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Multiobjective sizing optimization of seismic-isolated reinforced concrete structures

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Abstract

It is known that seismic isolation is able to protect structures from damage by reducing the earthquake effects on the superstructure rather than increasing the structural resistance. Base-isolated buildings are becoming more numerous all around the world, especially in areas subject to a high seismic hazard or where high safety levels are required. The cost of the isolation devices for ordinary buildings hinders a widespread adoption of the new technology. However, a well-designed base isolation system can largely reduce seismic loadings transferred to the superstructure and it not only enables to immediately reduce the superstructure building cost, but also to reduce the maintenance costs incurred after every earthquake during the building lifetime. To better understand these factors, this paper presents an efficient numerical optimization technique for comparing the responses of a base-isolated and a traditional fixed-base reinforced concrete ordinary building under the same type of solicitations and seismic spectra, as appropriate for each case. We start from a multiobjective optimization. The superstructure and the isolation system are generally designed separately in a building. In this work, we consider elastomeric isolators and we optimize at the same time the structural elements of the building (superstructure column and beam sections and reinforcements) and the isolator parameters (rubber type, maximum allowed displacement and elastomer size). We consider three objectives: minimization of the superstructure material cost, minimization of the top-floor acceleration and minimization of the top-floor displacement. This multiobjective optimization yields a set of trade-off optimal solutions (the so-called Pareto optimal designs) that can be post-processed with tools such as hierarchical clustering or decision-making algorithms and further analyzed. The purpose of this analysis is to identify similarities within data sets or choose a final optimal solution based on pre-defined priority criteria applied to the optimization objectives. We compare the base-isolated structure results with the solutions found for the same building with a traditional foundation fixed to the ground.

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Keywords: Multiobjective sizing optimization ; Base isolation ; Genetic algorithms ; Clustering analysis

1. Introduction

The concept of seismic isolation is more than 100 years old but only in recent years it was adopted in practice and is becoming an alternative to conventional seismic construction methods especially for buildings of strategic importance

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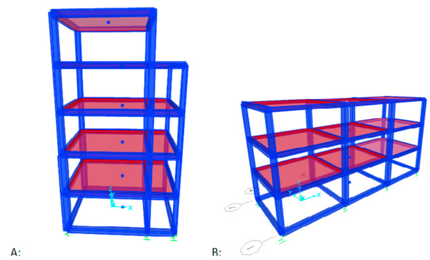


Fig. 1. Building three-dimensional extruded views from SAP2000. A: Asymmetric structure. B: Symmetric structure.

like hospitals or highly seismic regions. Base isolation uncouples a structure from the ground and significantly reduces both structural damages and damages to indoor furniture during an earthquake.

Recent studies appeared about the advantage of using base isolation also for standard buildings [1] and for structural design optimization in the base isolated case [2] [3].

In this work we performed a multiobjective sizing optimization of two simple buildings under seismic actions and with elastomeric isolators at the base. While the superstructure and the isolation system are generally designed separately, here we optimized at the same time the structural elements (superstructure column and beam sections and reinforcements) and the isolator parameters (rubber type, maximum allowed displacement and elastomer size). We considered three objectives: minimization of the superstructure material cost, minimization of the top-floor acceleration and minimization of the top-floor displacement. The purpose of this analysis is to identify similarities within data sets or choose a final optimal solution based on pre-defined priority criteria applied to the optimization objectives. A comparison with results found for a fixed based structure optimization is also presented.

2. Structural engineering application

We performed the seismic design of two structures isolated from the soil by means of elastomeric isolators, located in the Italian town of Reggio Calabria characterized by a high horizontal ground acceleration value ($a_g \simeq 0.27g$ for a life safety, or SLV, performance level spectrum). The structures are shown on Fig. 1. Structure [A] presents asymmetries both in elevation and in plan. It is composed by beams with two spans of length 6 m and 2 m in x direction and a span of 6 m in the y direction. There are six columns per floor, five floors for the first span and four for the second. Structure [B] is a symmetric three-storey building composed by beams with three spans of 6 m length in the x direction and a span of 6 m in the y direction. There are eight columns per floor. In both structures the floor to floor distance is 3 m. We considered a concrete of type C25/30 (confined characteristic compressive strength f_{ck} = 25 MPa and design compressive strength f_{cd} = 14.17 MPa) and a reinforcement steel of class B450A (yield stress f_{yk} = 450 N/mm^2).

Under each funding column there are equal isolators even if the columns are loaded differently. For structures of small dimensions it is not advantageous to use different isolators because this increases isolator testing and installation costs. We considered the elastomeric isolators of the "SI" series available from the *FIP Industriale* catalog [4]. These isolators are composed of alternating layers of elastomer and steel connected by vulcanization. The bearings usually have a circular section and are characterized by an adequate dissipative capacity, a high vertical stiffness and a small horizontal stiffness that makes them very flexible horizontally, thus enabling the building to move laterally under strong ground motion. These features enable an increase of the fundamental period of vibration and a reduction of the horizontal inter-floor displacement of the isolated structure, while still supporting vertical loads without appreciable failures. The vertical and horizontal stiffness of the isolators are determined by the dimensions of the layers of elastomer and steel and the mechanical characteristics of the elastomer. The isolator damping capacity is determined by the type of elastomeric compound. There are three types of compounds (soft, normal and hard) with a dynamic shear modulus varying from 0.4 to 1.4 MPa. The coefficient of equivalent viscous damping can be chosen in the interval from 10% to 15%. The isolators from the catalog are designed according to Italian seismic regulations [5] and [6] and are available for up to seven maximum allowed displacement values.

When a structure is isolated from the ground, the seismic actions on the columns are weaker than in the fixed-base case, and in that case the sections can be smaller. We aimed at verifying this assumption by this study.

To simulate the stresses in the structure for given vertical loads and seismic actions, the finite-element structural analysis software SAP2000 [7] was used. Beams and columns were represented with one-dimensional finite elements, while the floors were modeled by using two-dimensional elements with overloads and their structural weight. Since we wanted to focus on the isolation system, we did not consider perimeteral walls. The isolators were modeled with linear type links.

We performed a linear dynamic analysis with the response spectrum method (i.e. a multi-modal response spectrum analysis). The stresses in the structure for given vertical loads and seismic actions were computed with SAP2000. The prescriptions of Italian law NTC2008 [5] based on the Eurocodes were taken into account. For structure [A] we designed only the columns and isolating devices, while for structure [B] we also designed the beams according to the required compliance checks.

For the seismic loads we used the seismic response spectrum with the ground acceleration required for Reggio Calabria. We computed the resistance of the columns in the buckling verifications by enveloping the vertical (permanent and variable) loads (at the ultimate limit state, ULS) with the seismic combinations (in the x and y directions). Beam stresses (flexural design) were obtained only from the vertical loads at ULS (since the seismic combinations yielded negligible stresses). Displacements in the serviceability limit state (SLS) combinations were used for the damage verifications of the structure.

We considered three different seismic spectra: serviceability (SLS), SLV and collapse prevention limit state (SLC). The SLS spectrum was used for the top-floor displacement and inter-story drifts with a behavior factor $q = 1$. The SLV spectrum was used for the buckling verification of the columns. The behavior factor $q = 1.5$ in the base isolated structures, while $q = 3.12$ and $q = 3.9$ in the fixed-base asymmetric and symmetric structures respectively. The SLC spectrum (with $q = 1$) was used to compute the base displacement of the seismically isolated structure.

3. Description of the optimization problems for structures [A] and [B]

In both structures we considered three objectives to minimize: the top-floor acceleration, the top-floor displacement and the super-structure material costs. For structure [A] the material price consists in column concrete and reinforcement costs, while for structure [B] it also includes beam material costs. Concrete and steel cost respectively 127 euros/m^3 and 1 euro/Kg. Exact information on the price of the catalog [4] isolators was not available, but an estimate of the elastomeric isolator material costs was inferred from data found on iternet.

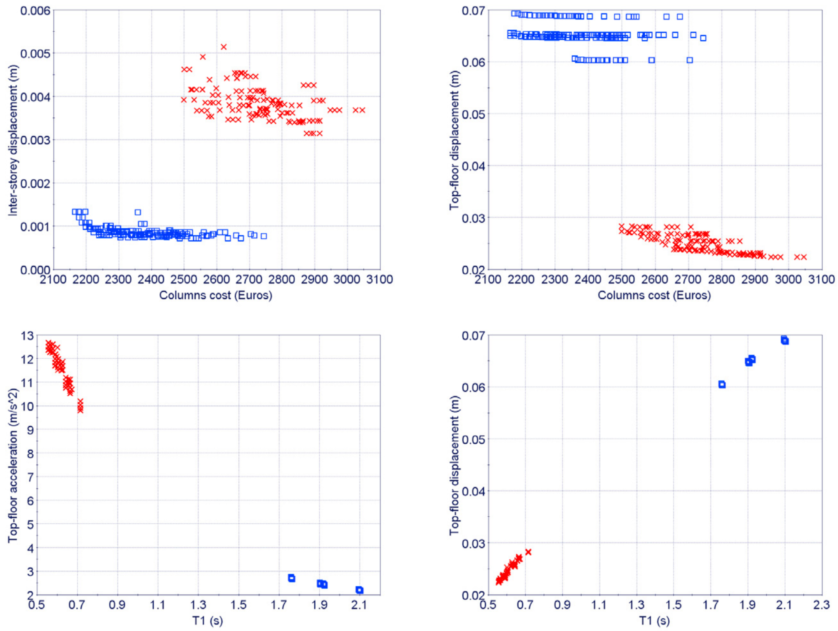
Structure [A] and [B] optimization problems have respectively 27 and 10 input variables. In [A], the super-structure input variables are: the column sections (in each floor they are different along the x direction; they change every two floors), the number of steel bars of the longitudinal reinforcement and the bar diameters for the different section types. In [B], the super-structure input variables are: the concrete sections for two types of columns (internal and external columns; columns are the same in each floor), the beam sections (all beams are identical and their dimensions follow the most loaded beam values) and sections of the beam and column reinforcements. For both [A] and [B] the isolating device input variables are the isolator maximum allowed displacement, elastomer type and elastomer layer dimensions[1] (which correspond to a pair of vertical and horizontal stiffness values). All the inputs have discrete values (taken from commercial catalogs).

We also considered three input constant parameters: the permanent and variable vertical loads (respectively 3000 N/m^2 and 2500 N/m^2) on the horizontal slabs used to represent the floors (these values are inserted like superficial loads in the SAP2000 file), and the isolator damping coefficient.

Problem [A] is hyper-constrained, since there are fifteen constraints (restrictions on the variation of column sections and the number and diameter of the reinforcing bars that change every two floors) on the input variables and thirty on the output variables. In output there are eight constraints for the buckling verification of the columns, sixteen for

[1] The isolator data in the catalog[4] are organized in pages corresponding to the allowed maximum displacement. Each page contains three tables corresponding to the elastomer type (soft, medium, hard). Table rows provide different values for isolator properties such as the elastomer layer thickness and stiffnesses.

Fig. 2. BI (empty squares) and FB (cross symbols) optimal solutions for structure [A].



the allowed percentage of reinforcing steel in a given concrete section, five for the SLS interstorey drifts (smaller than 0.01 m in an irregular plan structure), a constraint for isolator stiffness.

In [B] there are seven constraints on the input variables (allowed percentage of steel within given beam and column sections) and eight on the output variables (two for the compliance checks of load and resistance effects for the beam in the ULS, two for the column buckling, three for the SLS inter-storey drifts, with threshold value 0.015 m in the symmetric structure, and one for the isolator stiffness).

4. Simulations and optimization results

We performed optimizations with the genetic algorithm MOGA-II [8]. The use of genetic algorithms for solving multiobjective optimization problems is well established thanks to their capability of providing a set of non-dominated feasible solutions in a single run by evolving a population of candidate solutions. Moreover, MOGA-II is known to perform well on constrained problems with discrete variables.

We considered an initial population of 100 candidate designs and a directional crossover and mutation probabilities of 90% and 10% respectively. To achieve a reasonable convergence of results, 160 generations were executed.

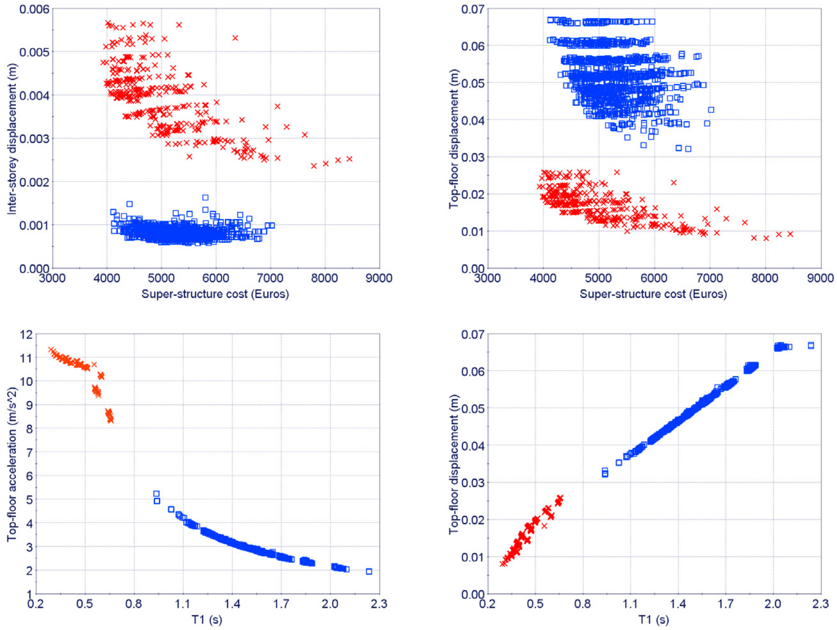
All simulations were performed with the multi-disciplinary optimization and integration platform modeFRONTIER [9] (mF). mF was integrated with SAP2000 by means of an Excel file, which controled the SAP2000 model by using a Visual Basic macro. The macro updated the SAP2000 model parameters with the values provided by mF for each proposed configuration. On the other hand, the macro wrote the output variable values provided by the SAP2000 calculations in the Excel file, where they were retrieved by mF and used by the optimization algorithm.

Our models do not take into account the shear reinforcements of the structure. The results provided must be considered only as guidelines for a designer who wants to determine the sections, the reinforcements and the elastomeric isolator features.

To better understand the effects of base isolation, we performed the sizing optimization for the base-isolated (BI) structures [A] and [B] described above and for fixed-base (FB) structures with the same super-structures as for [A] and [B]. In the FB optimizations MOGA-II was used with the same parameters as in the BI case, except for the number of generations which was 100.

Fig. 2 presents the optimal solutions found for the asymmetric structure [A] in the FB (cross symbols) and BI (squares) cases. The principal period T1 (first mode vibration period) and the top-floor displacement are bigger in the

Fig. 3. BI (empty squares) and FB (cross symbols) optimal solutions for structure [B].



BI case than in the FB, while inter-storey drifts, top-floor acceleration[2] and column cost are smaller. These findings met our expectation for the BI case. Smaller inter-storey drifts correspond to smaller damages during earthquake events (a BI structure can better absorb the seismic action) and this implies smaller maintenance and reparation costs.

Fig. 3 shows a comparison of the optimal results for the symmetric structure [B] in the FB (cross symbols) and BI (squares) cases. Acceleration, displacements and period T1 maintain the same trends as observed for [A] on Fig. 2, whereas the super-structure cost of [B] (which includes also the beam cost) does not appear to vary significantly except for a smaller upper bound of BI values. This behavior needs further investigation from our side. As it is, seismic isolation might appear to produce immediate cost reductions in the asymmetric case [A].

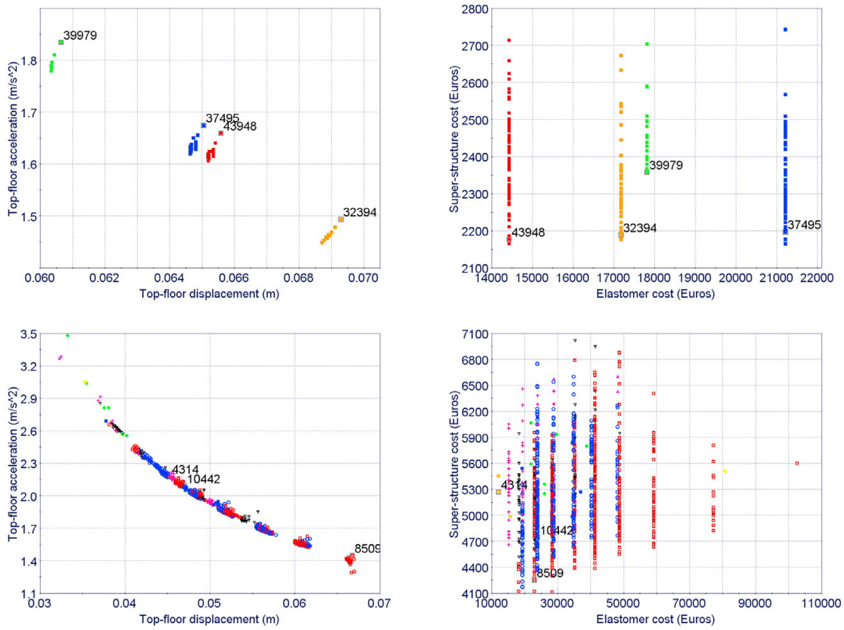
Once the optimal solutions are found, a final design should be chosen based on decision maker's preferences, like e.g. smaller initial costs (for the superstructure and/or isolating devices, in the BI case), or smaller actions and costs expected for maintaining the structure during its life cycle and/or after seismic events. Several post-processing decision making and data analysis tools are available in modeFRONTIER. Here we present a clustering analysis.

Hierarchical clustering [10] is a statistical method to find relatively homogeneous clusters of designs based on a similarity measure. At the start each design is a separate cluster, then the algorithm iteratively combines the clusters, linking designs together and reducing the cluster number at each step until only one cluster is left. The Euclidean distance is used as a measure for combining the clusters. The single-linkage clustering defines the distance between two clusters as the distance between their two closest members. It is able to detect elongated and irregular clusters.

Fig. 4 presents the optimal solutions found for the BI structures [A] (top panels) and [B] (bottom panels) classified with a single-linkage clustering on the isolator parameter values. Different color shades correspond to different clusters. In structure [B], the single-linkage algorithm correctly identified clusters corresponding to the isolator catalog tables (i.e. to different values of maximum allowed displacement and elastomer type), while in [A], where the optimizer found a very small number of isolators, each cluster corresponds to a single table raw (i.e. different pairs of stiffness values). The clustering analysis facilitates decision making. Let us take the reduction of the elastomer cost as preference criteria. As an example, we marked with a label some designs on Fig. 4. For structure [A], designs with the highest top-floor acceleration values within each cluster (top left panel) also have the smallest super-structure cost (top right). Choosing the compromise design 43948 for the top-floor acceleration and displacement yields large

[2] To perform the comparison, the top-floor acceleration was multiplied by the behavior factor for the FB and BI case (also on Fig. 3).

Fig. 4. Classification with single linkage hierarchical clustering: outcomes for structure [A] (top panels) and [B] (bottom panels).



savings both in the super-structure and isolation system costs. In structure [B], the design 4314 is a good compromise for the acceleration, displacement and superstructure cost and has the smallest elastomer cost.

5. Conclusions

A multiobjective sizing optimization of a symmetric and asymmetric reinforced concrete structure isolated at the base with elastomeric devices was presented. In this study, the elastomer cost is much higher than super-structure cost reductions allowed by the base isolation. However, low-cost optimized solutions can be selected. Results were analyzed by means of clustering techniques. The procedure is automated by using advanced software tools.

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