Life-Cycle of Structures and Infrastructure Systems

Editors
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LIFE-CYCLE OF STRUCTURES AND INFRASTRUCTURE SYSTEMS

Life-Cycle of Structures and Infrastructure Systems collects the lectures and papers presented at IALCCE 2023 - The Eighth International Symposium on Life-Cycle Civil Engineering held at Politecnico di Milano, Milan, Italy, 2-6 July, 2023. This Open Access Book contains the full papers of 514 contributions, including the Fazlur R. Khan Plenary Lecture, nine Keynote Lectures, and 504 technical papers from 45 countries.

The papers cover recent advances and cutting-edge research in the field of life-cycle civil engineering, including emerging concepts and innovative applications related to life-cycle design, assessment, inspection, monitoring, repair, maintenance, rehabilitation, and management of structures and infrastructure systems under uncertainty. Major topics covered include life-cycle safety, reliability, risk, resilience and sustainability, life-cycle damaging processes, life-cycle design and assessment, life-cycle inspection and monitoring, life-cycle maintenance and management, life-cycle performance of special structures, life-cycle cost of structures and infrastructure systems, and life-cycle-oriented computational tools, among others.

This Open Access Book provides both an up-to-date overview of the field of life-cycle civil engineering and significant contributions to the process of making more rational decisions to mitigate the life-cycle risk and improve the life-cycle reliability, resilience, and sustainability of structures and infrastructure systems exposed to multiple natural and human-made hazards in a changing climate. It will serve as a valuable reference to all concerned with life-cycle of civil engineering systems, including students, researchers, practitioners, consultants, contractors, decision makers, and representatives of managing bodies and public authorities from all branches of civil engineering.

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Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

Evaluation of the safety factor in masonry buildings as acceleration varies: A quick approach

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ABSTRACT: The topic addressed in this paper is the search for a quick method of evaluating the seismic behaviour of masonry buildings that can be easily extended to portions of historical buildings. The proposed method is the extension to the probabilistic field of the evaluation of safety factors already present in the literature. The method applied to the proposed case study shows how the fragility curves describing the variation of the safety factors with the variation of the expected accelerations could be a useful support tool in the planning of safeguard interventions and how they are able to show, in probabilistic terms, the possible impact of seismic improvement interventions on the expected structural response.

1 INTRODUCTION

The assessment of the seismic behaviour of existing buildings undamaged by the earthquake is an important topic for the classification and subsequent safety of the historic buildings in the entire Italian territory.

The procedure that leads to the large-scale seismic performance assessment of masonry buildings must necessarily be a simple and reliable procedure. It is assumed that it should provide elements in support of a possible assessment starting from data that can be easily found in the municipal archives without necessarily requiring visits and surveys on site (which are, however, not always possible).

Approaches that address the issue of studying the seismic vulnerability and the propensity to damage of the existing buildings have been developed over the last few years by the Italian scientific community, but often the post-earthquake assessment is the starting point (Rosti, Rota &Penna 2009; Zuccaro, Perelli, De Gregorio & Cacace 2021). The models proposed are often very refined models that require an in-depth knowledge of the building and professionals qualified in the use of the calculation processes and important processing times (Saloustros, Pelà, Roca & Portal 2015).

The purpose of this research is to find a procedure to estimate the global seismic performance of existing buildings not yet damaged by an earthquake, which is reliable and easily extendable to the assessment of an entire urban area. The procedure can be useful for public administrations as a tool on which to base maintenance planning.

The approach proposed here is a probabilistic extension, of the method proposed by Borri, De Maria & Casaglia (2014) and Borri, Corradi, Castori & De Maria (2015) relating to three types of simplified verification: simplified gravity verification, simplified global horizontal loading verification and simplified local mechanism verification. The results of the three simplified checks are compared with the safety levels required by the Italian NTC2018 (NTC Italian Building Code 2018) standards for the limit state of safeguarding human life (SLV) referred to the site in question, the building type considered and the intended use class. These results are expressed in terms of conventional safety factors.

To extend this procedure to the field of probabilistic prediction in Angieliu, Cardani & Garavaglia (2022) the construction of fragility curves which could describe the variation of the global safety factor, SF_G, was studied, as the expected accelerations vary in a certain seismic zone.

In this paper the method is also extended to the prediction of the variation of the local safety factor, SF_L; this evaluation requires somewhat more detailed information than that

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required by the evaluation of SF$_G$. The method is applied here on a case study on which the information allowed the evaluation of both factors. The SF$_G$ evaluation was performed for the initial situation of the building; the SF$_L$ evaluation was performed both for the initial situation of the building (pre-seismic improvement) and for the current situation (post-seismic improvement). The two probabilistic assessments were then compared.

2 THE DAMAGE PARAMETER SF

The expeditious assessment of the residual capacities of a building located in a seismic risk area requires the use of a parameter that is sufficiently reliable and quantifiable on the basis of data available from shared databases. A parameter that has these characteristics is the safety factor, SF, proposed by in Borri, De Maria & Casaglia (2014). The safety factor is a parameter capable of describing the performance of the structure when subjected to a certain acceleration. This performance is the measure of the loss in safety of the structure after the event, loss quantified through appropriate parameters.

In Borri, De Maria & Casaglia (2014) two types of safety parameters are distinguished: the global parameter, SF$_{G,}$ which describes the performance of the entire building and the local parameter, SF$_L$, which describes the possible collapse mechanism that can locally affect some points of the building.

The global parameter SF$_G$ can be obtained from the geometry of the structure, and from the empirical evaluation of the masonry quality, data easily available from existing databases (Cadastre, municipal archive, vulnerability cards, etc.) The local parameter, SF$_L$, requires, instead, a little more detailed knowledge of the structure; in fact, its evaluation requires the estimate of the analysis of the loads and the definition of the framework of the decks (more details in section 4).

The parameters SF$_G$ and SF$_L$ are deterministic and associated with a specific building. In Angjieliu, Cardani & Garavaglia (2022), such approach was the basis of the study for a probabilistic application that also showed the possibility of extending the method to the evaluation of the safety of the different types of masonry buildings as the expected acceleration values varied.

3 FRAGILITY CURVES

The method consists in the construction of curves that allow a probabilistic prediction of the occurrence of a certain phenomenon when a certain condition varies, such as the probability of reaching a certain damage threshold when the level of acceleration recorded varies, as in Garavaglia et al., (2008, 2021), but also in Singhal & Kiremidjian (1996), Flora, Perrone and Cardone (2020) or Sandoli, Lignola & Calderoni (2021). The safety factors SF$_G$ and SF$_L$ proposed in Borri, De Maria & Casaglia (2014) are able to describe this behaviour, so they can be assumed as damage indices to be studied from a probabilistic point of view.

The construction of the curves starts from the modelling, with an appropriate probability density function (p.d.f.) of the values of the selected variable, here generally called SF, present in a certain range of the ground acceleration a^*. Therefore, in the cases studied, the fragility curve defines the probability for a system to reach the loss of a certain value of SF at a defined acceleration $\bar{a}$. Once the damage threshold $\overline{sf}$ is defined, the probability of this threshold being reached at instant a^* is described by the area to the left, below the p.d.f. (dashed area**).**

On the opposite, the probability of exceeding this threshold is described by the area below the p.d.f. to the right in the solid area (Figure 1a).

By constructing the probability density function for the chosen random variable for each of the chosen intervals, or acceleration values, it is easy to see how it is possible to construct the fragility curve linked to the experimental evidence or, better called, the experimental fragility curve $F_{\bar{A}}(a^*)$ (Figure 1.b).

The area above the threshold $\overline{sf}$ is calculated using the survival function reported in (1):

$$\Im_{sf}(SF,\ a^*) = \Pr\{sf > SF\} = 1 - F_{sf}(SF,\ a^*) \tag{1}$$

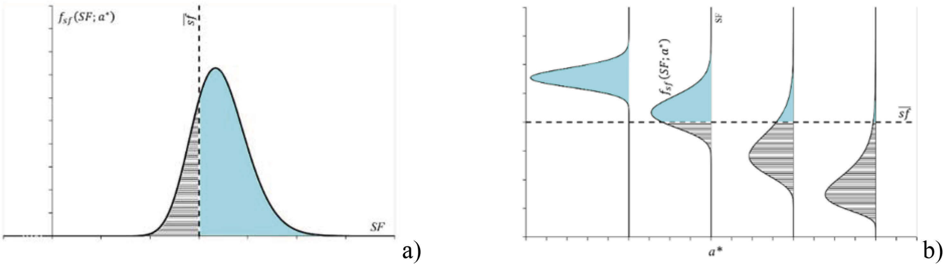


Figure 1. Probability of reaching and exceeding threshold $\overline{sf}$: (a) qualitative p.d.f. for a given value of a*; (b) p.d.f. built for different values of a^*.

where $F_{sf}(SF,\ a^*)$ is the cumulative distribution of sf at each acceleration a^* and describes the probability that the variable sf reaches values greater than a certain value SF, in this case $SF=\overline{sf}$.

The area below the threshold $\overline{sf}$ is given by the cumulative distribution $F_{sf}(SF,\ a^*)=\Pr\{sf \leq \overline{SF}\}$, which describes the probability that sf can assume values not exceeding SF, in this case $SF=\overline{sf}$. The investigated variable SF shown in Figure 1a will be modelled using a Log-Normal distribution, while the experimental fragility curves will be created using the Cumulative distribution function, $F_{sf}(SF,\ a^*)$ and considering the dashed areas in Figure 1b.

4 THE CASE STUDY

The case study chosen for the application of the proposed method is a rural building which shows the structural typology typical of rural areas in Lombardy.

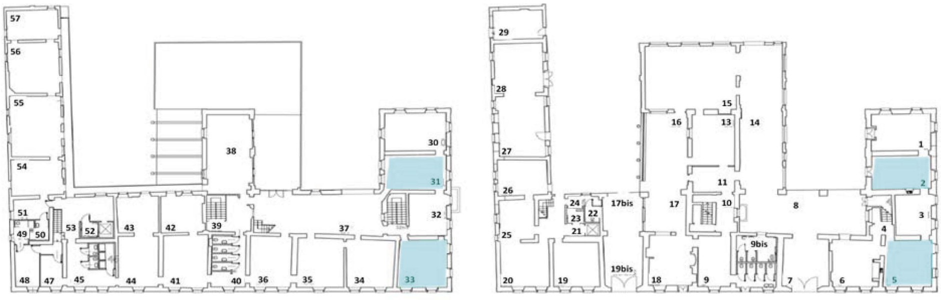
Cascina Cuccagna (Figure 2 and Figure 3) is located in Milan. The Milan area is classified as a seismic area, more precisely with a medium-low seismicity, but given that the typology is typical of the whole region, the behaviour the farmstead has been studied for a series of accelerations (PGA) foreseen for a medium-high area seismicity. Such areas are still present on the Lombard territory (eg: Salò area and Lake Garda).

As often happens, the construction of historic buildings evolves over the centuries and this induces points of vulnerability in the structures that may become real weaknesses in the event of seismic action. In a project funded by the Cariplo Foundation and conducted by ACCC (Associazione Consorzio Cantiere Cuccagna), Politecnico di Milano and Hydea (PRE.CU.R.S.OR project), the diagnostic and structural analysis of the farmstead showed points of static weakness and structural vulnerability that required both interventions of static reinforcement and of seismic improvement.

Figure 2. Cascina Cuccagna: aerial view.

4.1 *The overall behaviour of the building.*

As already explained, since the typological characteristics of Cascina Cuccagna are recurrent in Lombardy the evaluation of the factors SF_G and SF_L (Borri, De Maria & Casaglia 2014), is performed here for the acceleration interval (a_g) $0.15g<a_g\leq 0.25g$, typical of the Italian seismic



(a) (b)

Figure 3. Cascina Cuccagna: a) first floor; b) ground floor. The shadow areas are involved in seismic and static improvement.

zone 2. The design spectrum was constructed for this area and the characteristic acceleration parameters (PGA) were obtained as well as the spectral amplification factor, F_0, (Table 1).

Table 1. Seismic parameters Italian seismic zone 2 Garda Lake.

Years	PGA	F_0
30	0.042	2.551
50	0.057	2.483
475	0.158	2.483
975	0.206	2.485
2475	0.283	2.466

On the basis of some parameters, all or in part, easily available from existing databases (the number of floors above ground and their height, the covered surface, the presence in the plant of resistant walls in the x and y direction, their length and thickness, the possible characteristics of the masonry and its specific weight, the presence or absence of cracks and a plausible analysis of the loads) it is possible to measure the loss of the global safety factor as the values of accelerations imposed vary and construct the consequent curves of fragility.

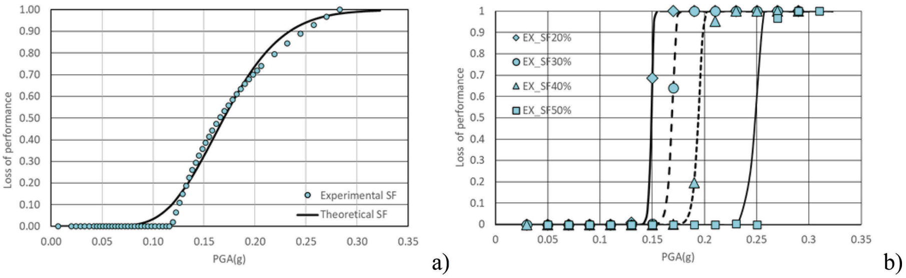
The application of the method proposed in Borri, De Maria & Casaglia (2014) made it possible to quantify the experimental parameter SF_G (assumed here as random variable) as the different accelerations imposed varied in a certain interval. Such values were then normalised to the maximum value ($1\text{-}SF_{Gmax}$) obtained and a probabilistic modelling was performed on them. The purpose of this modelling was to obtain a fragility curve which, as the acceleration set varied, could describe the probability of recording a loss value ($1\text{-}SF_G$) as a percentage of the maximum expected sever value ($1\text{-}SF_{Gmax}$). Figure 4a shows the curve of fragility for the building studied relative to a value of ($1\text{-}SF_{Gmax}$)=58%.

The experimental data were then modelled with a Gamma-type probabilistic curve.

Figure 4 shows that the structural typology examined responds quite well to the accelerations expected for the seismic zone 3 ($0.05g < a_g \leq 0.15g$), that is the seismic zone to which it belongs. In fact, the probable loss of performance in the 0.05g-0.15g interval (typical of seismic zone 3) is to be considered between 0 and 32% of ($1\text{-}SF_{Gmax}$), while for the 0.15g-0.25g interval (typical of seismic zone 2) the loss of performance is certainly more consistent and it is between 32% and 94% of ($1\text{-}SF_{Gmax}$).

4.2 *Fragility curves for different levels of performance loss SFG*

Following the approach presented in Section 3, a further investigation to be carried out is the assessment of the loss of performance for different percentage thresholds. In this way it is



a) b)

Figure 4. A) Fragility curve of the probability of reaching a value SF≤ $\overline{sf}$ ($\overline{sf} = 58\%$); b) Experimental (dots) and theoretical (lines) fragility curves describing the probability of losing for different levels of SF as acceleration varies.

possible to read the probability of reaching or exceeding a certain level of loss as the acceleration varies. In this case the experimental data are evaluated in absolute value and not normalised to the SF_{Gmax} value.

The experimental data were modelled with a Weibull-like probability function. The choice of the function is related to the behaviour of the event studied: the probability of reaching the level of maximum loss of performance increases as the acceleration value increases; such a phenomenon requires a probabilistic modelling with distributions having an increasing immediate risk function, Weibull and Gamma distributions respond well to this need. In the specific case it is believed that the Weibull distribution, with a hazard rate tending to infinity for increasing values of a_g, is the most correct distribution to describe the behaviour of the parameter (1- SF_G) as a_g varies.

For the case study of Cascina Cuccagna in Milan, Figure 4b shows the fragility curves for different loss thresholds.

Figure 4b shows the good overall behaviour of the structural typology of the farmstead. In fact, performance losses exceeding 50% are not detectable and losses of 50% seem to be predictable for accelerations around 0.20g-0.25g.

4.3 *A specific vulnerability of Cascina Cuccagna*

A building can show local vulnerabilities that can change the level of performance as the acceleration set varies. However, the knowledge of these vulnerabilities requires more in-depth investigations and the data necessary for it cannot be obtained from public documents, as is instead possible for the verification of overall behaviour.

In the proposed case study, during the development of the PRE.CU.R.SOR project, the survey and diagnostics carried out on the building made it possible to have sufficient elements to further investigate the local behaviour of a part of the building (Garavaglia, Anzani, Maroldi & Vanerio, 2020).

The documents collected showed a very marked flexural deformation in an inter-floor slab and the lack of clamping of the slab-perimeter walls (Figure 5). Failure to clamp the slab made the perimeter walls, subjected to the thrust of the roof, vulnerable to overturning. The evaluation of the local safety factor for the deteriorated situation, called “pre-improvement”, will then be proposed on this portion of the building.

The seismic improvement required the replacement of the main beam and the deteriorated elements of the strongly inflected floor, the stiffness of the floor was improved with the introduction of two layers of crossed boards and the masonry-floor clamping was obtained by means of inclined drills (Figure 6). The static improvement was carried out with the introduction of line break devices for the flexural improvement of the floor beams.

After the execution of work, a new evaluation of the local safety factor SF_L was carried out for the situation that we can call “post-improvement”.

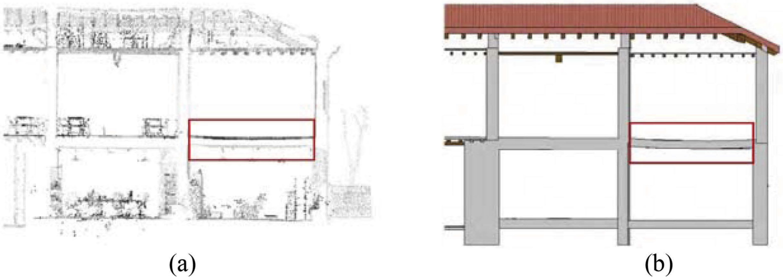


Figure 5. Survey of flexural anomaly in a floor beam (a) laser scanner survey (b) section redrawing.

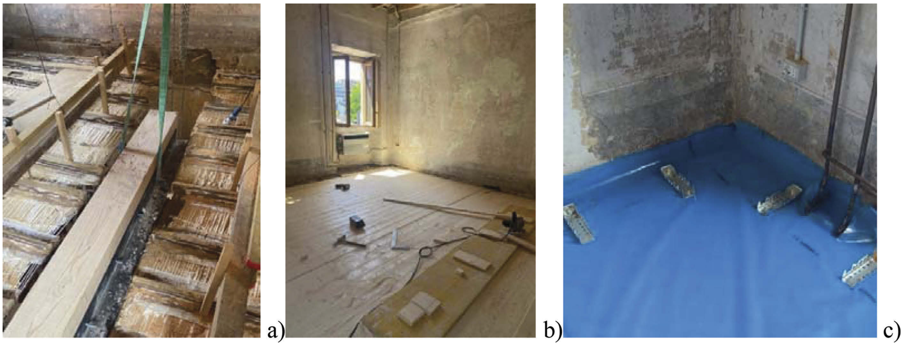


Figure 6. Room 33 seismic improvement actions (a) main beam replacement; (b) cross deck placement; (c) floor-wall connections with inclined drills.

4.4 *The local behavior and the parameter SFL*

The PRE.CU.R.SOR. project on *Cascina Cuccagna* has made it possible to have a significant and diagnostic documentation useful to formulate some hypotheses on the local behaviour of the walls and floors in the areas with the highest specific vulnerability.

Still applying the method proposed by Borri, De Maria & Casaglia (2014) for local mechanisms and considering the overturning mechanism, the database of local safety factors ($1\text{-}SF_L$) was built and the curves of fragility for the local behaviour of masonry portions were evaluated in the area subjected to static and seismic improvement. Local behaviour was assessed both in the original pre-improvement situation and in the post-improvement situation. The results are shown in the follow.

In Figure 7a it can be seen how the static improvement made to the floor of rooms 2 (ground floor) and 31 (first floor) has induced an improvement in local performance. In fact, for an acceleration of 0.15g (upper limit value and inferior respectively for the seismic zones 3 and 2 considered here) the expected loss of performance goes from 0.89 to 0.77 di ($1\text{-}SF_{Lmax}$ =78%), which is certainly still high, but the loss of performance analysed is a loss almost on the verge of collapse.

Figure 7b shows the fragility curves of the walls of rooms 5 (ground floor) e 33 (first floor) subjected to seismic improvement of the floor. In this case, the loss of performance recorded for the accelerations analysed is around 67% of the initial performance ($1\text{-}SF_{Lmax}$=67%). The figure shows how the seismic improvement has induced a more evident performance improvement; the expected loss of performance for an acceleration of 0.15g goes from 0.8 to 0.56 of ($1\text{-}SF_{Lmax}$=67%), showing how important it is to ensure a good clamping between vertical and horizontal elements.

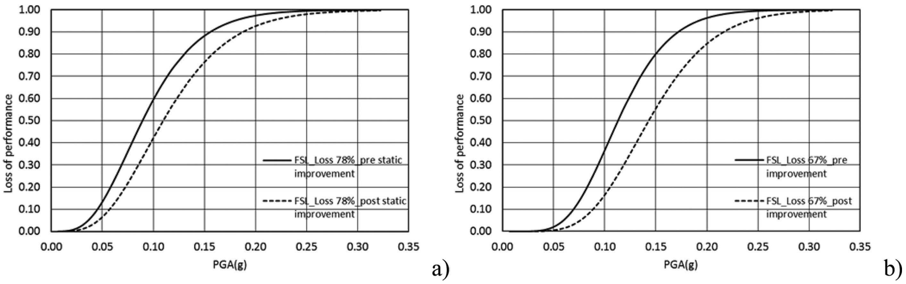


Figure 7. (a) Room 2-ground floor and 31-first floor (Figure 3 shadow area); fragility curve for pre and post static improvement; (b) Room 5-ground floor and 33-first floor (Figure 3 shadow area); fragility curves for pre - e post - seismic improvement.

4.5 *Curves of fragility for different levels of performance loss SFL for rooms 5 and 33*

Following the approach presented in Section 3, the fragility curves for different levels of performance loss were constructed for the rooms subjected to seismic improvement.

Figure 8 shows the results obtained for the initial situation (pre-seismic improvement) (Figure 8a) and for the current situation (post-seismic improvement) (Figure 8b).

From the two figures compared, it is possible to observe how the probability of exceeding the thresholds is translated on the acceleration axis of quantities varying from 0.019g for the curve relating to the loss of performance of 20% to 0.037g for the curve relating to the loss of performance of 50%.

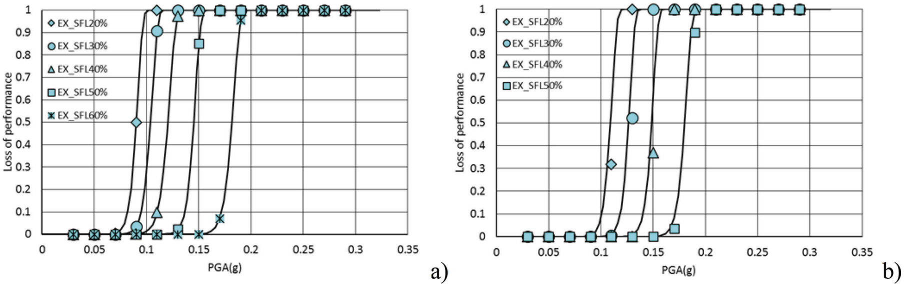


Figure 8. Fragility curves for different SF_L thresholds for rooms 5 and 33: (a) pre-seismic improvement; (b) post-seismic improvement.

Also from this analysis it is highlighted how the seismic improvement introduces an improvement of the local performances for all the investigated thresholds.

Considering that the examined structure is located in seismic zone 3, we can deduce that there have been implementation measures in the structure; the worst forecast seems to foresee a loss of local performance of no more than 40%.

5 CONCLUSIONS

The method proposed in this paper shows how the probabilistic evaluation of the global seismic performance of a historic masonry building can be carried out quickly, also on the basis of data already in the possession of public bodies, and how it can offer a first outline of priority interventions. The picture will certainly not be exhaustive, it would be important to investigate the local seismic performance as well, but these investigations require a more detailed information campaign.

The case study presented allowed us to investigate the variations of both the global and the local safety factor The results obtained show that the improvement in the behaviour of the building obtained with local seismic improvements is difficult to detect from the analysis on the variation of the global safety factor. However, the general method can already suggest to a public body or the municipality on which buildings it would be useful to plan more detailed diagnostics.

If it were also possible to undertake an investigation on the variation of local seismic factors, this analysis would be able to predict the impact of some structural choices on the future behaviour of the building, in terms of less loss of local safety.

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