Optimization as a Tool for Seismic Protection of Structures*

Original
Optimization as a Tool for Seismic Protection of Structures* / Marano, Giuseppe C.; Rosso, Marco M.; Melchiorre, J. (LECTURE NOTES IN CIVIL ENGINEERING). - In: Seismic Isolation, Energy Dissipation and Active Vibration Control of StructuresELETTRONICO. - [s.l] : Springer, 2023. - ISBN 978-3-031-21186-7. - pp. 100-113 [10.1007/978-3-031-21187-4_8]

Publisher:
Springer

Published
DOI:10.1007/978-3-031-21187-4_8

Optimization as a tool for seismic protection of structures[*]

Giuseppe C. Marano[1] [0000−0001−8472−2956], Marco M. Rosso[1] [0000−0002−9098−4132], and J. Melchiorre[1] [0000−0002−8721−8365]

Politecnico di Torino, DISEG, Department of Structural, Geotechnical and Building Engineering,
Corso Duca Degli Abruzzi, 24, Turin 10128, Italy
Corresponding Author: `giuseppe.marano@polito.it`

Abstract. Scientific research within seismic protection techniques is still nowadays an actual and vibrant field. The main goal of earthquake protection is to alleviate the effects of seismic events on civil structures and infrastructures to reduce both human losses and socio-economical impacts in the medium and long-term. Seismic protection techniques are mainly related to the base isolation systems for buildings or bridges, and to energy dissipation-based solutions with the adoption of special devices, e.g. metal hysteretic dampers, viscous dampers, and friction dampers. The optimization procedures play a fundamental role in the dynamic parametric identification of such devices. Current trends in the optimization field are the adoption of computational intelligence meta-heuristic algorithms, which have been inspired by a conjunction of the artificial intelligence community and nature-inspired phenomena. Specifically, the widespread use of meta-heuristic techniques combined with proper seismic protection optimization problem formulations leads to more cost-effective, high-performing, and innovative design solutions. In the present study, a brief review is argued presenting some optimization procedures to accomplish seismic protection tasks.

Keywords: seismic protection · viscous dampers · base isolation devices · meta-heuristic algorithms · optimization.

1 Introduction

Within the earthquake engineering discipline, seismic or earthquake protection refers to all the procedures implemented to mitigate and diminish the damaging effects of seismic events on civil engineering structures. The main pursued achievement is to reduce as much as possible losses, meant as human losses as a priority and considering, as well, administrative and socio-economical impacts on societies in the medium and long-term [22]. In the existing literature, earthquake risk mitigation appears somewhat more widespread terminology, albeit

---

[*] Supported by project ADDOPTML

it should properly refer to strengthening interventions only [14]. In order to achieve a better earthquake protection behavior of a structure, the most widespread techniques belong to two main categories: the foremost is denoted as *base isolation* systems, whereas the second class of approaches provides for the installation of special devices acting as *energy absorbers* of the seismic input energy loading [14]. The implementation of base isolators for protecting civil structures against the damaging effects of seismic loadings has become very frequent in recent decades. From the practical point of view, the base isolator devices create a decoupling layer at the top of the foundation level (substructure) which ensures that seismic input energy, and thus the induced damaging effects, of seismic shaking events, do not reach the structural system to be protected (superstructure). To perform that function, isolators permit relative movements between the structural systems and the substructure, i.e. substantially reducing the seismic demand in input to the superstructure, while providing sufficient vertical stiffness to effectively transmit vertical loads in foundations. These devices are commonly composed of thin reinforcing steel plates interspersed between thick rubber pads. The performance of a seismic isolator depends on many factors, such as the rubber typology, the compound, the thickness, and the process of vulcanization of the pads. Additionally, to provide a substantial increase of energy dissipation capacity to base isolators, a core made of lead may also be present [57,56,68]. On the other hand, the second class of energy-based approaches permits dissipating a part of the input energy coming from earthquake events with the advantage of employing devices that can easily be replaced, as necessary, after an event occurrence. The installation of energy adsorbers is extremely convenient both while designing a new structure and even for increasing the seismic protection of existing structures, acting as a retrofitting intervention [2,21,7]. The most widespread devices belongs to three main categories [13]: metallic yielding dampers [11], fluid viscous and viscoelastic dampers and friction-based devices [4,10].

In the following subsection, an introductory discussion related to structural vibration control devices is conducted, differentiating among active, passive, and semi-active techniques. In section 2, the mathematical optimization statements are presented and a brief overview of meta-heuristic algorithms is argued. Finally, in section 3, a brief literature review is presented related to some applications of optimization as a tool for seismic protection.

1.1 Active, passive and semi-active structural control devices

Since seismic protection mainly aims to improve or isolate the dynamic behavior of structures, structural control devices have been one of the main subjects of research in the field of earthquake protection engineering for many decades. Several vibration control devices have been proposed in order to reduce vibration due to dynamic loads. Due to their simplicity, efficiency, and reduced costs (compared with other strategies) they are now widely used in many civil engineering applications to reduce vibrations and therefore to increase structural protection against wind, earthquake, and similar events [45,43]. Structural control aims to provide a framework to determine the most effective action to be applied in order to enhance the safety and the dynamic behavior of a structure based on some measuring control response parameters of the structural system itself. Several approaches have been developed to effectively deal with dynamic loads induced by natural hazards, which can be classified as active, passive, hybrid, and semi-active damping strategies.

An *active* structural control system consists of an ensemble of sensors and actuators which can actively modify the response of the structure. Sensors are placed on the structural system to be protected in order to monitor both external excitation levels and the resulting structural response parameters. Based on the information retrieved from the sensors, the control algorithm computes the required control force able to modify the dynamical behavior of the structure and dissipate energy by governing the actuators [69,31]. The actuators usually require a considerable external power source of energy. Moreover, the power supply has to be guaranteed to the actuators to remain functional during seismic events, but this is a challenging task [9]. The control strategy is acknowledged as *feedback control* when only the structural response is measured, whereas it is denoted as *feed-forward control* when only the input excitation is measured. A third scenario is called *feedback-feed-forward* control, and it exploits the measurements of both the response and the excitation quantities [69]. The main advantages of an active control system are: (a) an improved response control of the protected structure; (b) a lower sensitivity to ground shaking behavior; (c) the mitigation of many other dynamic natural hazard input, e.g. wind excitation; (d) the possibility to find the best control strategy considering both computational effort and implementation costs. The latter point may refers to also improve human comfort over structural behavior under some peculiar circumstances [69]. For instance, systems denoted as tuned mass dampers (TMDs) may be also designed as active control systems to minimize the effect of vibrations and also providing immediate damping of vibrations [9]. Active damping strategies of structures rely on the input forces given by electrohydraulic or electromechanical actuators designed to influence several vibration modes of the system. Therefore, active damping is most suited for structures with many degrees of freedom and it is beneficial for a wide range of operating conditions and structures. However, the main drawbacks of active control systems are: (a) high implementation costs; (b) the need for a high-power supply during a natural events such as an earthquake; (c) the possibility of the structure destabilization when the control system is not well designed, or it presents a malfunctioning.

Passive damping strategies do not rely on any actuators and, thus, they do not require any external power source for operation because these devices leverage the motion of the structure to develop the control forces. They are used to increase the energy dissipation capacity of a structure through localized and discrete devices, which may consequently increase also the stiffness and strength of the protected structure. The forces imparted by passive devices are developed in response to the motion of the structure [31]. The passive vibration control techniques for protecting structures dissipate the seismic input energy into both kinetic and strain energy of the passive device, or even heat energy, e.g. in viscoelastic dampers [9]. The performances and efficiecy of passive control devices strongly depends on an optimized design of both the building and the passive device, e.g. the viscoelastic materials added to the building [9].

Hybrid vibration control refers to a combined application of active and passive control systems. A hybrid system incorporates both typologies of devices, this allows the structure to reach the highest levels of performance exploiting the best features of both strategies. Notably, even during a sudden absence of power supply, e.g. during an earthquake event, the hybrid control system remains functional via its mechanical elements [9]. Hybrid techniques are utilized typically in very high-end applications, such as skyscrapers or viaducts, and they incorporate both actuators connected to a high-power source of energy and devices such as isolators.

Control strategies based on *semi-active* devices can be considered as a class of active control systems, denoted also as controllable passive devices in [31], which require less energy than active control systems [9]. These systems combine the best features of both passive and active control systems, e.g. they are not affected by power supply cuts since they can rely on batteries [69,9]. A semi-active system leverages controllable passive devices capable of varying their mechanical properties and characteristic parameters such as damping coefficient and/or stiffness in real-time. The modification of these mechanical properties is based on a control loop that computes the necessary action of the device depending on some structural response control parameters and/or the input excitation level. Since no actuators are adopted in a semi-active system, also in this case as in the passive approach the motion of the structure is used to develop the control forces. Specifically, a noticeable example belonging to this class of vibration control devices is the so-called magnetorheological dampers. These dampers rely on a magnetorheological liquid which is sensible to viscosity increase when the magnetic field intensity from an e electromagnet increase, which strongly affects the damping characteristics [9]. Similarly to active control systems, the available semi-active control strategies are differentiated from what the sensors are demanded to monitor. Therefore, they are referred to as feedback, feed-forward, or feedback-feed-forward if the sensors monitor the response of the system, the excitation of the input, or both, respectively. Semi-active, hybrid, and active control of structures are considered the natural evolution of passive control techniques. They rely on devices capable of processing the data in real time, to develop control actions with the smallest time lag possible. This allows an improved structural behavior and enhanced safety of the structure [31].

2 Optimization strategies via meta-heuristic algorithms

The main purpose of solving an optimization problem is to find the minimum (or maximum) of certain mathematical functions, namely objective functions (OF) $f(\boldsymbol{x})$. Optimization problems may be stated in two different ways depending on the number of OF involved, i.e. single-objective problems and multi-objective ones. Furthermore, it is possible to differentiate the optimization problems between unconstrained or constrained problems, based on the imposed conditions that must be met by the final solution. Unconstrained optimization problems can be defined as:

$$\min_{\boldsymbol{x}\in\Omega}\{f(\boldsymbol{x})\} \tag{1}$$

meanwhile constrained optimization problems can be defined as:

$$\begin{aligned} &\min_{\boldsymbol{x}\in\Omega}\{f(\boldsymbol{x})\} \\ \text{s.t.}\quad &g_q(\boldsymbol{x}) \leq 0 \quad \forall q = 1, ..., n_q \\ &h_r(\boldsymbol{x}) = 0 \quad \forall r = 1, ..., n_r \end{aligned} \tag{2}$$

where the vector of the design variables, $\boldsymbol{x} = \{x_1, ..., x_j, ..., x_n\}^T$, is the vector that contains the parameters to be optimized in order to obtain the best solution for the problem. Thus, the search space appears as a multidimensional domain $\Omega = [x_1^l, x_1^u] \times ... \times [x_j^l, x_j^u] \times ... \times [x_n^l, x_n^u]$ defined by the Cartesian product (denoted by the × symbol) of admissible range of values for the design variables involved in the problem. In general, it is possible to define two different categories of constraints: inequality constraints $g_q(\boldsymbol{x})$ and equality constraints $h_r(\boldsymbol{x})$. Being that equality constraint can be converted into two inequality constraints without any loss of generality, it is possible to rewrite the problem considering only the inequality constraints in (2), i.e. $g_p(\boldsymbol{x}) \leq 0$, where $p = 1, ..., n_q, n_{q+1}, ..., n_p$, being $n_p = n_q + 2n_r$.

Over the past two decades, the use of meta-heuristic algorithms and, in particular, evolutionary algorithms for solving structural optimization problems has received much more attention. This is because such problems are often characterized by a discontinuous search space and the objective functions are not always differentiable. For this reason, it is often not possible to adopt gradient-based or quasi-newton methods, since the information about the first and second derivative of the objective function cannot be calculated. On the contrary, meta-heuristic algorithms do not require any first-order (gradient) or second-order (Hessian) information and seem to be more appropriate to handle complex optimization problems. Furthermore, the great majority of meta-heuristic algorithms take inspiration from natural phenomena and provide considerable simple implementations and, for this reason, they are widely used even by practitioners. One of the firstly developed meta-heuristic optimization procedures was the genetic algorithm (GA) proposed by J. Holland around the 1970s [47]. This algorithm still represents one of the most popular population-based evolutionary tools. This method tries to replicate the biological evolutionary process in order to mimic the Darwinian Evolutionary Theory that brings the population of solutions to evolve towards the best optimum. The procedure involves pseudo-random-based operators like crossover, mutation, and selection in order to reproduce the long-term process of evolution in a population with the survival of the fittest individuals [37]. Since the introduction of the genetic algorithm, many variations of it have been developed over the years, such as the Differential Evolution (DE) algorithm [70]. Within meta-heuristic algorithms, it is even possible to classify the various techniques among nature-inspired, swarm-based, physical-inspired phenomena, or statistical-based procedures [38]. A widespread example of a meta-heuristic swarm-based approach is the particle swarm optimization (PSO) algorithm [35,61,63] which is inspired by the behavior of fish schooling or birds flocking in nature. Other famous swarm-based optimization procedures are e.g. the ant colony optimization (ACO) algorithm [24,25], based on the simulation of the behavior of the ant colonies searching for food, or even the artificial bee colony (ABC) [33] and many others. It is worth mentioning some other examples of meta-heuristic algorithms such as the physical-inspired method denoted as simulated annealing (SA) [36], which is a single-solution-based meta-heuristic optimization approach inspired by the annealing in metallurgy, or the charged system search (CSS) algorithm [34]. Furthermore, some authors have developed meta-heuristics on the basis of statistical laws such as the estimation of distribution algorithm (EDA) [53,59].

In the last decades, the meta-heuristic algorithms have been applied in many engineering fields, highlighting their successful capabilities and effectiveness in dealing with real-world constrained problems [41,54,72,28,23,8,63], e.g. dealing with structural design [18,20,65,17,48] and structural optimization tasks [15,26,3,42,49,16,27,71]. In the following section, a brief review of some recent optimization applications for seismic protection is presented.

3 Brief review of optimization applications for seismic protection

A well-designed base isolation structural system permits both to reduce the seismic input demand to the superstructure and to reduce the maintenance cost for after seismic events. Furthermore, the performances of passive vibration control devices are extremely sensitive to their dynamic mechanical behavior. Thus, a reliable identification of their mechanical properties play an important key role. In [43], the authors proposed a dynamic identification approach of passive devices by comparing the experimental and the analytical value of the forces experienced by the device under investigation. The authors adopted an optimization procedure for the parametric identification of the passive device based on two evolutionary algorithms, the PSO and the DE. The goal was to minimize the integral difference of the damper's force in time between the experimental testing conducted on a real viscous damper and the analytical simulated response obtained by applying the same time history of displacements of the tested device. The base isolation systems and the superstructure building are usually designed separately, however in [58] the authors proposed a multi-objective optimization approach focused simultaneously on reinforced concrete superstructure elements (beams and columns) and on elastomeric base isolation design parameters, i.e. maximum allowed displacement, rubber type and size. To pursue this task, three objective functions have been considered related to minimization of the top-floor displacement, minimization of the top-floor acceleration, and minimization of the superstructure material cost. In [55], the authors proposed a reliability-based design optimization method with GA for sliding implant-magnetic base isolator bearing. To provide an efficient statement of the optimization problem, one of the main task is an efficient parameter choice. To provide a design parameter reduction, the authors in [55] adopted a variance-based sensitivity analysis. In literature the problem of selecting optimal design parameters is a recurrent issue. In [64], the author proposed an optimization criterion for selecting the design parameters of elasto-plastic dampers based on the dispersion of absolute accelerations of the protected structure during a seismic event. The authors of [66] proposed a method to calculate the optimum design of an original force-limiting floor anchorage system for the seismic protection of reinforced concrete (RC) dual wall-frame buildings. The proposed anchorage system limits the seismic solicitations interposing elasto-plastic links between two structural sub-systems. The optimal solution is obtained by the application of the DE meta-heuristic algorithm and the method is applied to a case study represented by a 12-storey prototype RC dual wall-frame building. The optimization of a passive control strategy that involves the application of a linear dissipative connection in a wall-frame system is presented in [29]. The seismic protection device is designed as a global protection system to protect both the structures. The problem is formulated as a multi-objective optimization problem with conflicting objective functions. The final goal is to use the genetic algorithm in order to minimize the displacements in the frame structure and the shear in the wall.

To test new nonlinear base isolation devices, the current procedure is to analyse the stochastic response and testing experimentally the device with small-scale prototypes [67]. The stochastic response of isolated building is thus derived from a nonstationary random process which usually undergoes to a time-dependent linearization procedure to characterize the time-history of the base isolator nonlinear restoring force. For instance, the authors in [67] adopted a stochastic optimization procedure based on the convergence of different performance indicators, such as base drift or structural acceleration. Moreover, when dealing with uncertainties, it become challenging to provide an effective tuning of base isolation design parameters. Especially due to the need of ensuring both sufficient decoupling properties between substructure and superstructure, possible energy-dissipation features and also enough stiffness to prevent excessice deformations. Thus, the authors in [39] explored an optimization method on a grid-search approach, relying on a probabilistic performance-based optimum seismic design for seismic isolators of a prototype of high-speed railway bridge. A multi-objective optimization process which lead to a Pareto-front optimal solutions has been also analysed in [12]. In this contribution, the earthquake excitation is treated as a non-stationary random process and the desing of frinction-based seismic isolators required a suitable probabilistic characterization of the dynamic response through Monte Carlo simulations.

In [44], a method for the optimal design of Tuned Mass Dampers (TMD) is proposed. The main idea is to define the optimum design of vibration absorbers utilized to reduce undesirable vibrational effects which are originated in linear structures by seismic excitations. The objective function to be minimized is represented by the dimensionless peak of displacement of the protected system with respect to the unprotected one. In [30] the authors proposed a multi-objective optimization of a single tuned mass damper to control vibrations induced in building structures under low-moderate earthquakes. In this case the objective functions consider both the economical and the performance aspects. The optimal design aims to minimize the costs and to maximize the performance in order to control the damage level and the behaviour of components and equipment. In this case the economic cost is considered directly proportional to the mechanical properties of the device while the performance are evaluated as the ratio between the absolute accelerations of the protected structure and the unprotected one. In [19] the optimization of a multi-tuned mass damper inerter (MTMDI) is performed by using the genetic algorithm. The MTMDI system links two adjacent high-rise buildings as an unconventional seismic protection strategy. The authors analysed a real case study of two adjacent high-rise buildings connected by two corridors equipped with the proposed MTMDI system. The optimization problems aimed to minimize the displacement, the inter-story drift and the accelerations on the structure. The problems are treated separately and it is found that the optimally designed MTMDI outperforms both conventional MTMD and single TMDI in acceleration control.

It is worth noting that seismic isolation concepts could also be adopted for protecting equipments, e.g. medical ones in a hospital or some other in some strategic buildings, to avoid damage and remain functional during and after earthquake events. For instance, in [32] the authors provide an optimization design of an equipment isolator denoted as resilient sliding isolation system. This device is composed of a restoring spring and a slider, thus, the design parameters are the period of the system (related to the spring stiffness) and the friction coefficient, respectively.

In conclusion, it is important to keep in mind that the seismic protection techniques described above could benefit from integration with monitoring techniques. In particular, the installation of a comprehensive system that allows monitoring of the structural system with non-destructive techniques (NDT) [52,51,40,46] associated with real-time protection, dampers installation, and damage modeling systems [1,50,6,62,5,60] could be an interesting future development in the field of earthquake engineering. This would further increase the safety and reliability of structures and infrastructure by reducing seismic damage and simultaneously reducing maintenance cost for after seismic events, helping to extend the nominal life of the structures.

4 Conclusions

The brief review reported in the current document shows that the design and optimization of seismic protection devices is still an active and debated research topic. Indeed, besides the optimization algorithms actually implemented, a proper and more efficient optimization problem statement still represents a challenging task. As a matter of fact, the problem statement represents the starting point that tremendously affects the overall effectiveness and engineering soundness of the final result. In particular, a proper choice of the design variables to be included in the design vector, as well as the definition of the objective function to be considered, represents a crucial step in the optimization process. In the case of seismic protection devices, differently than in other fields, the minimization of the cost related to seismic devices themselves rarely constitutes the main objective of the procedure. In general, the optimization problem is pursuing the goal of maximizing the performance of the protection device to be designed. Therefore, the considered objective functions may promote the structural system performances rather than the device's costs themselves. Actually, the production and installation costs of the seismic protection devices are negligible compared with the restoration costs associated with hypothetical seismic-induced severe structural damages. In addition, such devices improve extending the nominal service life of the structure while reducing the maintenance costs. It is worth noting that seismic protection device optimization problems are often multi-objective problems. It is evident that the complexity of the problem cannot be solved by considering a single optimal solution. In general, it is desirable adopting optimization methods that provide designers with the most promising solutions space (e.g. Pareto front) from which the designer may choose the optimal trade-off solution considering conflicting aims. The authors believe that the present brief review may be very helpful to identify the promising future developments within the examined research field. Oversimplified modeling assumptions may lead to design solutions that are quite far from the actual ones which effectively capture all the complex phenomena involved in the seismic protection problems. Therefore, artificial intelligence and, in particular, machine learning techniques are increasingly becoming standard tools because of their capabilities and versatility. These methods should permit to study of more complex problems by reducing the number of simplifications assumptions. In future works, it will be possible to highlight how AI and machine learning techniques can produce significant results when applied to complex earthquake engineering problems. Seismic protection optimization applications with meta-heuristic algorithms represent the first steps in the AI-based direction to reach high-performance and cost-effective protection devices. The upcoming research on seismic protection techniques presents a very promising path in the direction of considering increasingly complex phenomena hitherto neglected, reaching desirable unprecedented levels of efficiency, safety, and reliability never previously achieved.

Acknowledgments

This research was supported by project MSCA-RISE-2020 Marie Skłodowska-Curie Research and Innovation Staff Exchange (RISE) - ADDOPTML (ntua.gr) The authors would like to thank the project ADDOPTML for funding supporting this research.

References

1. Aloisio, A., Alaggio, R., Fragiacomo, M.: Dynamic identification and model updating of full-scale concrete box girders based on the experimental torsional response. Construction and Building Materials **264**, 120146 (2020)
2. Aloisio, A., Boggian, F., Tomasi, R.: Design of a novel seismic retrofitting system for rc structures based on asymmetric friction connections and clt panels. Engineering Structures **254**, 113807 (2022)

3. Aloisio, A., Pasca, D.P., Battista, L., Rosso, M.M., Cucuzza, R., Marano, G., Alaggio, R.: Indirect assessment of concrete resistance from fe model updating and young's modulus estimation of a multi-span psc viaduct: Experimental tests and validation. Elsevier Structures **37**, 686–697 (01 2022). https://doi.org/10.1016/j.istruc.2022.01.045
4. Aloisio, A., Pelliciari, M., Sirotti, S., Boggian, F., Tomasi, R.: Optimization of the structural coupling between rc frames, clt shear walls and asymmetric friction connections. Bulletin of Earthquake Engineering pp. 1–26 (2022)
5. Aloisio, A., Rosso, M.M., Alaggio, R.: Experimental and analytical investigation into the effect of ballasted track on the dynamic response of railway bridges under moving loads. Journal of Bridge Engineering **27**(10), 04022085 (2022)
6. ALOISIO, A., Rosso, M.M., Huang, D., Iqbal, A., Fragiacomo, M., Pei, S.: Nonlinear sdof analytical model of mass-timber building with post-tensioned rocking walls (2022)
7. Aloisio, A., Rosso, M.M., Iqbal, A., Fragiacomo, M.: Hysteresis modeling of timber-based structural systems using a combined data and model-driven approach. Computers & Structures **269**, 106830 (2022)
8. Asso, R., Cucuzza, R., Rosso, M.M., Masera, D., Marano, G.C.: BRIDGES MONITORING: AN APPLICATION OF AI WITH GAUSSIAN PROCESSES. In: 14th International Conference on Evolutionary and Deterministic Methods for Design, Optimization and Control. Institute of Structural Analysis and Antiseismic Research National Technical University of Athens (2021). https://doi.org/10.7712/140121.7964.18426
9. Bekdaş, G., Nigdeli, S.M., Kayabekir, A.E.: Introduction and overview: Structural control and tuned mass dampers. In: Optimization of Tuned Mass Dampers, pp. 1–13. Springer (2022)
10. Boggian, F., Tardo, C., Aloisio, A., Marino, E.M., Tomasi, R.: Experimental cyclic response of a novel friction connection for seismic retrofitting of rc buildings with clt panels. Journal of Structural Engineering **148**(5), 04022040 (2022)
11. Bruschi, E., Quaglini, V., Calvi, P.M.: A simplified design procedure for seismic upgrade of frame structures equipped with hysteretic dampers. Engineering Structures **251**, 113504 (2022)
12. Bucher, C.: Probability-based optimal design of friction-based seismic isolation devices. Structural Safety **31**(6), 500–507 (2009)
13. Chopra, A.: Dynamics of structures 4th edition, 2019
14. Coburn, A., Spence, R.: Earthquake protection. John Wiley & Sons (2003)
15. Cucuzza, R., Costi, C., Rosso, M.M., Domaneschi, M., Marano, G., Masera, D.: Optimal strengthening by steel truss arches in prestressed girder bridges. Proceedings of the Institution of Civil Engineers - Bridge Engineering pp. 1–51 (01 2022). https://doi.org/10.1680/jbren.21.00056
16. Cucuzza, R., Rosso, M.M., Aloisio, A., Melchiorre, J., Giudice, M.L., Marano, G.C.: Size and shape optimization of a guyed mast structure under wind, ice and seismic loading. Applied Sciences **12**(10), 4875 (2022)
17. Cucuzza, R., Rosso, M.M., Marano, G.: Optimal preliminary design of variable section beams criterion. SN Applied Sciences **3** (08 2021). https://doi.org/10.1007/s42452-021-04702-5
18. De Domenico, D., Qiao, H., Wang, Q., Zhu, Z., Marano, G.: Optimal design and seismic performance of multi-tuned mass damper inerter (mtmdi) applied to adjacent high-rise buildings. The Structural Design of Tall and Special Buildings **29**(14), e1781 (2020). https://doi.org/https://doi.org/10.1002/tal.1781
19. De Domenico, D., Qiao, H., Wang, Q., Zhu, Z., Marano, G.: Optimal design and seismic performance of multi-tuned mass damper inerter (mtmdi) applied to adjacent high-rise buildings. The Structural Design of Tall and Special Buildings **29**(14), e1781 (2020)

20. De Tommasi, D., Marano, G., Puglisi, G., Trentadue, F.: Morphological optimization of tensegrity-type metamaterials. Composites Part B: Engineering **115**, 182–187 (2017). https://doi.org/10.1016/j.compositesb.2016.10.017
21. Di Trapani, F., Malavisi, M., Marano, G.C., Sberna, A.P., Greco, R.: Optimal seismic retrofitting of reinforced concrete buildings by steel-jacketing using a genetic algorithm-based framework. Engineering Structures **219**, 110864 (2020)
22. Di Trapani, F., Sberna, A.P., Marano, G.C.: A genetic algorithm-based framework for seismic retrofitting cost and expected annual loss optimization of non-conforming reinforced concrete frame structures. Computers & Structures **271**, 106855 (2022)
23. Di Trapani, F., Tomaselli, G., Sberna, A.P., Rosso, M.M., Marano, G.C., Cavaleri, L., Bertagnoli, G.: Dynamic response of infilled frames subject to accidental column losses. In: Pellegrino, C., Faleschini, F., Zanini, M.A., Matos, J.C., Casas, J.R., Strauss, A. (eds.) Proceedings of the 1st Conference of the European Association on Quality Control of Bridges and Structures. pp. 1100–1107. Springer International Publishing, Cham (2022)
24. Dorigo, M.: Optimization, learning and natural algorithms. Ph. D. Thesis, Politecnico di Milano (1992)
25. Dorigo, M., Gambardella, L.M.: Ant colony system: a cooperative learning approach to the traveling salesman problem. IEEE Transactions on evolutionary computation **1**(1), 53–66 (1997)
26. Fiore, A., Marano, G., Greco, R., Mastromarino, E.: Structural optimization of hollow-section steel trusses by differential evolution algorithm. International Journal of Steel Structures **16**(2), 411–423 (2016). https://doi.org/10.1007/s13296-016-6013-1
27. Fiore, A., Trentadue, F., Greco, R., Marano, G.C., De Marco, G., Sardone, L., Lagaros, N.D.: Optimización de volumen para arcos empotrados. Hormigón y Acero **71**(292), 71–76 (2020)
28. Greco, R., Marano, G.: Identification of parameters of maxwell and kelvin-voigt generalized models for fluid viscous dampers. JVC/Journal of Vibration and Control **21**(2), 260–274 (2015). https://doi.org/10.1177/1077546313487937
29. Greco, R., Marano, G.C.: Multi-objective optimization of a dissipative connection for seismic protection of wall-frame structures. Soil dynamics and earthquake engineering **87**, 151–163 (2016)
30. Greco, R., Marano, G.C., Fiore, A.: Performance–cost optimization of tuned mass damper under low-moderate seismic actions. The Structural Design of Tall and Special Buildings **25**(18), 1103–1122 (2016)
31. Housner, G., Bergman, L.A., Caughey, T.K., Chassiakos, A.G., Claus, R.O., Masri, S.F., Skelton, R.E., Soong, T., Spencer, B., Yao, J.T.: Structural control: past, present, and future. Journal of engineering mechanics **123**(9), 897–971 (1997)
32. Iemura, H., Taghikhany, T., Jain, S.K.: Optimum design of resilient sliding isolation system for seismic protection of equipments. Bulletin of Earthquake Engineering **5**(1), 85–103 (2007)
33. Karaboga, D., Basturk, B.: A powerful and efficient algorithm for numerical function optimization: artificial bee colony (abc) algorithm. Journal of global optimization **39**(3), 459–471 (2007)
34. Kaveh, A., Talatahari, S.: A novel heuristic optimization method: charged system search. Acta mechanica **213**(3), 267–289 (2010)
35. Kennedy, J., Eberhart, R.: Particle swarm optimization. vol. 4, pp. 1942–1948 (1995), `https://www.scopus.com/inward/record.uri?eid=2-s2.0-0029535737&partnerID=40&md5=e6bf04ae50f3268ae545d88ed91d1fc5`
36. Kirkpatrick, S., Gelatt Jr, C.D., Vecchi, M.P.: Optimization by simulated annealing. science **220**(4598), 671–680 (1983)

37. Lagaros, N.D., Papadrakakis, M., Kokossalakis, G.: Structural optimization using evolutionary algorithms. Computers & Structures **80**(7), 571–589 (2002). https://doi.org/10.1016/S0045-7949(02)00027-5
38. Lagaros, N.D., Plevris, V., Kallioras, N.A.: The mosaic of metaheuristic algorithms in structural optimization. Archives of Computational Methods in Engineering pp. 1–36 (2022)
39. Li, Y., Conte, J.P.: Probabilistic performance-based optimum design of seismic isolation for a california high-speed rail prototype bridge. Earthquake Engineering & Structural Dynamics **47**(2), 497–514 (2018)
40. Manuello, A., Masera, D., Carpinteri, A.: Ae damage assessment in the bell tower of the turin cathedral. In: Key Engineering Materials. vol. 817, pp. 579–585. Trans Tech Publ (2019)
41. Marano, G., Trentadue, F., Greco, R.: Stochastic optimum design criterion of added viscous dampers for buildings seismic protection. Structural Engineering and Mechanics **25**(1), 21–37 (2007). https://doi.org/10.12989/sem.2007.25.1.021
42. Marano, G., Trentadue, F., Petrone, F.: Optimal arch shape solution under static vertical loads. Acta Mechanica **225**(3), 679–686 (2014). https://doi.org/10.1007/s00707-013-0985-0
43. Marano, G.C., Greco, R., Quaranta, G., Fiore, A., Avakian, J., Cascella, D.: Parametric identification of nonlinear devices for seismic protection using soft computing techniques. In: Advanced Materials Research. vol. 639, pp. 118–129. Trans Tech Publ (2013)
44. Marano, G.C., Greco, R., Trentadue, F., Chiaia, B.: Constrained reliability-based optimization of linear tuned mass dampers for seismic control. International Journal of Solids and Structures **44**(22-23), 7370–7388 (2007)
45. Marano, G.C., Trentadue, F., Greco, R.: Stochastic optimum design criterion for linear damper devices for seismic protection of buildings. Structural and Multidisciplinary Optimization **33**(6), 441–455 (2007)
46. Marasco, G., Rosso, M.M., Aiello, S., Aloisio, A., Cirrincione, G., Chiaia, B., Marano, G.C.: Ground penetrating radar fourier pre-processing for deep learning tunnel defects' automated classification. In: International Conference on Engineering Applications of Neural Networks. pp. 165–176. Springer (2022)
47. Martí, R., Pardalos, P.M., Resende, M.G.C.: Handbook of Heuristics. Springer Publishing Company, Incorporated, 1st edn. (2018). https://doi.org/10.1007/978-3-319-07124-4
48. Melchiorre, J., Manuello, A., Marmo, F., Adriaenssens, S., Marano, G.: Differential formulation and numerical solution for elastic arches with variable curvature and tapered cross-sections. European Journal of Mechanics-A/Solids **97**, 104757 (2023)
49. Melchiorre, J., Bertetto, A.M., Marano, G.C.: Application of a machine learning algorithm for the structural optimization of circular arches with different cross-sections. Journal of Applied Mathematics and Physics **9**(5), 1159–1170 (2021)
50. Melchiorre, J., Manuello, A., Sardone, L., Marano, G.C.: Damaging configurations in arch structures with variable curvature and tapered cross-section. WCCM-APCOM 2022 **900** (2022)
51. Niccolini, G., Carpinteri, A., Lacidogna, G., Manuello, A.: Acoustic emission monitoring of the syracuse athena temple: Scale invariance in the timing of ruptures. Physical Review Letters **106**(10), 108503 (2011)
52. Niccolini, G., Manuello, A., Marchis, E., Carpinteri, A.: Signal frequency distribution and natural-time analyses from acoustic emission monitoring of an arched structure in the castle of racconigi. Natural Hazards and Earth System Sciences **17**(7), 1025–1032 (2017)

53. Pelikan, M., Hauschild, M.W., Lobo, F.G.: Estimation of distribution algorithms. In: Springer handbook of computational intelligence, pp. 899–928. Springer (2015)
54. Pelliciari, M., Marano, G., Cuoghi, T., Briseghella, B., Lavorato, D., Tarantino, A.: Parameter identification of degrading and pinched hysteretic systems using a modified bouc–wen model. Structure and Infrastructure Engineering **14**(12), 1573–1585 (2018). https://doi.org/10.1080/15732479.2018.1469652
55. Peng, Y., Ma, Y., Huang, T., De Domenico, D.: Reliability-based design optimization of adaptive sliding base isolation system for improving seismic performance of structures. Reliability Engineering & System Safety **205**, 107167 (2021)
56. Quaglini, V., Pettorruso, C., Bruschi, E.: Experimental and numerical assessment of prestressed lead extrusion dampers (2021)
57. Quaglini, V., Pettorruso, C., Bruschi, E.: Design and experimental assessment of a prestressed lead damper with straight shaft for seismic protection of structures. Geosciences **12**(5), 182 (2022)
58. Rizzian, L., Léger, N., Marchi, M.: Multiobjective sizing optimization of seismic-isolated reinforced concrete structures. Procedia engineering **199**, 372–377 (2017)
59. Rosso, M., Melchiorre, J., Cucuzza, R., Manuello, A., Marano, G.C.: Estimation of distribution algorithm for constrained optimization in structural design. WCCM-APCOM2022
60. Rosso, M.M., Aloisio, A., Cucuzza, R., Marano, G.C., Alaggio, R.: Train-track-bridge interaction analytical model with non-proportional damping: Sensitivity analysis and experimental validation. In: European Workshop on Structural Health Monitoring. pp. 223–232. Springer (2023)
61. Rosso, M.M., Cucuzza, R., Di Trapani, F., Marano, G.C.: Nonpenalty machine learning constraint handling using pso-svm for structural optimization. Advances in Civil Engineering **2021** (2021)
62. Rosso, M.M., Asso, R., Aloisio, A., Di Benedetto, M., Cucuzza, R., Greco, R.: Corrosion effects on the capacity and ductility of concrete half-joint bridges. Available at SSRN 4160407
63. Rosso, M.M., Cucuzza, R., Aloisio, A., Marano, G.C.: Enhanced multi-strategy particle swarm optimization for constrained problems with an evolutionary-strategies-based unfeasible local search operator. Applied Sciences **12**(5) (2022). https://doi.org/10.3390/app12052285
64. Rutman, Y.L., Ostrovskaya, N.V.: Damping optimization in seismic isolation systems. In: Key Engineering Materials. vol. 828, pp. 129–135. Trans Tech Publ (2020)
65. Sardone, L., Rosso, M.M., Cucuzza, R., Greco, R., Marano, G.C.: Computational design of comparative models and geometrically constrained optimization of a multi domain variable section beam based on timoshenko model. In: 14th International Conference on Evolutionary and Deterministic Methods for Design, Optimization and Control. Institute of Structural Analysis and Antiseismic Research National Technical University of Athens (2021). https://doi.org/10.7712/140121.7961.18535
66. Scodeggio, A., Quaranta, G., Marano, G.C., Monti, G., Fleischman, R.B.: Optimization of force-limiting seismic devices connecting structural subsystems. Computers & Structures **162**, 16–27 (2016)
67. Shan, J., Shi, Z., Hu, F., Yu, J., Shi, W.: Stochastic optimal design of novel nonlinear base isolation system for seismic-excited building structures. Structural Control and Health Monitoring **25**(7), e2168 (2018)
68. Shinozuka, M., Chaudhuri, S.R., Mishra, S.K.: Shape-memory-alloy supplemented lead rubber bearing (sma-lrb) for seismic isolation. Probabilistic Engineering Mechanics **41**, 34–45 (2015)
69. Soong, T., Spencer, B.: Active, semi-active and hybrid control of structures. Bulletin of the New Zealand Society for Earthquake Engineering **33**(3), 387–402 (2000)

70. Storn, R., Price, K.: Differential evolution–a simple and efficient heuristic for global optimization over continuous spaces. Journal of global optimization **11**(4), 341–359 (1997)
71. Trentadue, F., Fiore, A., Greco, R., de Marco, G., Sardone, L., Marano, G., et al.: Volume optimization of end-clamped arches. In: Proceedings of the International Fib Symposium on Conceptual Design of Struct (Madrid: Torroja Institute). pp. 49–56 (2019)
72. Xue, J., Lavorato, D., Bergami, A., Nuti, C., Briseghella, B., Marano, G., Ji, T., Vanzi, I., Tarantino, A., Santini, S.: Severely damaged reinforced concrete circular columns repaired by turned steel rebar and high-performance concrete jacketing with steel or polymer fibers. Applied Sciences (Switzerland) **8**(9) (2018). https://doi.org/10.3390/app8091671