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ADVANCEMENTS AND CHALLENGES IN DIRECT LOSS-BASED SEISMIC DESIGN

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Abstract: *Provisions in seismic design codes generally focus on collapse prevention or life safety for major, rare earthquakes and damage prevention for minor, frequent ones. The evolution of theoretical knowledge, modelling abilities, and actual damage observations led to higher awareness of the implications of code provisions on earthquake risk. The economic consequences of the 1994 Northridge (USA) earthquake symbolically led to a paradigm shift in evaluating structural performance. This led to performance-based earthquake engineering, now considered a standard for risk/loss assessment. Different research efforts improved the common force-based design to include risk-related concepts within the design process, such as methods targeting displacement, seismic fragility, mean annual frequency of exceeding a given damage state, losses, resilience metrics. This paper focuses on the recently developed direct loss-based design (DLBD), which allows designing structures that achieve a given loss-related metric under the relevant site-specific seismic hazard virtually without design iterations (generally less than three). After describing the design methodology, this paper discusses: 1) the efficacy of the procedure for the design of new reinforced concrete buildings -monolithic or base isolated- and the retrofit of existing ones; 2) the necessary validation studies needed to maximise the scope of DLBD; 3) the methodological advancements needed to improve the accuracy of the embedded loss-estimation module; 4) the operational advances to render DLBD appealing in the practice.*

Introduction and Motivation

Seismic design codes prioritize collapse prevention or life safety for major earthquakes and damage prevention for minor ones. Increased knowledge and damage observations have highlighted the need for evaluating the implications of these provisions on earthquake risk, leading to the development of probabilistic assessment methods such as performance-based earthquake engineering (PBEE, SEAOC Vision 2000 Committee (1995).

PBEE is the state-of-the-art approach to calculate a loss metric for a given building configuration (i.e., assessment), including structural and non-structural components. Different design procedure incorporated (portions of) PBEE to obtain risk- or loss-based design approaches, i.e., establishing an appropriate building configuration such that a value of a selected risk/loss metric is met. Some examples may include: yield point spectra (Aschheim and Black, 2000); methods targeting seismic fragility (e.g. Aljawhari et al. 2022; Long et al., 2015); yield frequency spectra [12]; probabilistic displacement-based design (Franchin et al., 2018; Franchin and Pinto, 2012); risk-targeted force-based design (Žižmond and Dolšek, 2019). An extensive review of such design approaches is given in (Vamvatsikos et al., 2016).

Since loss assessment is a highly non-linear problem, most procedures are iterative: they involve repeated applications of an assessment formula while revising a guess design candidate until a loss target is met. If carried out manually, this approach may be cumbersome for the preliminary design phase since each iteration usually requires time-consuming non-linear time-history analyses (NLTHA). If carried out using an optimisation algorithm, it may limit the design experience, since the designer can only set an objective function to minimise, and then accept the result of the optimisation.

Direct Loss-Based Design (DLBD; (Gentile and Calvi, 2023; Gentile and Galasso, 2022) was recently proposed to address the above limitations. DLBD allows designing structures that achieve a specific loss-related target under the seismic hazard at a particular site. The term "direct" emphasizes the designer's ability to specify a loss target as the first input of the process and achieving it virtually without design iterations.

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After briefly describing DLBD, this paper discusses the recent advances in this research topic, describing the existing DLBD applications: design of reinforced concrete (RC) buildings, both monolithic (Gentile and Calvi, 2023) or base-isolated (Suarez et al., 2023), and retrofit of existing RC buildings (Rubini et al., 2023). This paper also identifies some challenges in developing/adopting DLBD, also considering required research efforts to overcome those. Finally, some final remarks are provided.

Direct Loss-Based Design (DLBD)

DLBD involves a flexible and fast mapping of different SDoF systems (using the described simplified loss assessment module) to a selected loss metric. This allows identifying the force-displacement curve of an ideal system complying with a selected target loss. This is followed by the detailing of the relevant structural members to comply with the selected force-displacement curve.

This Section provides a non-exhaustive, high-level description of DLBD. The relevant details of the methodology are provided in (Gentile and Calvi, 2023). The code implementation of DLBD is freely available (github.com/robgen/lossBasedDesign).

Simplified earthquake loss assessment

The adopted loss assessment method (Figure 1) is based on a *surrogate probabilistic seismic demand model* (PSDM) for single-degree-of-freedom (SDoF) systems. The adopted PSDM is a bi-linear model that can calculate the distribution of ductility demand (μ) conditioned on the intensity measure $R = SA/f_y$, where SA is the pseudo-spectral acceleration at the elastic period of the selected SDoF system and f_y is its yield strength normalized by the total weight. The PSDM parameters (slope a, and standard deviation σ) are derived from two Gaussian process regressions (Gentile and Galasso, 2022) trained on a dataset of 10,000 inelastic SDoF systems subjected to cloud-based nonlinear time-history analyses using 100 natural ground motions. The result is an analytical formulation for (a, σ) given four input parameters: $hyst$: the hysteresis model, T: the elastic period of vibration, f_y as defined above, and h: the hardening ratio.

Lognormal *fragility relationships* are analytically derived based on the PSDM, which assumes a Lognormal distribution of the residuals. They can be calculated for a set of structure-specific damage states (e.g., slight, moderate, extensive, and complete damage) identified by the ductility thresholds μ_{DS}. One possibility involves choosing four damage states: slight, moderate, extensive, and complete damage.

The loss assessment module can alternatively involve a *low-refinement building-level analysis* using a vulnerability relationship, and a *medium-refinement storey-level analysis* using a vulnerability curve for the structure and storey loss functions for non-structural components. High-refinement component-based methodologies are deemed unsuitable for preliminary design and they are not envisioned within DLBD. For the low-refinement method (Figure 1), building-level vulnerability relationships are analytically derived combining fragility relationships and consequence models mapping loss metrics (e.g., economic losses) to different DSs, which include structural and non-structural damage.

The medium-refinement method is suggested if the designer has enough information to confidently characterise an inventory of non-structural components since the preliminary design phase. This first involves a vulnerability relationship capturing only the structural damage, derived as above except adopting a consequence model only including structural damage. Non-structural damage is captured through storey loss functions, which quantify the mean value of a storey-level consequence variable (e.g., economic loss) of a group of non-structural components conditioned on an appropriate engineering demand parameter (EDP). Storey loss functions are defined for each storey, separately for acceleration- (α) and drift-sensitive (θ) non-structural components. Storey-level vulnerability relationships (loss vs SA) for each group of non-structural components are obtained converting the storey loss functions using appropriate $EDP(SA)$ relationships. The $\theta(SA)$ is defined combining the surrogate PSDM with displacement shapes appropriate for a given lateral resisting system (e.g., Priestley et al. 2007). The $\alpha(SA)$ relationship is obtained from an acceleration shape formulation provided by the Federal Emergency Management Agency (FEMA 2012). Finally, the structural-only vulnerability relationship is summed to the storey-level ones to obtain a building-level vulnerability relationship.

Indirect economic losses refer to anything not directly related to building damage: for residential buildings, they may involve the cost of relocating the displaced building occupants during the emergency phase and the time required to repair and refurbish the damaged building. Those may be accounted for using a calibrated non-linear mapping between direct and indirect losses (e.g., Calvi et al. 2021). This allows defining a building vulnerability curve combining direct and indirect losses.

Loss metrics (e.g., expected annual loss, EAL) are finally derived by appropriately integrating the above building vulnerability curve against a hazard curve representing the mean annual frequency of exceeding different SA levels. It is herein suggested to exploit relevant existing hazard models (e.g., Stucchi et al. 2011) to simplify the preliminary design process. Ad hoc probabilistic seismic hazard analysis may instead be used for a refined verification of the final design.

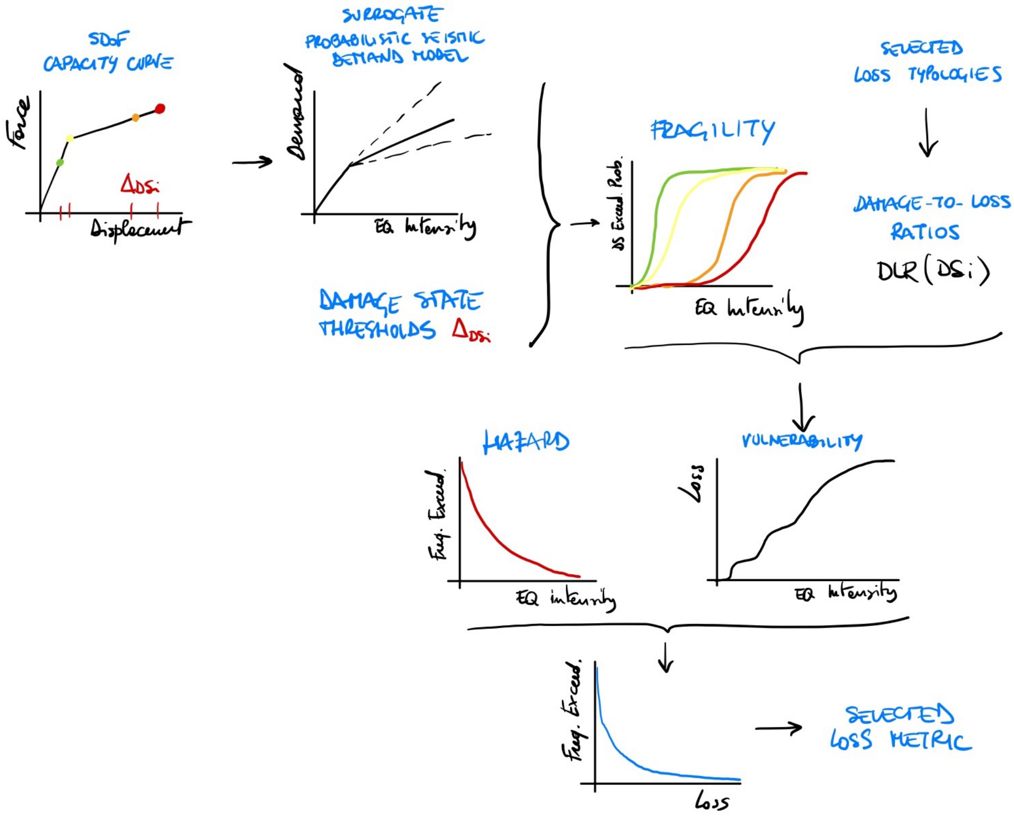

Figure 1: Simplified loss assessment method (low-refinement level) at the basis of DLBD: this allows mapping the selected loss metric for a set of seed SDoF systems

Design procedure

For a given lateral resisting system (e.g., RC frames) the first phase of DLBD involves some *preparatory steps*, including:

- Obtaining hazard curves that cover a wide range of secant-to-yielding periods
- Selecting appropriate DSs, together with reasonable ductility thresholds relatively to the (unknown) ductility capacity of the design SDoF system
- Choosing the loss typology (e.g., direct economic losses, repair time), a relevant loss metric (e.g., EAL), a relevant damage-to-loss and/or storey loss functions
- Determining the basic geometric properties of the structure (e.g., number of storeys, bays, inter-storey height).

The *core steps* of DLBD first involve selecting a relevant loss target (e.g., EAL=0.3% of the total reconstruction cost). Therefore, the loss assessment method scribed above is used to calculate the relevant loss metric for several seed SDoF systems defined by different combinations of the parameters $hyst, T, f_y, h$ and the ductility capacity μ_{cap}. An illustrative example of such mapping is shown in Figure 1a.

Once the loss mapping is complete, the seed SDoF system meeting the desired loss target are selected. Among those, the *candidate design SDoF systems* are the ones complying with the code-based seismic performance checks for any DS (e.g., using the Capacity Spectrum Method, Freeman 2004). In addition, the designer may also disregard the SDoF system exceeding a selected upper bound value of the mean annual frequency of exceeding the complete DS (e.g., between 10^{-5} and 10^{-4}, Dolšek et al. 2017). The final design SDoF system can be chosen arbitrarily among the candidate design SDoF systems (Figure 1b), which may be based on non-seismic design requirements. This approach allows the designer to meet the loss target while also accommodating non-seismic design constraints.

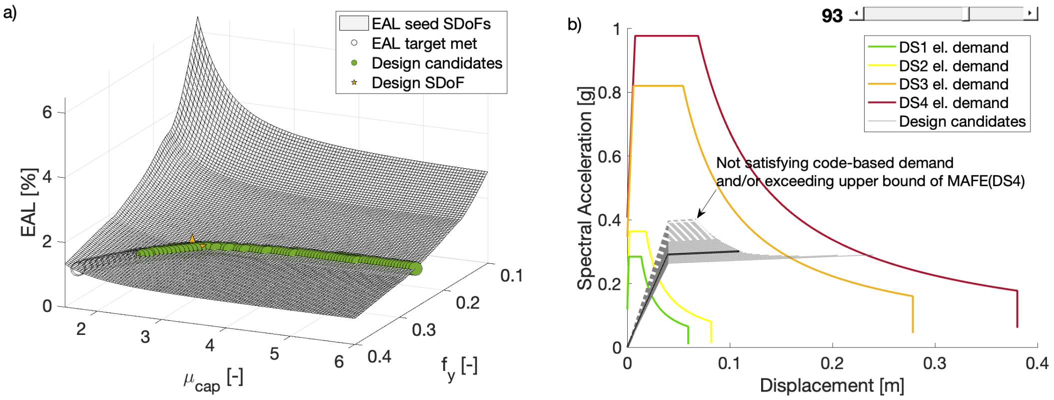

Figure 2: a) Expected annual loss of the seed SDoF systems; b) capacity curves of the candidate design SDoF systems. MAFE: mean annual frequency of exceedance; DS: damage state. Modified after Gentile and Calvi (2023)

After determining the design SDoF system, the structural members in the lateral resisting system must be detailed to conform to the design SDoF system's backbone and produce a favourable plastic mechanism. This *structural detailing phase* is not an integral part of DLBD. Essentially, any design and analysis method can be used to achieve this goal, including trial and error. Although structural detailing is not discussed herein, the principles of direct displacement-based design (Priestley et al., 2007) are suggested for this phase, as described in detail in Gentile and Calvi (2023).

Conceptual design

DLBD allows bringing risk/loss-based considerations within the conceptual design phase. By repeating the loss mapping assuming different geometries, materials, lateral resisting systems, etc., the designer is allowed to critically think about their choices against the implications in terms of loss, which are not always trivial to anticipate based on experience due to the high non-linearity of the loss estimation problem.

Figure 2 shows an illustrative example of conceptual design for a three-storey RC building in which a frame and a wall lateral resisting systems are compared. In this exercise, both direct and indirect losses are considered, and the detailed set of assumptions for the preliminary steps of DLBD are provided in Gentile and Calvi (2023).

Although the provided example may seem particularly simple, it shows how DLBD may drive the conceptual design phase. For example, some values of the target EAL (e.g., 2.4%) are not achievable using a wall lateral resisting system, and therefore a frame may be preferred. Moreover, the absence of intersections between the two loss mappings suggests that the choice of yield strength and ductility capacity may not have a significant impact on the conceptual design phase.

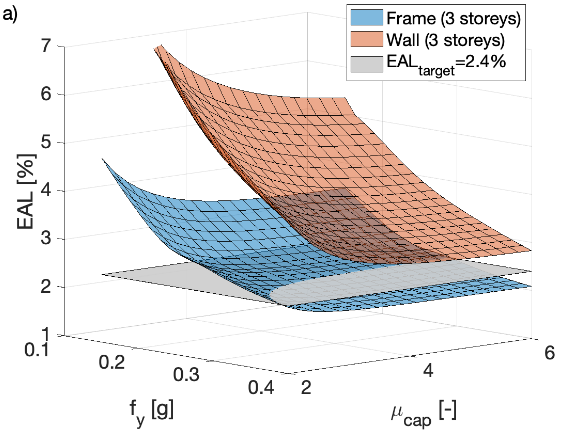

Figure 3: RC frame vs wall conceptual design for a 3-storey building using direct and indirect loss mapping (illustrative example). Modified after Gentile and Calvi (2023)

Existing applications of DLBD

Design of monolithic RC frame and wall buildings

The first application of DLBD refers to RC building composed of frame and wall lateral resisting systems. The specific DLBD methodology for RC frames and walls exactly follows the general guidelines discussed above without requiring any extra and/or modified steps.

The validation study (Gentile and Calvi, 2023) involves 16 rectangular-plan concrete buildings, consisting of frames in the longitudinal direction and walls in the transverse direction, resulting in a total of 32 case-study lateral resisting systems. The case studies are designed using the low-refinement loss assessment module and refer to different geometries, hazard profiles, and target losses. Each case study is subject to a comprehensive earthquake loss assessment methodology involving non-linear time-history analyses of multi-degree of freedom models. The benchmark loss predictions are compared to the pre-determined target losses by measuring the relative discrepancy $(EAL_{NLTHA} - \mathrm{EAL}_{\mathrm{target}})/EAL_{target}$. As shown in Figure 3, the DLBD estimations are all conservative and mostly fall below the 20% error threshold. Only four frame case studies show an error in the range [21.5%, 31%]. The error for the wall case studies is considerably smaller: only five case studies show an error in the range [15%, 22%].

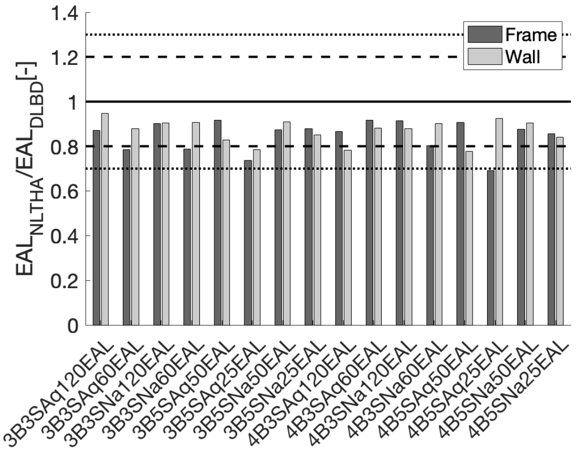

Figure 4: Ratio of NLTHA-based EAL versus the simplified DLBD-based one. Modified after Gentile and Calvi (2023)

Design of base-isolated RC frame and wall buildings

Suarez et al. (2023) provide a DLBD procedure for low-rise, base-isolated structures. An SDoF representation of base-isolated structures may not be justifiable, given the fundamental differences in the dynamic behaviour of the isolation layer, where all the non-linearity is concentrated, and the super structure, usually designed to remain elastic. Therefore, this procedure requires some modifications in the simplified loss assessment module.

The surrogate PSDM is applied to the isolation layer only, while the seismic demand of the (elastic) super structure is calculated using appropriate displacement and acceleration profiles. Finally, since none to slight damage is expected for the super structure, the medium-refinement loss assessment method is needed: losses are separately calculated for the isolation layer, the super structure, the acceleration- and drift-sensitive non-structural components.

A preliminary validation study (Suarez et al., 2023) involves a three-storey medical clinic with a RC wall lateral resisting system for the super structure and lead rubber bearing base isolation. The structure is in a high-seismicity region and is designed to achieve a target EAL=0.017% of the total reconstruction cost, considering direct losses only. Although direct-only economic loss may not be the most appropriate loss type to consider for isolated structures, the preliminary results shows that the procedure provides a reasonable error, such as a 9.6% relative error of the target EAL with respect to refined NLTHA-based results (Figure 4). DLBD for base-isolated structures is currently being extended to include more-relevant loss metrics such as downtime.

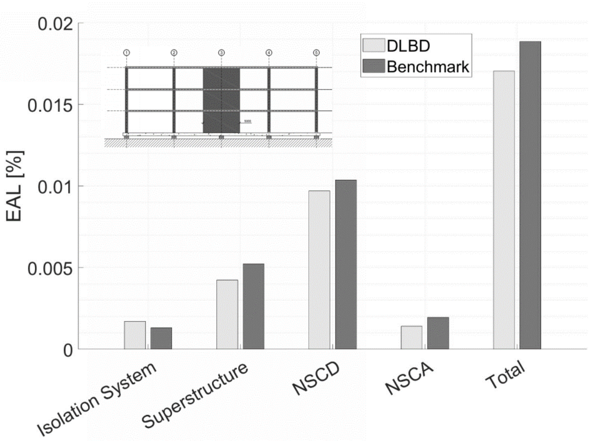

Figure 5: Direct loss-based design for a three-storey, RC medical clinic base-isolated with lead rubber bearings. Modified after Suarez et al. (2023)

Design of retrofit solutions for RC buildings

Rubini et al. (2023) provide a DLBD procedure to retrofit existing RC frame buildings using different techniques (i.e., RC column jacketing, addition of external RC walls). For this direct loss-based retrofit procedure, the general guidelines discussed above directly apply without the need for modifications. An additional preparatory step is required to analyse the as-built structure.

This involves analysing the local hierarchy of strength of each beam-column joint subassembly, and consequently the likely plastic mechanism of the frame. The related force-displacement capacity of the frame is calculated. Moreover, the base shear capacity of the structure is also calculated in the so-called “beam-sway” global mechanism, which is characterized by plastic hinges at the ends of all the beams: this is the frame lateral capacity associated with a retrofit strategy that inverts the local hierarchy of strength of the sub-assemblies such that a strong-column, weak-beam behaviour is ensured. Finally, the lateral force capacity of the foundations is assessed: this is used as the upper-bound force capacity for retrofit interventions that do not include foundation strengthening. The above quantities (reflected in the loss mapping, Figure 5) may be calculated via a numerical pushover analysis or using analytical methods such as SLaMA (simple lateral mechanism analysis; New Zealand Society for Earthquake Engineering 2017; Gentile et al. 2019).

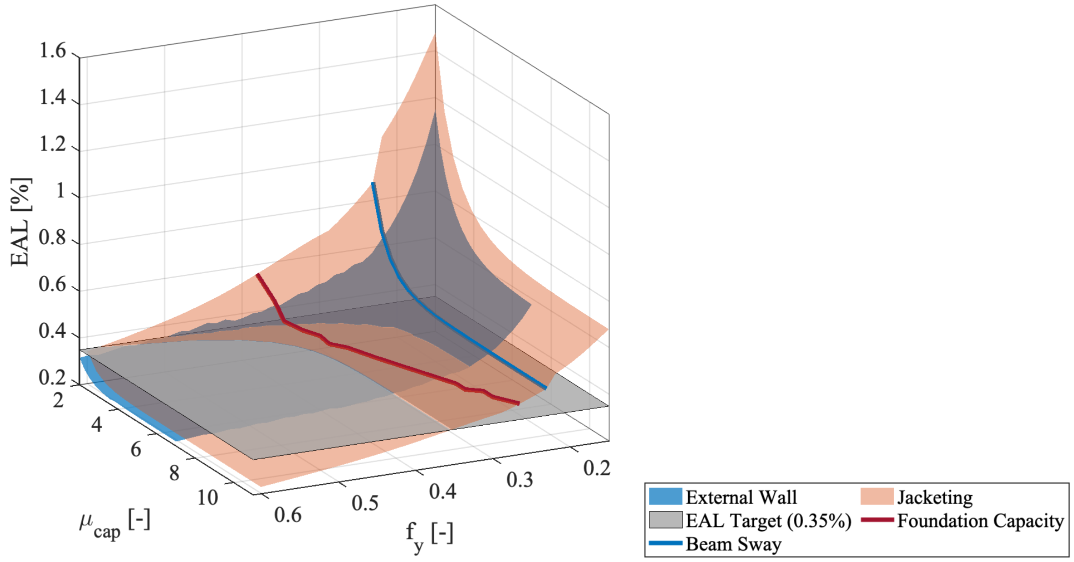

Figure 6: Direct loss-based retrofit used for conceptual design. Modified after Rubini et al. (2023)

A preliminary validation study by Rubini et al. 2023 involves four retrofit configurations for RC frame buildings: concrete jacketing involving all the columns; concrete jacketing involving a selected number of columns; addition of an external RC wall only connected via the floor diaphragms; enlargement of the exterior columns to effectively transform them into interior RC walls (i.e., achieving a dual-system behaviour). DLBD is carried out selecting the low-refinement loss analysis method, and the results are benchmarked against refined NLTHA-based results.

Although the validation study is being refined and enlarged, the preliminary results indicate that the DLBD estimations are conservative for all the illustrative applications, with errors ranging between 4% and 17%.

Challenges and research outlook

The available applications of DLBD confirm its promising potential. However, more research efforts are needed to enhance the methodology and to increase its scope so that it can meet the requirements of modern structural design. The following key areas are identified:

1. **Further validation.** DLBD should be validated using more-refined loss assessment methodologies (e.g., FEMA 2012). A sensitivity study is needed to investigate the loss-estimation error due to both the assumptions intrinsically embedded in DLBD (e.g., surrogated PSDM) and the quality of the calibration of its input parameters (e.g., damage-to-loss ratios)
2. **Integration with state of the art.** To enhance the overall design process, DLBD should integrate features of other advanced risk/loss-based design procedures (e.g., Sinković et al. 2016, and others cited in the introduction).
3. **Scope increase.** DLBD should be expanded to include other design use cases involving different materials, lateral resisting systems, and structural typologies (e.g., bridges). At least arguably, any design use case for which a direct displacement-based design is available can be “upgraded” to DLBD.
4. **Integrated code implementation.** Different applications of DLBD should be implemented adopting a shared software architecture. A graphical user interface may maximise the impact of DLBD in the engineering practice
5. **Indirect losses.** A detailed calibration of the model for indirect losses (Calvi et al., 2021) is required
6. **Alternative loss metrics.** DLBD should be refined and validated to consider different types of conventional (e.g., downtime, environmental impact), or people-centric loss metrics (e.g., wellbeing losses; Markhvida et al. 2020)

7. **Lifecycle design**. The loss-assessment module at the core of DLBD should be enhanced to account for the overall losses within a given time horizon (e.g., Gentile et al. 2021). This would also allow including an insurance coverage within the designed building solution
8. **Other hazards.** DLBD should be developed for other hazards (e.g., flood, wind). A multi-hazard approach should be finally targeted
9. **Other design "dimensions".** The DLBD philosophy should be applied to other relevant dimensions of the building/structural performance. For example, the assessment procedure by Bianchi et al. (2022) may be embedded in DLBD to provide an integrated design methodology targeting both hazard-related and energy efficiency economic losses.

Final remarks

DLBD allows designing structures that would achieve -rather than be bounded by- a given loss-related metric under the relevant site-specific seismic hazard (by analogy with the words of Priestley, 2007). The term "direct" denotes the designer's capacity to set a loss target as an input parameter before conducting any analysis and to achieve it reasonably with minimal design iterations, usually two or three.

After describing the design procedure from a high-level perspective, this paper shows the recently-developed applications of DLBD for the design of RC frame and wall buildings, both monolithic or base-isolated, and the retrofit of existing ones using different strategies and techniques. The available validation studies involve benchmarking the target loss of several case-study buildings against loss assessments involving non-linear time-history analyses of refined numerical models. The recorded errors are deemed compatible with the preliminary design phase, and therefore DLBD is deemed dependable for the existing applications.

Although the available applications of DLBD indicate its promising potential, more research efforts are needed to enhance the methodology and to increase its scope so that it can meet the requirements of modern structural design. This paper provides a research outlook indicating some potential areas of improvement to be targeted in future investigations.

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