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Multi-objective optimization of elastomeric bearings to improve seismic performance of old bridges using eigen analysis and genetic algorithms

Key words: seismic isolation, OpenSees, genetic algorithms, Eurocode 8

Introduction

Bridges are a vital link in a road transport network, and their closure during extreme events such as earthquakes poses a threat to emergency services. In addition, the economic consequences can be severe in case of prolonged closure of these structures. Because of their importance for access to and evacuation of earthquake-affected areas, bridges and viaducts must remain operational with minimum capacity criteria after an earthquake. Some old bridges in Morocco are 40 years old or more. Consequently, they were designed without considering important seismic details that have been incorporated in recent codes and are not in conformity with the new seismic hazards. In addition, the effect of corrosion on transverse and longitudinal reinforcement of the piles contribute heavily on the reduction of the strength and ductility of the structure.

Many attempts have been made to provide old bridges additional ductility and strength, and seismic isolation remains the most practical and effective way to achieve it. The interest of an isolation system is the gain in lateral flexibility of the connection between the deck and the supports. This additional flexibility allows the fundamental period of vibration of the structure to be shifted to larger ranges of values. The seismic response of the structure is reduced and can approach the elastic range or with limited ductility.

However, an excessively prolonged period of vibration of the isolated bridges, using over flexible bearings, could lead to higher displacements between the deck and the piers, causing great damage on joints and bearings, spacing and discontinuity of the deck, and in some critical cases the unseating of the superstructure.

Many studies found in literature on optimal design of the seismic isolation system have been conducted during past decades. For example, Alhan and Gavin (2005) studied the seismic risk analysis of vital equipment by specifying the reliability of each component of the isolation system by considering the reliability of the entire isolated structure, for different seismic hazard levels. It includes uncertainties such as isolation system and ground motion characteristics by mean of Monte Carlo simulation techniques to determine failure probabilities. Léger, Rizzian and Marchi (2017) performed a multi-objective reliability-based design optimization of reinforced concrete structures with elastomeric base isolators, considering vertical loads and isolator damping as sources of uncertainties, and having the objective of minimizing displacement and forces at the floor level to limit damage. Mishra, Roy and Chakraborty (2017) considered optimizing the reliability of isolation systems at the base to overcome the damaging effects of seismic action and taking into consideration the uncertainties of the system. The concept of total probability theory is used to evaluate the unconditional response of structures under parameter uncertainty and a multi-story building isolated with elastomeric bearings to illustrate the effects of parameter uncertainties on the optimal performance of isolation systems. Roy and Chakraborty (2015) performed a robust optimization of the base isolation systems considering random parameters of the isolators, the structure and the seismic action. This optimization is conducted by minimizing the sum of the maximum displacement values of the structure floors and their standard deviation. Scozzese, Dall'Asta and Tubaldi (2019) analyzes this problem by proposing a general framework to explore the seismic risk sensitivity of structural systems with respect to system properties that vary within defined ranges. The results obtained show that the response of the structure varies considerably with damping properties. Scruggs, Taflanidis and Beck (2006) proposes a probabilistic approach to isolation systems based on structures modeled as linear dynamic systems subjected to stochastic seismic loads. Matsagar and Jangid (2004) studied the seismic response of bridges isolated by elastomeric bearings subjected to bi-directional seismic loads.

This research aims to provide a good understanding of the effects of seismic isolation as a rehabilitation method on the seismic performance of typical bridges, by formulating a multi-objective optimization problem, in order to efficiently design isolation system to retrofit exiting bridges, and determine a set of optimal compromising solutions that took into consideration the conflicting objectives cited before.

This procedure is coupled with a three-dimensional numerical model of the structure created using OpenSees, which allows a very detailed representation of the behavior of the structures, in order to quantify the effect of vibration period extension on seismic analysis results (displacements and stresses) (Alkhamis, Ghasemi, Gholinezhad, Shabakty & Abdullah, 2018).

Elastic response spectra

The reference representation of the seismic action in the Eurocodes is in the form of response spectra of an equivalent single degree of freedom system, with a viscous damping of 5% as a reference. In addition, Eurocode 8 adopt reference peak ground acceleration (PGA) on rock from zonation maps, developed using a probabilistic approach. Maps of statistical values (median, mean, 15th and 85th percentiles) were derived at return periods Tncr of 50, 225, 475 and 975 years and were finally used to propose a new seismic zonation supporting the regulation for the seismic of bridges (Fig. 1), these accelerations correspond to return periods Tnrc, for the design of the seismic action of bridges of medium importance. For bridges of Class III, PGAs are multiplied by the importance factor, recommended as 1.3, considered having major economic and social impact, and are crucial for communications and immediate post-earthquake period.

Probability of not being exceeded during a defined return period and present the different limit states summarized as follows (Table 1):

- The operational limit state advocating a frequent seismic action, with a return period of 50 years relative to a duration less than the service life of the structure.
- The immediate use limit state advocating occasional seismic action, with a return period corresponding to a duration equivalent to twice the service life of the structure, which is 225 years.

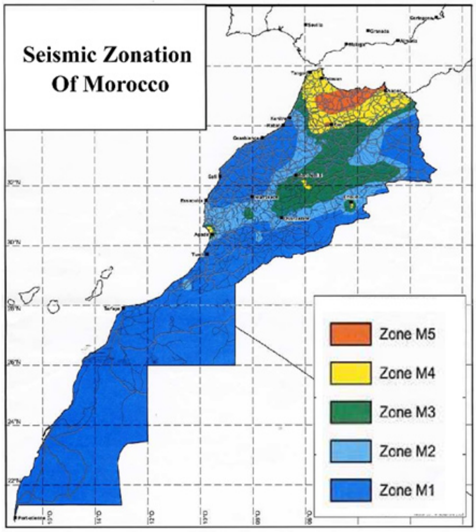

FIGURE 1. Seismic zonation map of Morocco

- The limit state of structural safety advocating a rare seismic action, with a probability of not being exceeded of 10% corresponding to a return period of 475 years.
- The near-collapse limit state advocating a very rare seismic action with a probability of not being exceeded of 2% with a return period of 975 years.

TABLE 1. PGAs adopted for the bridge study example

Parameter	Operational	Immediate use	Life safety	Near collapse
Tncr [year]	50	225	475	975
PGA [$m \cdot s^{-2}$]	0.65	0.91	1.26	1.91

Two types of spectra shape for each ground type are adopted in accordance to Eurocode 8, type 1 for moderate to large magnitude earthquakes and type 2 for low-magnitude ones at close distance (Table 2; Kolias, Fardis, Pecker & Gulyanessian, 2012)

TABLE 2. Standard horizontal elastic response spectra recommended in the EC8

Ground type	Spectrum type 1				Spectrum type 2			
	S	Tb	Tc	Td	S	Tb	Tc	Td
A	1.00	0.15	0.40	2.00	1.00	0.05	0.25	1.20
B	1.20	0.15	0.50	2.00	1.35	0.05	0.25	1.20
C	1.15	0.20	0.60	2.00	1.50	0.10	0.25	1.20
D	1.35	0.20	0.80	2.00	1.80	0.10	0.30	1.20
E	1.40	0.15	0.50	2.00	1.60	0.05	0.25	1.20

Consequently, the elastic response spectrum adopted to conduct seismic analyses, for ground type B, are summarized in Figure 2.

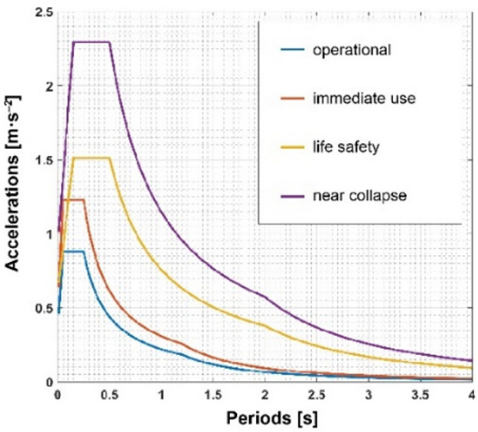

FIGURE 2. Elastic spectrum for different limit states

Low-damping elastomeric bearings

Elastomeric bearings (Fig. 3) are used as an effective and simple means of providing partial isolation of the structure. The vibration period of the structure is shifted to higher values due to the increased flexibility provided by the elastomers. And thus the seismic demand in terms of seismic forces is reduced. In practical, the reduction of the horizontal stiffness of the total system (K_{eff}) increases its fundamental period $T_{eff} = 2\pi\sqrt{\frac{M}{K_{eff}}}$ relative to that of the initial structure. The acceleration spectrum shows that this period shift brings about a substantial reduction in the spectral acceleration. However, the displacement spectrum clearly shows that the displacement is also increased substantially.

FIGURE 3. Laminated elastomeric bearings

The elastomers show an elliptical hysteretic behavior with an equivalent viscous damping of 6% and their shear behavior can be considered as linear. This behavior is defined by the stiffness modulus of the elastomers. The damping they offer is consistent with the default value of 5% used in linear analysis.

Such bearings are designed to resist all non-seismic horizontal and vertical actions. Consequently, different types of ultimate limit states verifications must be done for all types of elastomeric bearings, and are detailed thereafter. The main physical parameter of the elastomer used in the design of the bearing is its conventional shear modulus (G), with a nominal value G of the conventional shear modulus is 0.9 MPa.

The dimensions in plan, the thickness and the number of elastomer layers determines the population of standard sized bearings meeting previous non-seismic requirements. The incredible number of feasible solutions make the computational time cost unrealistic, guiding us to use a multi-objective optimization approach using genetic algorithm (Xie & Zhang, 2018).

Multi-objective optimization

The use of isolation and damping techniques is an effective means of achieving the desirable level of seismic performance and safety. However, it is difficult to achieve the desired design objectives at each of the seismic hazard levels while taking full advantage of the benefits offered by isolation and damping systems. In practice, the design is performed for a single-hazard performance level, typically corresponding to the highest seismic hazard, and the consequences of that design on performance for lower seismic hazard levels are accepted, without any optimization. Such a design approach generally results in seismic protection solutions that provide no or very limited improvement in the performance of the bridge structure for more frequent and smaller seismic events, because the isolation system is unlikely to be activated during such earthquakes. Damage prevention under frequent events will require that the bridge needs to be designed to respond elastically to this level of seismic hazard. If, instead, the protection system is designed to fully engage under the lower level event, the bridge is susceptible to excessive deformation through the isolation system and, therefore, significant damage or even the possibility of collapse under a stronger earthquake. Ideally, a bridge protection system based on isolation and damping should have a positive impact on the seismic performance at the different hazard levels (Rizzian, Léger & Marchi, 2017). In a context of structure design based on the performance approach, multi-objective optimization allows to take into consideration the achievement of several objectives simultaneously (Dezfuli & Alam, 2013). This capability is all the more useful when these objectives behave in a conflicting way, i.e. the improvement of one objective cannot be done without deteriorating the performance of the remaining objectives. The multi-criteria optimization problem is expressed by the following relation (Ohsaki, Yamakawa, Fan & Li, 2019):

Minimize

$$y(x) = \{f_1(x), f_2(x), ..., f_n(x)\}, x \in \theta \quad (1)$$

Subject to

$$h(x) \leq 0 \quad (2)$$

where:

x – input variables of the considered system,

f – function reflecting an objective,

n – number of objective functions,

h – constraint function.

The result of the multi-objective optimization is a set of solutions representing the best compromise of the different objective functions. The Pareto front is the graphical representation of these optimal solutions (Kwag & Ok, 2013). To deal with multi-objective optimization problems, GA toolbox, a MATLAB optimization toolbox was used. It incorporates the NSGA-II (non-dominated sorting genetic algorithm II). This algorithm has shown good results in solving complex multi-objective optimization problems, being able to find diverse solutions of the Pareto front with little computational effort. The algorithm begins by generating a population of 50 individuals in the design space. The values of the objectives are calculated for the different individual solutions and the optimization criterion is chosen from the set of options such as the number of generations, the limit calculation time, and the tolerance function (Pourzeynali, Salimi & Kalesar, 2013). The individuals are then ranked according to the objective values. It creates an order among the individuals by mean of fitness assignment. A selection criterion filters out the candidate solutions with poor fitness and retains those with acceptable fitness to enter the reproduction process with a higher probability. A new generation in the genetic algorithm is created through reproduction from the previous generation. Three mechanisms (elitist, crossover, and mutation) are primarily used to create a new generation. The algorithm finished by obtaining best individuals that satisfies the termination criteria (Pourzeynali, Malekzadeh & Esmaeilian, 2012).

Description of the bridge

In order to investigate the effectiveness of the proposed optimization of the seismic performance of the structure, a reinforced concrete girder bridge (Fig. 4) located in the city of Casablanca, Morocco, is selected.

FIGURE 4. Reinforced concrete girder bridge

An investigation program is conducted in order to determine material characteristics of the supports, carrying out exhaustive surveys of damage, in-situ tests, and laboratory tests on concrete cores and finally inspecting the state of corrosion of the reinforcements (Table 3; Abbadi & Lamdouar, 2019). The distribution of the reinforcement inside piles (Fig. 5) is evaluated using magnetic auscultation with pachometer, the device also provides an estimate of the cover and the diameter of the detected reinforcement. For the characterization of the concrete properties, sclerometric auscultation is conducted confirmed with core tests (Table 4; Abbadi & Lamdouar, 2018).

TABLE 3. Main characteristics of the bridge study example

Property	Description
Year of construction	1978
End supports	abutment with front wall with integrated header and return walls for support on the landside
Intermediate supports	piers with multiple piles (05), tied by headbands
Superstructure	11 reinforced concrete beams
Support devices	laminated elastomer: 11 for each support
Number of spans	4
Bias	100 g
Total length	49.36 m
Overall width	10.25 m
Rolling width	7 m
Air draft	5.33 m

FIGURE 5. Visual examination of columns

TABLE 4. Mean values ($\bar{x}$) and standard deviations (SD) of material properties

Property	$\bar{x}$	SD
Longitudinal reinforcement spacing [cm]	17	3
Transverse reinforcement spacing [cm]	15	2
Longitudinal reinforcement diameter [cm]	25	0
Transverse reinforcement diameter [cm]	8	0
Concrete cover [cm]	3	0.5
Compressive concrete strength [MPa]	31.1	5.4

Verifications of elastomeric bearings

Four types of ultimate limit state verification must be made for elastomeric laminated bearings of any type:

- the maximum total distortion at any point in the bearing is limited;
- the thickness of the shrink discs must be sufficient to withstand the tension they are subjected to;
- the stability of the support device must be ensured against rotation, buckling and sliding;
- the actions applied by the bearing device on the rest of the structure must be checked (direct effect of the bearing device on the structure and indirect effect due to the deformations of the bearing device).

The verifications are carried out for several horizontal deformations of the elastomer, corresponding to the displacements that it undergoes during a seismic event (Fig. 6). A reduced area (A_r) (Fig. 7) is calculated as follow:

$$A_r = A' \cdot \left(1 - \frac{v_x}{a'}\right) \tag{3}$$

where:
A' – effective area of the elastomer,
v_x – lateral displacement,
a' – dimension in plane of the elastomer.

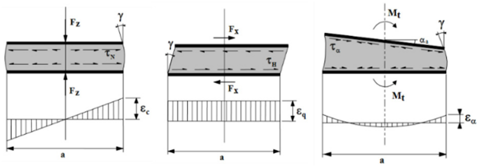

FIGURE 6. Illustrations of the verifications

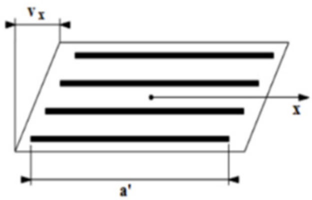

FIGURE 7. Reduced area due to horizontal strains

Numerical study

The deck is modeled by beam-column elements with linear behavior. The modulus of elasticity is determined for a concrete with a characteristic strength of 34 MPa. The supports are modeled for characteristic concrete strengths according to the state of confinement of each pier composing these supports (Table 5; Abbadi & Lamdouar, 2018). Each support is composed of five piles connected by a common beam. The Popovics behavior law is used to model the concrete, referenced as “concrete04” in OpenSees. The bearings are modeled as “zero length” elements with a linear elastic behavior law. The modulus of elasticity in the lateral directions corresponds to that of elastomers, while that in the vertical direction is infinitely stiff.

TABLE 5. Material properties of concrete and reinforcement for different levels of corrosion

Parameter	Column				
	C0	P1	P2	P3	C4
Core concrete					
E [GPa]	13.21	7.94	10.16	13.21	10.16
f'_{cc} [MPa]	31.05	38.6	34.04	31.05	34.04
ε'_{cc} (10^{-3})	2.35	3.86	3.35	2.35	3.35
ε_{cu} (10^{-3})	3.55	5.60	4.56	3.55	4.56
Cover concrete					
E [GPa]	15.87	21.11	17.41	15.87	17.41
f'_{c0} [MPa]	22.23	29.56	24.38	22.23	24.38
ε'_{c0} (10^{-3})	1.4	1.4	1.4	1.4	1.4
ε_{cu} (10^{-3})	2.1	2.1	2.1	2.1	2.1
Reinforcement					
Yield stress [MPa]	235	235	235	235	235
ε_{cu} (10^{-3})	3.55	5.60	4.56	3.55	4.56

Multi-objective analysis using 3D OpenSees Model

A finite element analysis with a 3D model coupled with a multi-objective analysis is conducted to obtain periods and eigen modes. The algorithm generate a population of 50 individuals in the design place, issued from a custom function that respect calculated stiffness’s (Fig. 8). Pushover analysis determines the performance points consisting on moment-displacement values for each limit states in the longitudinal (Fig. 9) and transverse directions (Fig. 10). Tournament option is chosen to execute the selection process, and a crossover fraction of 0.8 is taken to produce the next generation. Thereafter mutation process intervene where small random changes in the individuals in the population are created, which provide genetic diversity and enable the genetic algorithm to search a broader space, and arithmetic function crossover is used to create children’s that are a random arithmetic mean of two parents.

The objectives to be optimized simultaneously are expressed as follows:

$$f_{d,i\in\{OP,IU,LS,NC\}} = Disp_{Acc\in\{OP,IU,LS,NC\}} \quad (4)$$

$$f_{f,i\in\{OP,IU,LS,NC\}} = Forces_{Acc\in\{OP,IU,LS,NC\}} \quad (5)$$

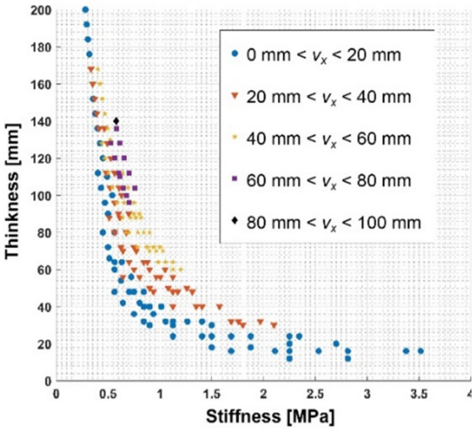

FIGURE 8. Flowchart of feasible elastomeric bearings characteristics and the corresponding allowable maximum displacements

The Pareto fronts of optimal solutions are presented as a set of points that represented the best compromising responses in terms of displacements and moments for the four limit states considered in the transverse (Fig. 11a) and longitudinal directions (Fig. 11b).

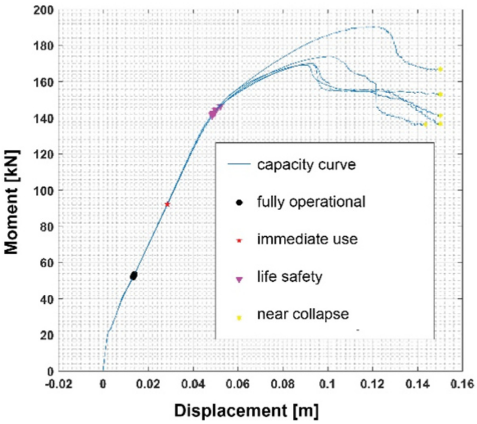

FIGURE 9. Limit states at longitudinal direction

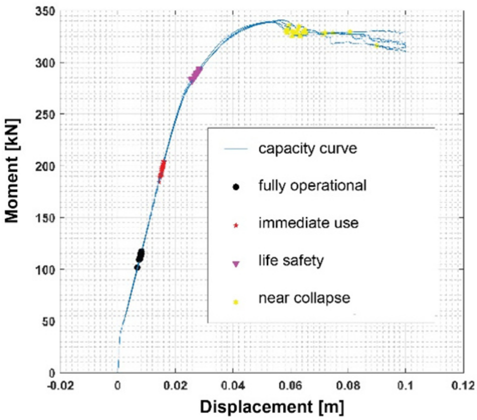

FIGURE 10. Limit states at transverse direction

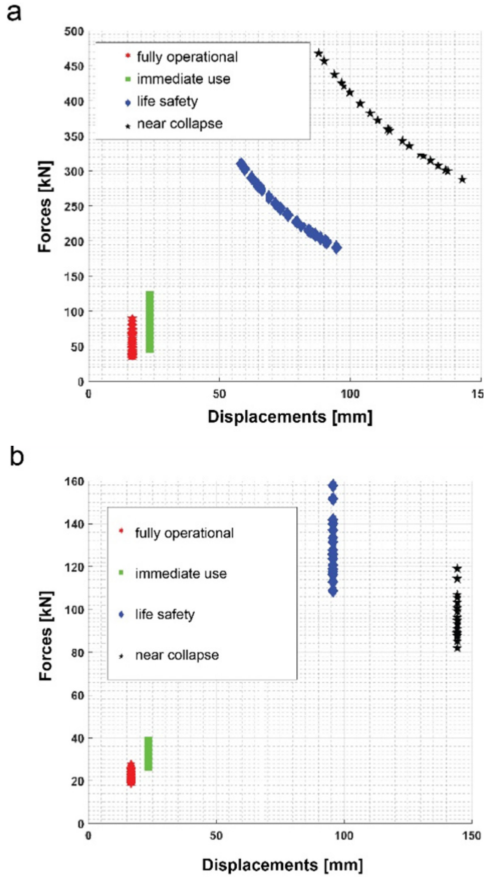

FIGURE 11. Optimal values of accelerations and displacements for various bearing stiffness's in the transverse (a) and longitudinal (b) direction

Multi-objective analysis using two degree of freedom model

The seismically isolated bridge is assumed to be fixed at the base of the columns and the bridge superstructure is assumed to be relatively rigid with respect to the bridge bearings and columns. Therefore, the isolated regular bridge is modeled as a system with two degrees of freedom in the lateral and transverse direction (Jara & Casas, 2006).

The multi-objective optimization is conducted according to the same procedure of the analysis using 3D OpenSees model and the results are summarized in Figure 12a for the transverse and Figure 12b for the longitudinal direction.

The results of the optimization show that the objectives in terms of ductility and forces are considerably improved. In the transverse direction, the demand for forces is reduced by more than 100%, while the ductility demand is reduced by 50% for large seismic actions. In the longitudinal direction, the improvement is less important, about 50% for forces and almost stable for ductility. It should be noted that the results of the optimization based on the simplified model in two degrees of freedom are in agreement with the results of the optimization based on numerical modelling.

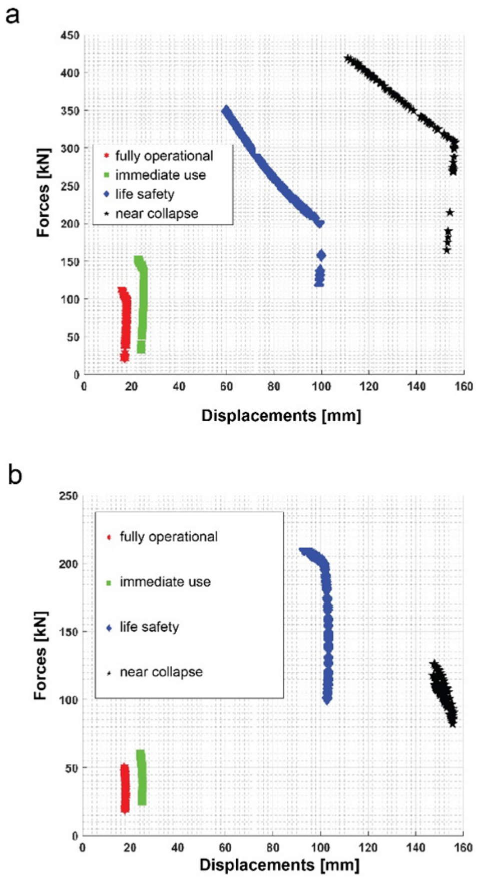

FIGURE 12. Optimal values of accelerations and displacements for various bearing stiffness's in the transverse (a) and longitudinal (b) direction

Multi-objective analysis using equivalent single degree of freedom analysis

The use of simple equivalent single degree of freedom systems (Fig. 13) has been recognized for many decades as the simplest way to obtain information on the dynamic response of isolated structures subjected to seismic excitations. For the analysis of bridge structures in the longitudinal and transverse directions, it is common to divide the structure into two model elements: the substructure and the superstructure. Most of the mass of the bridge is located at the deck (superstructure), and the effect of the substructure mass is neglected when Conversely, the stiffness of the substructure has a significant effect on the behavior of the structure and must be considered accurately. The superstructure is modelled as a rigid body with infinite axial stiffness. For straight bridges, the motion of the superstructure in the longitudinal and transverse directions can be considered decoupled. Using these simplifying assumptions, SDOF analyses can be used for the seismic analysis of most isolated ordinary bridges, and consequently in order to check eigenvalue analysis in OpenSees. Thus, the entire bridge is represented as a simple oscillator that consists of the total mass concentrated at the upper end of a single pole with the same stiffness and damping properties as the bridge substructure. k1 and c1 are the lateral stiffness and viscous damping coefficients. Both coefficients represent the contribution of substructure elements, including intermediate supports, abutments, and isolation and damping devices.

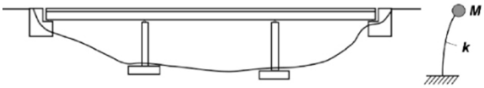

FIGURE 13. SDOF modeling of bridges

For a bridge design with isolation at the top of the piers and abutments, the equivalent stiffness is determined according to Equation (6). The two terms in this expression represent two springs placed in series. The first term is the stiffness contribution of the piers and their bearings, while the second term represents the two abutments and their bearings.

$$k_{eq} = \sum_{j=1}^{n} \frac{k_{pier,j} \cdot k_{isol,j}}{k_{pier,j} + k_{isol,j}} + \sum_{j=1}^{2} \frac{k_{abut,j} \cdot k_{isol,j}}{k_{abut,j} + k_{isol,j}} \quad (6)$$

Assuming that the abutments are infinitely rigid with respect to the piers, the equation becomes:

$$k_{eq} = \sum_{j=1}^{n} \frac{k_{pier,j} \cdot k_{isol,j}}{k_{pier,j} + k_{isol,j}} + \sum_{j=1}^{2} k_{isol,j} \quad (7)$$

Consequently, the Pareto fronts are plotted as presented in the transverse (Fig. 14) and longitudinal (Fig. 15) directions.

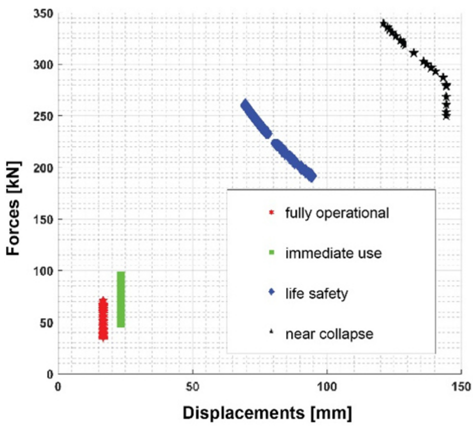

FIGURE 14. Optimal values of accelerations and displacements for various bearing stiffness's in the transverse direction

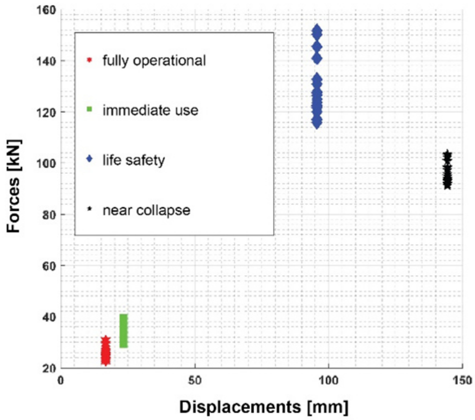

FIGURE 15. Optimal values of accelerations and displacements for various bearing stiffness's in the longitudinal direction

The results of the optimization based on the equivalent single degree of freedom model are in agreement with the two degree of freedom model and also with the results of the optimization based on numerical modelling, which allows to validate the adapted methods.

Results and discussion

This study proposes an optimal design method of the seismic isolation system for existing bridges. The method combine finite element methods with multi-objective optimization approach, enabling two major advantages. First, the multi-objective optimization using genetic algorithms can handle mutually multiple conflicting objectives with affordable computational cost, producing a set of optimal solutions helping the designer to choose between multiple alternatives. Second, the use of linear analysis allow the assessment of the structure in the elastic range using elastomeric bearings, in such a way that displacements, representing service conditions of the bridge, remains acceptable. Third, the actual behavior of the columns materials properties is taken into account, picturing the real response of the structure, verified and validated by analytical simplified SDOF model. The case study demonstrates that the proposed approach might constitute an efficient tool to optimize seismic performance in terms of forces applied to columns and deck displacements, in accordance with the limit state requirements described in the Eurocode 8, under various earthquake loads. The capacity curves of the columns gives the forces and displacements corresponding to each of the limit states reflecting the damage occurred. However, this method focuses on the elastic behavior of the structure and the period shift created by the bearings without taking into account the energy dissipation and the increase of damping in the structure. Also all the solutions proposed for limit states LS and NC do not allow to reach the seismic performance objectives expected for the structure. It is then necessary to solicit the bearings in the post-elastic domain, integrating equivalent damping and rigidity. The confrontation of the results of the three methods shows a good agreement for different values of elastomer stiffness's, which allows us to validate the numerical model built with OpenSees. Thereafter, Pareto fronts are generated in the longitudinal and transverse directions, and for different limit states. The first objective function is the acceleration where the second objective function is the displacement.

Conclusions

In this study, we provide a multi-objective optimization method for specifying the isolation elastomer bearings characteristics such that an optimal performance of existing bridges, in terms of both accelerations and displacements, achieved under the elastic spectra specified in the Eurocode 8 for multiple limit states. The linear response of the structure is estimated from the eigenvalue analysis conducted on a 3D OpenSees numerical model. Periods are obtained for the transverse and longitudinal directions. Displacements and accelerations are directly calculated by mean of limit states elastic spectra. The results are compared and validated with the idealization of the structure as an SDOF and 2DOF systems The optimal stiffness of bearings are evaluated by selecting the displacement and accelerations as the objective functions which to be minimized. The goal is finding so called Pareto-optimal solutions by using a fast and elitist non-dominated sorting genetic algorithm (NSGA-II) in MATLAB. From the trends of the results of the present study, following conclusions are drawn:

- Isolation bearings with different stiffness values gives a range number of seismic behaviors to the structures, and optimal solutions tend to decrease displacement and acceleration limits fixed by the seismic demands.
- All the solutions afforded by the NSGA-II optimization algorithm constitutes the best stiffness bearings values to minimize the displacements and accelerations for all the limit states considered.

- A substantial decrease of the forces in the columns is achieved while keeping displacements of the superstructure within acceptable limits.
- It has been observed for non-collapse and life safety limit states that the requirements do not meet for any of the isolation bearings susceptible to be used to the structures. In such a case, a non-linear analysis is needed in order to take into account the post-elastic behavior of the bearings and the columns. An additional damping and dissipation energy must be taken into account consequently.
- This study focuses on the global linear behavior of partially isolated exiting bridges, and constitute a prelude to a more advanced analysis, such as pushover and non-linear time history.

It's of great importance to investigate the robustness of the solutions proposed regarding system uncertainties such as traffic load, stiffness variations, constitutive materials behavior.

References

Abbadi, M.S. & Lamdouar, N. (2018). Structural evaluation updating based on quality control and proof loads. *MATEC Web of Conferences*, *149*, 02014. https://doi.org/10.1051/matecconf/201814902014

Abbadi, M.S. & Lamdouar, N. (2019). Pushover analysis of RC columns subjected to multiple degrees of transverse reinforcement corrosion. *International Journal of Civil Engineering and Technology*, *10*(11), 313-322.

Alhan, C. & Gavin, H.P. (2005). Reliability of base isolation for the protection of critical equipment from earthquake hazards. *Engineering Structures*, *27*(9), 1435-1449.

Alkhamis, M., Ghasemi, M.R., Gholinezhad, A., Shabakhty, N. & Abdullah, W. (2018). Performance-based Optimum Retrofitting Design of Concrete Bridge Piers. *Jordan Journal of Civil Engineering*, *12*(4), 637-653.

Dezfuli, F.H. & Alam, M.S. (2013). Multi-criteria optimization and seismic performance assessment of carbon FRP-based elastomeric isolator. *Engineering Structures*, *49*, 525--540.

Jara, M. & Casas, J.R. (2006). A direct displacement-based method for the seismic design of bridges on bi-linear isolation devices. *Engineering structures*, *28*(6), 869-879.

Kolias, B., Fardis, M.N., Pecker, A. & Gulvanessian, H. (2012). *Designers' guide to Eurocode 8: design of bridges for earthquake resistance*. London: ICE Publishing.

Kwag, S. & Ok, S.Y. (2013). Robust design of seismic isolation system using constrained multi-objective optimization technique. *KSCE Journal of Civil Engineering*, *17*(5), 1051-1063.

Léger, N., Rizzian, L. & Marchi, M. (2017). Reliability-based design optimization of reinforced concrete structures with elastomeric isolators. *Procedia Engineering*, *199*, 1193--1198.

Matsagar, V.A. & Jangid, R.S. (2004). Influence of isolator characteristics on the response of base-isolated structures. *Engineering Structures*, *26*(12), 1735-1749.

Mishra, S.K., Roy, B.K. & Chakraborty, S. (2013). Reliability-based-design-optimization of base isolated buildings considering stochastic system parameters subjected to random earthquakes. *International Journal of Mechanical Sciences*, *75*, 123-133.

Ohsaki, M., Yamakawa, M., Fan, W. & Li, Z. (2019). An order statistics approach to multiobjective structural optimization considering robustness and confidence of responses. Mechanics *Research Communications*, *97*, 33-38.

Pourzeynali, S., Malekzadeh, M. & Esmaeilian, F. (2012). Multi-objective optimization of semi-active control of seismically exited buildings using variable damper and genetic algorithms. *International Journal of Engineering*, *25*(3), 265-276.

Pourzeynali, S., Salimi, S. & Kalesar, H.E. (2013). Robust multi-objective optimization design of TMD control device to reduce tall building responses against earthquake excitations using genetic algorithms. *Scientia Iranica*, *20*(2), 207-221.

Rizzian, L., Léger, N. & Marchi, M. (2017). Multiobjective sizing optimization of seismic-isolated reinforced concrete structures. *Procedia Engineering*, *199*, 372-377.

Roy, B.K. & Chakraborty, S. (2015). Robust optimum design of base isolation system in seismic vibration control of structures under random system parameters. *Structural Safety*, *55*, 49-59.

Scozzese, F., Dall'Asta, A. & Tubaldi, E. (2019). Seismic risk sensitivity of structures equipped with anti-seismic devices with uncertain properties. *Structural Safety*, *77*, 30-47.

Scruggs, J.T., Taflanidis, A.A. & Beck, J.L. (2006). Reliability-based control optimization for active base isolation systems. *Structural Control and Health Monitoring: The Official Journal of the International Association for Structural Control and Monitoring and of the European Association for the Control of Structures*, *13*(2-3), 705-723.

Xie, Y. & Zhang, J. (2018). Design and optimization of seismic isolation and damping devices for highway bridges based on probabilistic repair cost ratio. *Journal of Structural Engineering*, *144*(8), 04018125. https://doi.org/10.1061/(ASCE)ST.1943-541X.0002139

Summary

Multi-objective optimization of elastomeric bearings to improve seismic performance of old bridges using eigen analysis and genetic algorithms. Old bridges present several seismic vulnerabilities and were designed before the emergence of seismic codes. In this context, partial seismic isolation has given a special attention to improve their seismic performance. In particular, elastomeric bearings are the simplest and least expensive mean for this, enabling to resist both non-seismic actions and earthquake loads. In order to assess the initial structural performance and the improvement done by the isolation, this paper attempts to combine multi objective optimization using genetic algorithms with linear and non-linear analysis using FE program OpenSees. A prior screening of the columns states is settled and then a multi objective optimization of a population of standard sized bearings meeting non-seismic and stability requirements is established to optimize the linear and non-linear behavior of the structure, finding the best compromise between displacements and forces at the columns.

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