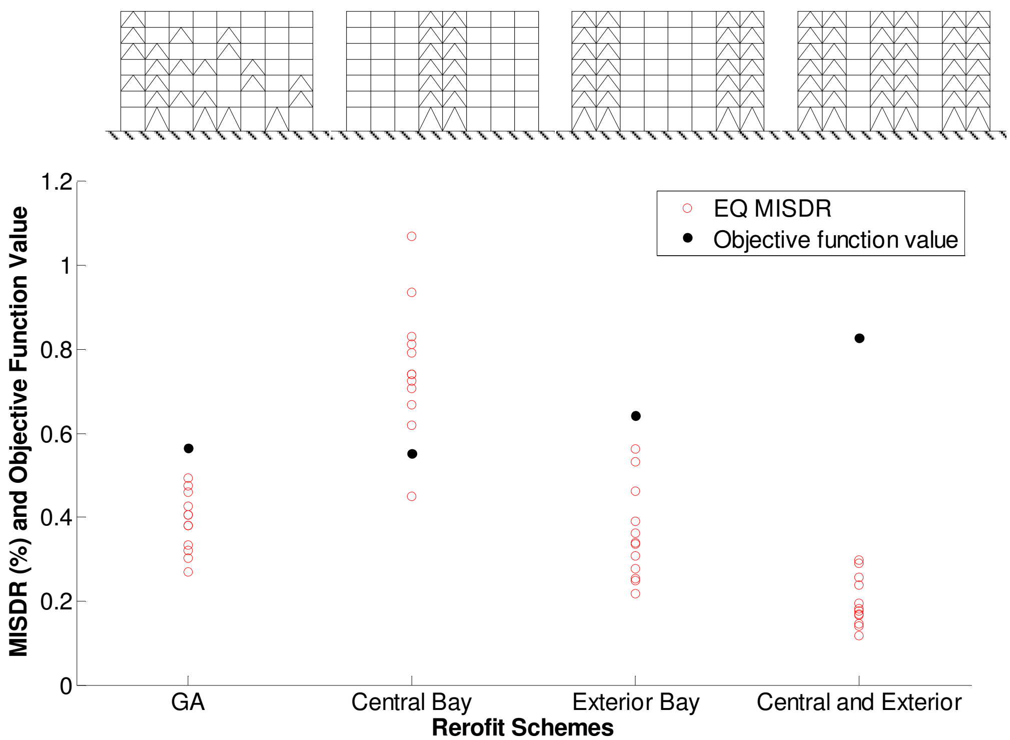

Figure 5: Comparison of Retrofit Scheme Results

5. DISCUSSION AND CONCLUSION

The genetic algorithm was able to generate a retrofit scheme that was equal or superior to several basic retrofit schemes. If the priority balance between performance and cost were to be changed, then the decision of which scheme to apply would change. With a more complex structure, generation of a scheme from engineering expertise would become more difficult while the GA would only require more time to generate a solution that accounted for the complexity of the structure. As the complexity of the problem increases, further use of advanced optimization and computation methods would be required.

The parameters used in the objective function could be improved to more accurately represent the performance of the structure. By using a combined cost of retrofit application and structure damage, a more accurate objective function can be applied (e.g. Koduru and Haukaas, 2010). The improved objective function would also be more applicable to real-world situations as a direct cost estimate could be used for decision making.

Consideration of the computation time is also important for optimization method selection. As parallel computing availability increases, its impact on the practical usage of optimization methods will increase. Simulating multiple earthquake records simultaneously, as was done in this paper, greatly reduced the time to complete the full optimization algorithm. Depending on the structure of the optimization and simulation method chosen, there are many levels where parallel computing concepts could be applied to greatly reduce the overall time for calculation.

Due to the differences in serial and parallel computing, the selection of the best optimization method would depend on the computation facilities available. Additionally, the structure of the problem can impact which optimization method provides the best or fastest solution. Thus, more investigation into different optimization algorithms is required.

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