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Seismic retrofit of reinforced concrete frames by direct loss-based design

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Abstract

This paper introduces a procedure for the retrofit design of reinforced concrete (RC) frame buildings to achieve the desired target level of earthquake-induced loss for a given seismic hazard profile. The methodology is "direct" because the loss target is specified in the first step of the procedure, and, in principle, no design iterations are required. The target loss level is defined based on designer/client preferences and/or external constraints (e.g., foundation capacity). The proposed procedure relies on a simplified loss assessment enabled by a surrogate model defining the probability distribution of the seismic deformation demands of single degree of freedom (SDoF) systems given different ground-motion intensity levels. Combined with a hazard curve and a building-level damage-to-loss model, such a surrogate model is used to map candidate SDoF force-displacement curves to their earthquake-induced loss by assuming a given retrofit strategy. In this case, the considered retrofit strategy involves changing the frame's local hierarchy of strength to ensure a global plastic structure mechanism. Under such assumptions, a designer can select a design force-displacement curve among those that comply with the chosen loss target. The detailing of the retrofitted frame is carried out according to the direct displacement-based design principles and the Simplified Lateral Mechanism Analysis (SLaMA). The procedure is applied to an under-designed RC frame building retrofitted with concrete jacketing. A benchmark loss estimate is calculated using non-linear time-history analyses for loss assessment purposes. The proposed procedure shows satisfactory compliance with the benchmark loss, emphasising the procedure's effectiveness in practice.

Keywords: retrofit; loss; reinforced concrete; jacketing; loss-based design.

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1. Introduction and motivation

In most earthquake-prone areas, under-designed structures that cannot sustain severe seismic demands contribute significantly to seismic risk. Therefore, risk mitigation strategies such as seismic retrofit should be employed to reduce the expected economic and human losses (e.g., in terms of casualties). In Italy, the "Sismabonus" program strongly incentives seismic structural retrofit of existing buildings by deducting 110% of the retrofit cost from the household taxes for the subsequent five financial years (Consiglio dei Ministri, 2017).

Although modern retrofit design methodologies fulfil code requirements, they generally do not enable a designer to explicitly optimise the structure using a risk-informed decision variable (e.g., economic loss). In recent years, various studies have proposed procedures to select a specific retrofit strategy or retrofit design between different alternatives, motivating the choice through cost-benefit analysis (e.g., Cardone et al., 2019), simplified probabilistic approaches (e.g., Nuzzo et al., 2020), or multi-criteria methods (e.g., Caterino et al., 2009; Gentile and Galasso, 2020). Other authors proposed iterative, trial-and-error algorithms to select the optimal design using various performance metrics (e.g., Di Trapani et al.). However, these proposals might be computationally expensive and/or time-consuming.

For the design of new structures, Direct Loss-Based Design (DLBD; Gentile and Calvi, 2022) enables a designer to directly find the structural design solution complying with a target expected annual loss (EAL). Such DLBD relies on a surrogate probabilistic seismic design model (PSDM) based on Gaussian Process (GP) regressions (Gentile and Galasso, 2022). The proposed surrogate model maps the parameters (i.e., backbone force-displacement curve, hysteretic behaviour) controlling the dynamic behaviour of equivalent single degree of freedom (SDoF) systems to the parameters of their PSDM. Combined with asset-level fragility analyses and vulnerability models, such a surrogate model allows mapping the SDoF systems to their EAL subjected to a site-specific seismic hazard profile. This empowers the designer to control the EAL of the considered structure without iterations.

This paper applies this new design approach to the seismic retrofit of reinforced concrete (RC) frame buildings, considering column concrete jacketing as a retrofit technique. The retrofit strategy involves altering the as-built structure's undesirable plastic mechanism, ensuring plastic hinges in the beams only (i.e., a beam sway, BS, mechanism). This framework is applied to a case-study old-code Italian RC frame building. As a validation, a loss assessment is performed on the retrofitted structure through cloud-based non-linear time-history analysis (of a refined numerical model). Finally, the analysis output is compared to the initial EAL target, and the findings from such an illustrative application are critically discussed, highlighting the limitations of the proposed approach.

2. Methodology

The steps required to perform DLBD for retrofit design are summarised as follows. Before completing the main procedure steps, some basic data and design assumptions should be provided by the designer:

- Analyse the as-built structure to assess its plastic mechanism. By using the Simple Lateral Mechanism Analysis (SLaMA; e.g., NSZEE, 2006; Gentile et al., 2019), calculate the displacement capacity of the structure assuming a BS mechanism to be used for the retrofit design (i.e., this will be the final mechanism of the retrofitted structure);
- Calculate the base shear threshold to ensure BS mechanism, which is the minimum base shear associated with a weak beam-strong column design given the as-built beam capacity;
- Define the effective height (H_{eff}) and effective mass (M_{eff}) of the building according to displacement-based design (DBD; Priestley et al., 2007). These represent the height and the mass of the SDoF approximation of the as-built structure.
- Provide a set of site-specific hazard curves in terms of spectral acceleration (SA) covering an adequate range of vibration periods. Code-based models (e.g., Stucchi et al., 2011) are generally suitable for this step;
- Define a set of damage states (DS) in terms of the (unknown) ductility capacity at peak strength (μ_{cap}) of the retrofitted structure, which is an intermediate design parameter to be calculated in the following steps (e.g., DS = [0.5, 1, 0.75μ_{cap}, μ_{cap}]);
- Consistent with the chosen DSs, select appropriate building-level damage-to-loss-ratios (DLRs) representing the repair-to-reconstruction cost for each given DS (e.g., Gentile and Galasso, 2020)

The core steps of the procedure involve defining the force-displacement curve of the design structure according to the desired EAL target:

- The EAL target is defined according to the client's (or designer's) preferences;
- A set of seed SDoF systems is defined based on a large number of combinations of hysteresis model (*hyst*), elastic period (T), yield strength (f_y), hardening, yield displacement (d_y) and seed ductility capacity (μ_{cap}).
- Using the surrogate PSDM (Gentile and Calvi, 2022) and DS thresholds, the fragility curves of the seed SDoF systems are derived. Then, accounting for both the selected hazard profile and DLRs, vulnerability relationships and EALs of each seed SDoF system are calculated;
- The set of SDoF systems complying with the target EAL is first selected. Within this pool, only those not exceeding a user-defined threshold for the mean annual frequency of exceeding the complete-damage DS (commonly related to near-collapse) and complying with the code-based displacement checks are considered as design candidates;
- Choose the final design SDOF arbitrarily between the set of design candidates. The demand in the lateral resisting elements to retrofit is found according to DBD equations. Design the column jacketing for this demand such that the retrofitted structure complies with the backbone of the chosen SDoF system.

3. Case-study application

3.1. Response analysis of the as-built structures

The case study analysed in this paper is a four-storey regular RC frame structure simulated designed accordingly to an older Italian building code (Decreto-Legge, 1939). Hence, this building was designed according to the effective stresses principle and only for gravity loading. Its spans are five-meter long, and the inter-storey height is equal to three meters. The total mass of the building is equal to 190 tons, and the effective mass is 153 tons. The structure shows a soft-storey mechanism on the third floor (Fig. 1a shows the summary of the beam-column-joint hierarchy of strength calculated using SLaMA). Therefore, the third-floor column-sway pushover (Fig. 1b) is selected as the most meaningful approximation of the structure's behaviour because it is associated with the lowest base shear between all the possible mixed-sway and column-sway mechanisms.

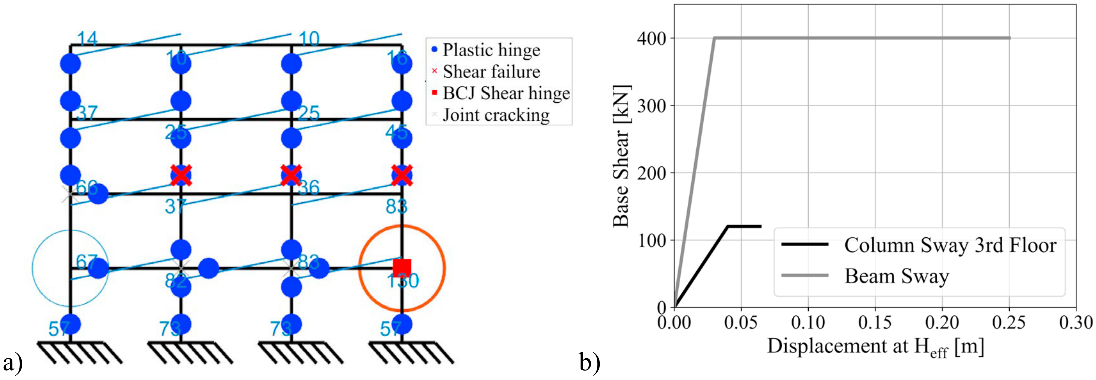

Fig. 1. a) Global mechanism of the case study building: the red circle highlights the joint causing failure, while the thinner blue circle represents the first yielding joint. b) Bilinear pushover approximations of the case study building from SLaMA.

3.2. Definition of the base-shear threshold for the beam-sway plastic mechanism

One of the main goals of the proposed retrofit methodology is to alter the as-built structure mechanism to obtain a BS failure mechanism. To do this, the f_y (hence the base shear V_b) ensuring the BS mechanism can be calculated using the equation of DBD for new frame structures. Particularly, Eq. 1 and Eq. 2 will be used to determine this threshold.

In Eq. 1 $M_{c,i}$ is the base moment capacity of the *i-th* column, H_1 is the height of the first storey, V_b is the base shear and γ is a design parameter representing the height of the contra flexure point in the first storey columns. γ is usually taken as 0.6 to account for the increased rotational stiffness of the column base because of the foundation presence:

$$\sum_{i=1}^{ncolumns} M_{c,i} = \gamma H_1 V_b \tag{1}$$

In Eq. 2, OTM is the over-turning moment, which is the base shear multiplied by effective height, $M_{b,ends,j}$ is the sum of the moment capacity at the ends of the beam in the external bay, L_{bay} is the bay length, and L_{base} is the total length of the frame.

$$OTM = V_b H_{eff} = \sum_{i=1}^{ncolumns} M_{c,i} + \sum_{j=1}^{nfloors} M_{b,ends,j} \frac{L_{bay}}{L_{base}} \tag{2}$$

Eq. 1 is substituted in Eq. 2 to obtain Eq. 3:

$$\frac{\sum_{i=1}^{ncolumns} M_{c,i}}{\sum_{j=1}^{nfloors} M_{b,ends,j}} = \frac{L_{base}}{L_{bay}} \frac{1}{\frac{H_{eff}}{\gamma H_1} - 1} \tag{3}$$

In Eq. 3, the only unknown is $M_{c,i}$. Indeed, H_{eff} is a function of only geometry and mass parameters, $M_{b,ends,j}$ is known as part of the as-built structure data/information, and all the other parameters are either geometrical or chosen by the designer. Therefore, the sum of column base moments that would ensure a BS mechanism in a new building with the same beam geometry can be found, and consequently, the minimum V_b for beam sway can be defined.

In the presented case study, the sum of the ends moment of the beams at each floor is 285 kNm and the ratio between columns and beams moment by Eq. 3 is 0.77. Hence, the base column moment is calculated as 885 kNm, and the base shear is 480 kN.

The columns are retrofitted through RC jackets using the above column moments and assuming a uniform column capacity. SLaMA is carried out on the retrofitted structure as a final verification of the retrofit process. The beam-column-joint hierarchy (Fig. 2a) and force-displacement curve (Fig. 2b) of the structures are displayed in the following image.

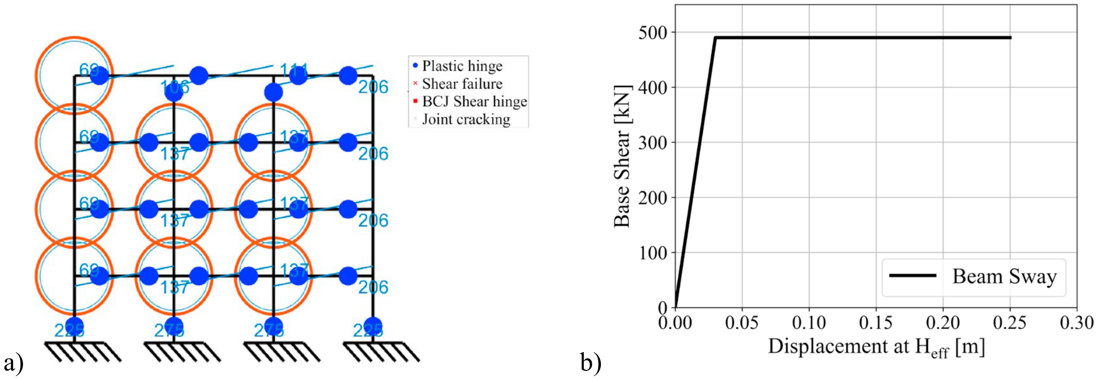

Fig. 2. a) Global mechanism of the building retrofitted accordingly to the base shear threshold that ensures a BS mechanism. b) Bilinear pushover approximation from SLaMA.

3.3. Hazard curve definition, damage states and damage to loss ratios

The building of this case study is assumed to be located in L'Aquila, Italy, and an appropriate site-specific hazard curve is adopted (Stucchi et al, 2011).

As shown in the preliminary steps introduced above, damage states were defined as functions of the ductility at peak strength: μ_{DSi}= [0.5, 1, 0.75μ_{cap}, μ_{cap}]. These DSs correspond to slight damage, moderate, extensive, and complete damage. DLRs consistent with these DSs are defined as DLRs = [7, 15, 50, 100]% of reconstruction cost. These DLRs are appropriate for direct economic losses of Italian RC buildings and are coherent with the DSs (e.g., Cosenza et al. 2018).

3.4. EAL target selection

EAL target should be decided according to the client's and/or designer's preferences. Theoretically, there are no constraints on choosing the EAL target; yet, requiring a beam-sway mechanism effectively results in having a lower bound on the f_y. Therefore, for this case study, an EAL of 0.4% of the total reconstruction cost is selected.

3.5. Seed SDoF systems

For this application, 360 seed SDoF systems are defined considering all the possible combinations of the parameters defined as follows:

- Hardening ratio: commonly, a value of 0.05 is used for frames. However, this parameter is conservatively set to zero, also consistent with the prediction obtained using SLaMA;
- Yield strength: this parameter is equal to the yield base shear normalised by the effective mass. This parameter ranges between 0.32 (which is the minimum threshold to ensure a BS plastic mechanism) and 0.5. 60 points are used to cover this interval. This number of points allows, if needed, the designer to use linear interpolation between the grid points without significant error;
- Hysteresis model: since all the seeds are expected to result in a BS plastic mechanism, the Takeda Fat hysteresis model is used (Gentile and Galasso, 2021);
- Yield Displacement: this is a function of material and geometry defined according to DBD; for this specific case study, the yield displacement is 3 cm;
- Displacement ductility at DS4: the DS4 displacement of the system assuming a BS mechanism is 28 cm (4/3 of the DS3 displacement, shown in Fig. 2b), which corresponds to a ductility capacity approximately equal to 8. The retrofitting is likely to produce a DS4 ductility capacity equal to or higher than the one corresponding to a BS mechanism. Considering the above, a seed ductility capacity between 4 and 10 is selected.
- Fundamental period: this parameter is derived depending on the seed's yield displacement and force.

The above parameters are used to map the EAL of the seed SDoF systems (Fig. 3a), accounting for the given hazard curve. Figure 3b shows the bilinear force-displacement approximations of the candidate SDoF systems complying with the target EAL=0.4%, a mean annual frequency of exceeding DS4 smaller than the set threshold (0.005; e.g., Dolšek et al., 2017), and the displacement checks at each DS according to the current Italian seismic code (Consiglio dei Ministri, 2018). Fig. 3b also shows the design spectra for the selected site according to the abovementioned code. Among the candidates, the arbitrarily selected design SDoF system is shown as a thick black line in Fig. 3b, and its properties are shown in Table 1.

Table 1. Pushover parameters of the chosen seed. The displacements and yield strength (f_y) values are obtained from the surrogate model; the base shear is calculated by multiplying the normalised f_y by the effective mass of the building.

Damage State	Displacement [m]	f_y [-]	Base Shear Target[kN]
Yield (DS2)	0.03	0.38	577
Ultimate (DS4)	0.28	0.38	577

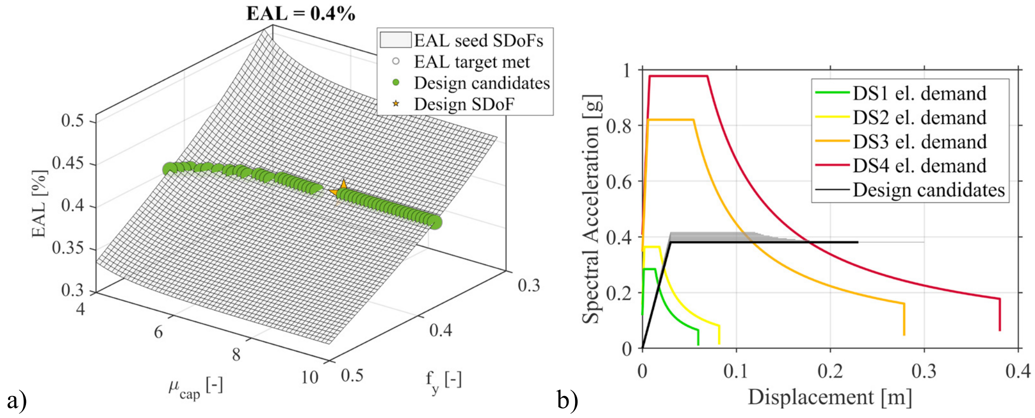

Fig. 3. a) Loss surface output for the case study building, the seeds meeting the 0.4% target loss are displayed in green. b) Force-displacement capacity curves of design candidates.

3.6. Structural detailing

Once the target force-displacement curve is obtained, all the columns are jacketed to resist the given demand. For simplicity, the same jacket is applied to all the columns of the considered case study. However, the methodology allows a designer to freely choose the retrofit design and detailing, given that the required capacity is assured. For the selected design SDoF system, the total moment capacity at the base of the columns is equal to 1,600 kNm, according to the base shear in Table 1. The jacket is designed by considering the section as monolithic, the concrete resistance is the jacket one (the neutral axis at ultimate is usually less than the jacket thickness), and the as-built reinforcement bars contribution is neglected.

The building is finally re-analysed using SLaMA for a final check on the plastic mechanism (that is BS; Fig. 4a), and comparing the resulting force-displacement curve with that of the design SDoF system (Fig. 4b). The discrepancies with the design SDoF force-displacement curve are deemed sufficiently small, and therefore no design iteration is performed.

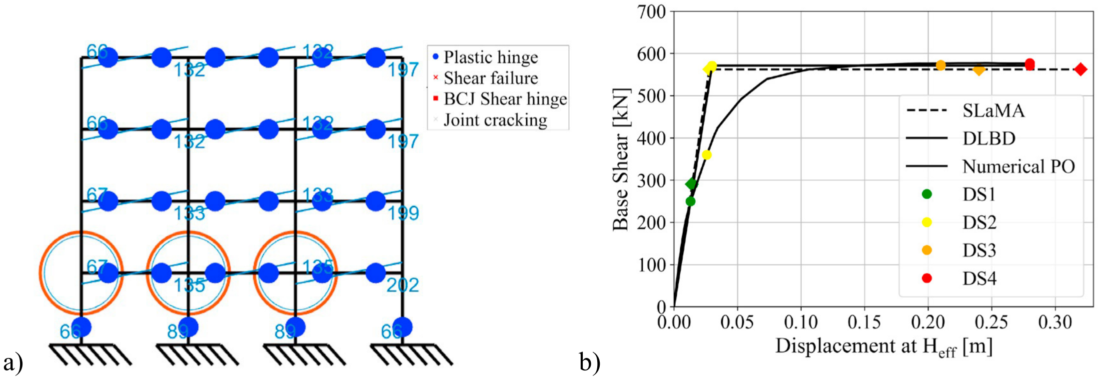

Fig. 4. Retrofitted building: a) Beam-sway plastic mechanism. b) Force-displacement curve compared to that of the design SDoF.

4. Validation against refined loss assessment

To verify the effectiveness of the proposed DLBD for retrofit design, a refined loss assessment of the output structure is performed. First, the structure is modelled in the finite element software Ruaumoko (Carr, 2016), according to

Gentile and Galasso (2021). Then, pushover analysis (Fig. 4b) is run to check the base shear capacity and the damage state values.

Using the SIMBAD (Selected Input Motions for displacement Based Assessment and Design) strong-motion database (Smerzini et al., 2014), cloud-based time-history analysis (Jalayer and Cornell, 2009) is performed to assess the retrofitted structure capacity. The ground motions are scaled by a factor of two to ensure sufficient data for DS3 and DS4. The considered IM is SA at T_1 as in the PSDM, while the Engineering Demand Parameter (EDP) is the displacement at effective height, Fig. 5a.

Fragility functions are obtained from the cloud using least squares based on power law (e.g., Jalayer and Cornell, 2009). In Fig. 5b, the numerical fragility relationships are checked against those predicted by the surrogate model ('Surrogated' in the legend). Finally, the building's vulnerability and EAL are calculated using the L'Aquila hazard curve. In Fig. 6, the vulnerability relationships obtained through the numerical/refined model and those obtained through the surrogate model are compared and plotted with the hazard curve. The numerical EAL is 0.42%, which is very close to the target set at the beginning of the procedure (0.4%).

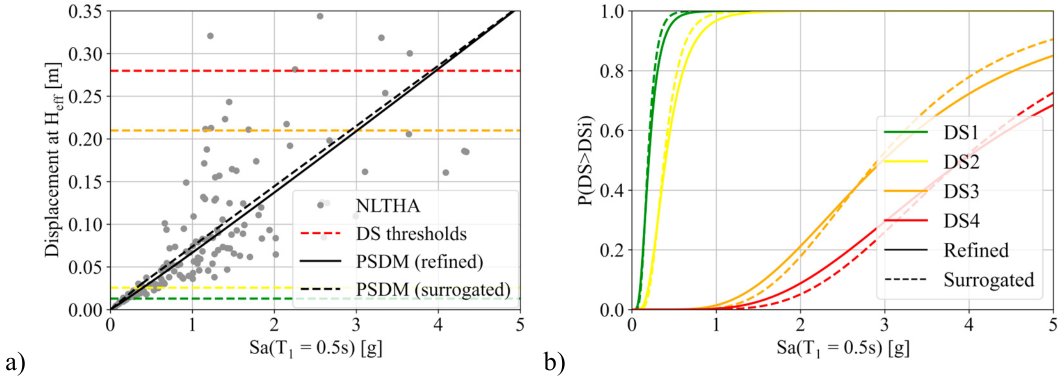

Fig. 5. a) Cloud-based time-history analysis output (THA in the legend) and probabilistic seismic demand model (PSDM). b) Building-level fragility functions.

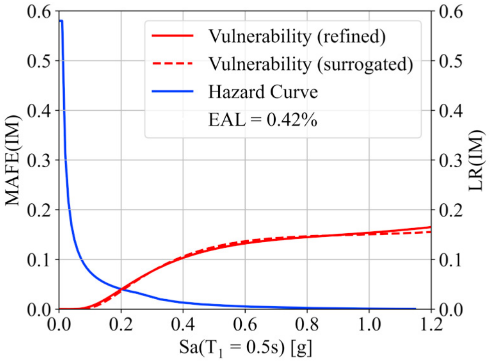

Fig. 6. Vulnerability relationships and loss assessment output. MAFE(IM): mean annual rate of exceedance of the intensity measure (IM) level. LR(IM): mean loss ratio given the IM level.

5. Conclusions and limitations

This paper presented a methodology for the direct loss-based design of retrofit solutions for existing reinforced concrete buildings based on concrete jacketing of columns. According to DLBD, a designer chooses the desired loss target that is achieved in principle without iterations by following the proposed procedure, resulting in an efficient design approach. Indeed, once the structural detailing is completed, loss assessment is not needed if the target force-displacement curve is met. It is worth noting that the designer may still use non-linear time-history analyses to verify the performance of the designed structure, thus only after having applied DLBD. The proposed procedure is computationally efficient since a surrogate probabilistic seismic demand model replaces computationally expensive non-linear time-history analyses deemed incompatible with the preliminary design phase.

The proposed DLBD was showcased for the retrofit design of an existing pre-code reinforced concrete regular frame. The failure mechanism of the building was changed to a desirable beam-sway mechanism. The loss target was set to a reasonably low threshold (0.4%), and the column jacketing was designed to meet the target force-displacement curve. A cloud analysis was used to calculate the building's expected loss numerically. The obtained expected annual loss threshold (0.42%) demonstrates a successful design procedure.

Although the methodology is promising, a few limitations can be defined, and the authors are currently working towards overcoming those. First, the procedure shown in this paper depends on the beam-sway threshold. Indeed, a structure with base shear lower than the BS threshold would indicate a mixed-sway mechanism. Hence the retrofit detailing should be different, and some of the equations above would not be valid. This limitation is critical if the foundation capacity is lower than the required base shear. However, the designer can either retrofit the foundations or choose retrofit techniques that require new foundations (e.g., adding a shear wall). Other limitations are related to the choice of the specific retrofit technique. However, the designer can choose the most appropriate strategy based on the as-built structure, as long as it is coherent with the parameters input in the surrogate model.

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