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DIRECT LOSS-BASED SEISMIC DESIGN: STATE OF THE ART AND CURRENT CHALLENGES

Roberto Gentile[1]

[1] Institute for Risk and Disaster Reduction (IRDR), University College London (UCL)
Gower st., London
e-mail: r.gentile@ucl.ac.uk

Abstract

Seismic design codes typically aim to prevent collapses or ensure safety during major, infrequent earthquakes, while minimizing damage during minor, frequent ones. However, advancements in theoretical knowledge, modeling capabilities, and observed damage have increased awareness of the impact of these codes on earthquake risk. The 1994 Northridge earthquake in the US caused significant economic consequences, prompting a paradigm shift towards performance-based earthquake engineering for risk and loss assessment. Several research efforts suggest replacing traditional force-based design with methods targeting displacements, seismic fragility, mean annual frequency of exceeding a damage state, losses, and resilience metrics. This paper focuses on direct loss-based design (DLBD), a newly developed method that enables designing structures to achieve a desired loss-related metric under site-specific seismic hazard virtually without design iterations. The paper explores the effectiveness of DLBD for designing new reinforced concrete buildings -monolithic or base-isolated- or retrofitting existing ones, the validation studies required to expand its scope, improvements needed for more accurate loss-estimation methods, and operational advances to make DLBD appealing in the practice.

Keywords: Instructions, ECCOMAS Thematic Conference, Structural Dynamics, Earthquake Engineering, Proceedings.

1 INTRODUCTION

Seismic design codes prioritize the prevention of collapse or life safety during major earthquakes, and damage prevention during minor ones. However, with increased knowledge and damage observations, there is a need to evaluate the implications of these provisions on earthquake risk. Performance-based earthquake engineering (PBEE) has been developed to address this need. PBEE is a state-of-the-art approach that calculates a loss metric for a given building configuration, including both structural and non-structural components. Different design procedures have incorporated portions of PBEE to obtain risk- or loss-based design approaches. These procedures include yield point spectra [1], seismic fragility targeting (e.g. [2,3]), yield frequency spectra [12], probabilistic displacement-based design [5,6], and risk-targeted force-based design [7], among others. An extensive review of such design approaches is given in [8]. Most PBEE procedures are iterative, involving repeated applications of an assessment method (often involving non-linear time history analyses, NLTHAs) while revising a guess design candidate until a loss target is met. However, this approach may be cumbersome if carried out manually and may limit the design experience if carried out using an optimization algorithm, since the designer can only set an objective function to minimise, and then accept the result of the optimisation.

To address these limitations, Direct Loss-Based Design (DLBD [9,10]) has been proposed. DLBD allows designing structures that achieve a specific loss-related target under the seismic hazard profile at a particular site. DLBD is a direct approach, which means the designer can specify a loss target as the first input of the process and achieve it virtually without design iterations. This paper briefly describes DLBD and discusses recent advances in this research topic. The paper also identifies some challenges in developing and adopting DLBD and provides some final remarks. The existing DLBD applications include the design of monolithic [10] or base-isolated [11] reinforced concrete buildings and the retrofit [12] of existing reinforced concrete buildings.

2 DIRECT LOSS-BASED DESIGN (DLBD)

The process of DLBD involves mapping various single degree-of-freedom (SDoF) systems to a chosen loss metric in a flexible and efficient manner, as outlined in Section 2.1. This allows for the identification of an ideal system's force-displacement curve that meets the target loss. The next step is to detail the relevant structural members to comply with the chosen force-displacement curve.

This section provides a brief, non-exhaustive overview of DLBD, with further details on the methodology available in the work in [10]. The code implementation for DLBD is also freely available at github.com/robgen/lossBasedDesign.

2.1 Loss assessment module

The loss assessment methodology utilized in this study is based on a *surrogate probabilistic seismic demand model* (PSDM) for single-degree-of-freedom (SDoF) systems. The PSDM used is a bi-linear model that can compute the distribution of ductility demand (μ) given the intensity measure $R = SA/f_y$, where SA denotes the pseudo-spectral acceleration at the elastic period of the chosen SDoF, and f_y is the yield strength normalized by the total weight. The PSDM parameters (slope a, and standard deviation σ) are obtained from two Gaussian process regressions that have been trained on a dataset of 10,000 inelastic SDoFs subjected to cloud-based nonlinear time-history analyses using 100 natural ground motions for each SDoF [9]. This results in an analytical formulation for (a, σ) based on 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 computed for a set of structure-specific damage states identified by the ductility thresholds μ_{DS}, including slight, moderate, extensive, and complete damage. For *loss assessment*, a *low-refinement building-level analysis* using a vulnerability relationship or a *medium-refinement storey-level analysis* using a vulnerability curve for the structure and storey loss functions for non-structural components can be alternatively used. High-refinement component-based loss assessment methodologies are not considered suitable for preliminary design and are not included in DLBD.

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 can confidently characterize the inventory of non-structural components likely present in the building since the preliminary design phase. The vulnerability relationship for this method captures only the structural damage, while 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), which is usually an acceleration (α) or an inter storey-drift (θ). Storey-level vulnerability relationships (loss vs SA) for each group of non-structural components are obtained by converting the storey loss functions (loss vs EDP) using appropriate EDP(SA) relationships. The θ(SA) is defined combining the surrogate PSDM with displacement shapes appropriate for a given lateral resisting system, while the α(SA) relationship can be obtained using an acceleration shape formulation (e.g., the one provided by the Federal Emergency Management Agency [13]). Finally, the structural-only vulnerability relationship is summed to the storey-level ones to obtain a building-level vulnerability relationship.

Indirect economic losses, such as the cost of relocating the displaced building occupants during the emergency phase and the time required to repair and refurbish the damaged building, can be accounted for using a calibrated non-linear mapping between direct and indirect losses (e.g., [14]). A building vulnerability curve combining direct and indirect losses is then defined.

Loss metrics (e.g., expected annual loss, EAL) are derived by integrating the hazard curve (representing the mean annual frequency of exceeding different SA levels) with the building vulnerability curve. Existing hazard models are suggested to simplify the preliminary design process, while ad hoc probabilistic seismic hazard analysis may be used for a refined verification of the final design.

2.2 Main design procedure

DLBD first requires some *preparatory steps*, which are specialised for a selected lateral resisting system (e.g., RC frames). The designer should:

- Define/obtain hazard curves covering a wide range of secant-to-yielding periods
- Select an appropriate set of DSs. Each DS must be accompanied by a reasonable ductility threshold defined relatively to the (unknown) ductility capacity of the design SDoF
- Choose the loss typology (e.g., economic losses), a relevant loss metric (e.g., EAL), an appropriate damage-to-loss model and/or storey loss functions for non-structural components
- Determine the basic geometric properties of the structure (e.g., number of storeys, bays, inter-storey height). This is usually done considering gravity-load design.

The first of the *core steps* of DLBD involves selecting a loss target (e.g., EAL=0.3% of the total reconstruction cost). Subsequently, several seed SDoF systems are defined combining of the parameters $hyst, T, f_y, h$ and the ductility capacity μ_{cap}. For each of them, the relevant loss metric is calculated using th loss assessment method in Section 2.1. Figure 1a shows an illustrative example of such mapping.

The seed SDoF that meet the selected loss target are selected from the mapping. Such selected seeds are subjected to the code-based seismic performance checks for all DSs (e.g., using the Capacity Spectrum Method [15]). Among those compliant with the code, the SDoFs 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) are also excluded. The remaining SDoFs are named *candidate design SDoFs*, and the final *design SDoF* can be chosen arbitrarily among those (Figure 1b). Such choice may also be based on non-seismic design requirements.

Once the design SDoF is identified, its backbone curve is used to design the structural members of the lateral resisting system, as well as ensuring a favourable plastic mechanism. The *structural detailing phase* is not an integral part of DLBD: any method that allows achieving this goal can be used, including trial and error. The principles of direct displacement-based design [17] are suggested for this phase, as described in detail in [10].

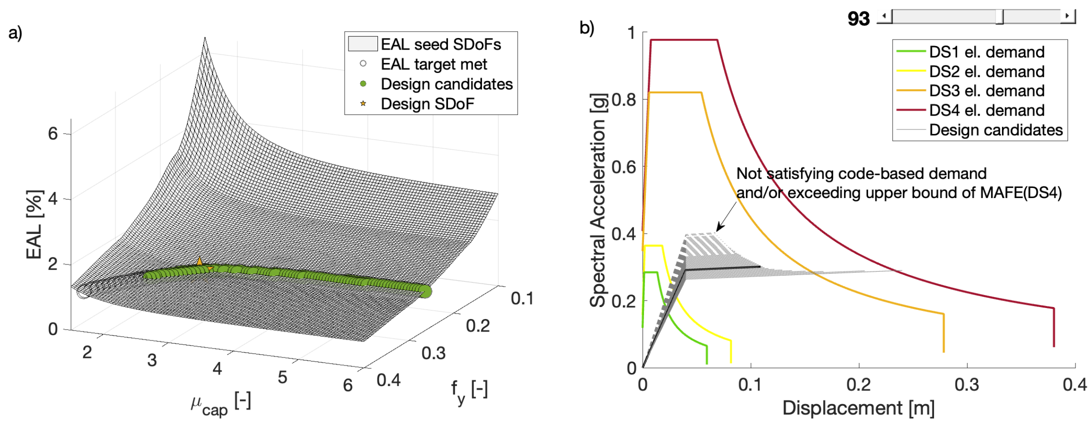

Figure 1: a) Expected annual loss of the seed SDoFs; b) capacity curves of the candidate design SDoFs. MAFE: mean annual frequency of exceedance; DS: damage state. Modified after [10]

2.3 Conceptual design phase

DLBD enables risk and loss-based considerations to be incorporated into the conceptual design phase. Through repeated loss mapping with different parameters such as geometry, materials, and lateral resisting systems, designers can assess their choices against potential loss implications. This is particularly useful as estimating losses can be challenging due to the non-linear nature of the problem, making it difficult to rely on design experience alone.

An example of a conceptual design for a three-storey RC building is presented in Figure 2, comparing a frame and a wall lateral resisting system. The exercise considers both direct and indirect losses, and detailed assumptions for the preliminary steps of DLBD are provided in [10].

While the example presented may appear straightforward, it illustrates how DLBD can guide the conceptual design phase. For instance, it highlights that certain target EAL values (such as 2.4%) cannot be met with a wall lateral resisting system, indicating that a frame may be a better option. Additionally, the lack of intersections between the two loss mappings suggests that the selection of yield strength and ductility capacity may not significantly impact the conceptual design phase.

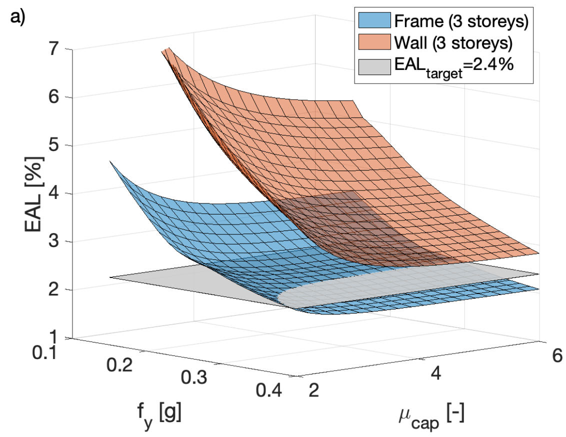

Figure 2: RC frame vs wall conceptual design for a 3-storey building using direct and indirect loss mapping (illustrative example). Modified after [10]

3 EXISTING APPLICATIONS OF DLBD

3.1 Reinforced concrete buildings

The first discussed use of DLBD involves an RC building that incorporates both frame and wall lateral resisting systems. The methodology for analyzing RC frames and walls within DLBD adheres to the same guidelines presented in Section 2, without necessitating any additional or altered procedures.

The validation study [10] comprises 16 rectangular-plan concrete buildings that incorporate frames in the longitudinal direction and walls in the transverse direction, leading to a total of 32 lateral resisting systems. The case studies are designed using the low-refinement loss assessment module and account for variations in geometry, hazard profiles, and target losses. Each case study undergoes a refined earthquake loss assessment methodology, which includes 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 $(EAL_{NLTHA} - EAL_{target})/EAL_{target}$. The conservative DLBD estimations, depicted in Figure 3, mostly lie below the 20% error threshold. Only four case studies for frames exhibit an error within the [21.5%, 31%] range. In contrast, the wall case studies indicate considerably smaller errors, with only five case studies having an error within the [15%, 22%] range.

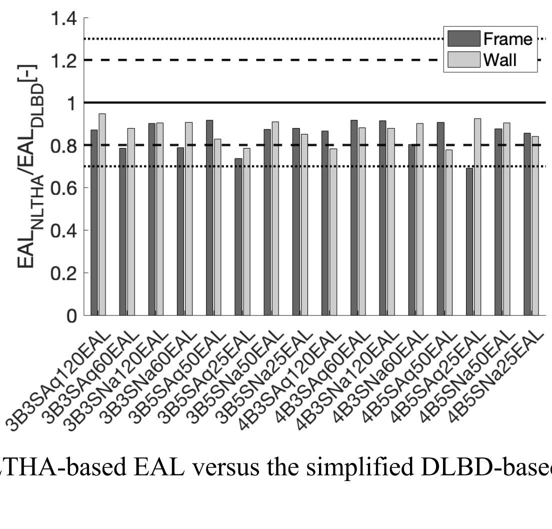

Figure 3: Ratio of NLTHA-based EAL versus the simplified DLBD-based one. Modified after [10]

3.2 Base-isolated reinforced concrete buildings

Suarez et al. [11] propose a DLBD procedure for low-rise, base-isolated structures. Such procedure requires certain modifications in comparison to the procedure outlined in Section 2.1, since representing base-isolated structures using a single-degree-of-freedom (SDoF) model may not be appropriate. This is because the isolation layer exhibits fundamentally different dynamic behaviour and non-linearity compared to the superstructure, which is instead designed to remain elastic.

The surrogate PSDM is applied to the isolation layer only, while the seismic demand of the (elastic) super structure is calculated using a 2DoF approximation, and appropriate displacement and acceleration profiles. Finally, since none to slight damage is expected for the super structure, the medium-refinement loss assessment method must be used: losses are modelled separately for the isolation layer, the super structure, the non-structural components (acceleration- and drift-sensitive).

A preliminary validation study 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.

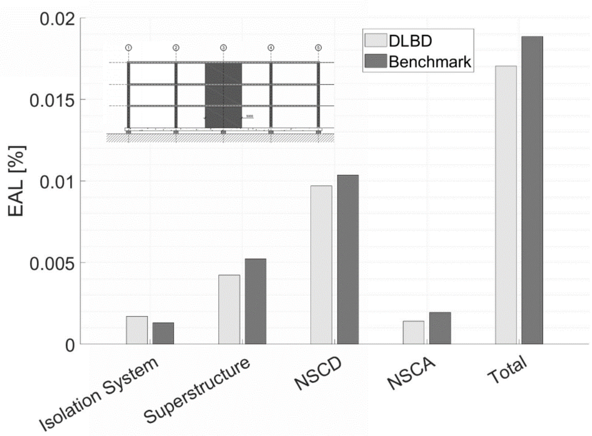

Figure 4: Direct loss-based design for a three-storey, RC medical clinic base-isolated with lead rubber bearings. Modified after [11]

3.3 Retrofit of existing reinforced concrete buildings

A DLBD procedure to retrofit existing RC frame buildings is provided by Rubini et al. [12]. It allows using different techniques (i.e., RC column jacketing, addition of external RC walls). The general guidelines in Section 2 directly apply for this procedure; without the need for modifications. However, the analysis of the as-built structure must be added as an additional preparatory step.

The process involves an analysis of the local strength hierarchy of each beam-column joint subassembly and its potential plastic mechanism within the frame. This allows determine the force-displacement capacity curve of the frame, according to its plastic mechanism. Additionally, the structure's force-displacement capacity is also calculated assuming a "beam-sway" global mechanism, which involves plastic hinges at the ends of all the beams. This lateral capacity is associated with a retrofit strategy that aims to ensure a strong-column, weak-beam behavior by reversing the local strength hierarchy of the subassemblies. Finally, the capacity of the foundations to resist lateral forces is assessed, and this is considered as the upper limit for frame retrofit interventions that do not involve a foundation intervention. The above quantities (reflected in the loss mapping, Figure 5) may be calculated via a numerical pushover analysis or using SLaMA (simple lateral mechanism analysis; [18,19]).

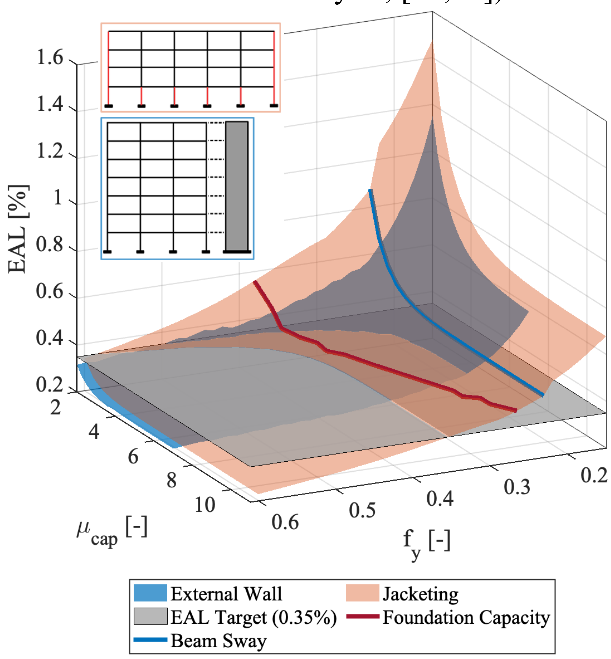

Figure 5: Direct loss-based retrofit used for conceptual design. Modified after [12]

A preliminary study was conducted to validate four retrofit configurations for deficient RC frame buildings. These configurations include concrete jacketing of all columns, jacketing of selected columns, addition of an external RC wall only connected via floor diaphragms, and enlargement of exterior columns to achieve a dual-system behavior. The DLBD method was used with the low-refinement loss analysis method, and the results were compared to refined NLTHA-based results. Although the study is being refined and expanded, initial findings suggest that DLBD estimates are conservative for all configurations, with errors ranging from 4% to 17%.

4 RESEARCH OUTLOOK

The current applications of DLBD demonstrate its potential, but further research is necessary to improve and broaden its methodology to meet modern structural design needs. Several essential areas for improvement have been identified:

- **Further validation.** DLBD needs to be validated using more-refined loss assessment methodologies (e.g., [13]). A sensitivity study is needed to investigate the loss estimation error due to the assumptions inherently embedded in DLBD and the quality of its input parameters calibration, such as damage-to-loss ratios.
- **Integration with state of the art.** To enhance the overall design process, DLBD should integrate advanced features of other risk/loss-based design procedures (e.g., [20] and others cited in Section 1).
- **Scope increase.** DLBD should be expanded to include other materials, lateral resisting systems, and structural typologies such as bridges.

- **Integrated code implementation.** A software architecture capable to accommodate different applications is desirable. A graphical user interface may maximise the impact of DLBD in the engineering practice.
- **Indirect losses.** A detailed calibration of the model for indirect losses [14] is required
- **Alternative loss metrics.** DLBD should be refined and validated to consider different types of conventional loss metrics, such as downtime, environmental impact, or people-centric loss metrics, such as wellbeing losses [21].
- **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., including the model in [22]). This would also allow including an insurance coverage within the designed building solution.
- **Other hazards.** DLBD should be developed for other hazards such as flood and wind. A multi-hazard approach should be finally developed.
- **Other design dimensions.** The DLBD philosophy should be applied to other relevant dimensions of the building/structural performance. For example, the assessment procedure in [23] may be embedded in DLBD to provide an integrated design methodology targeting both hazard-related economic losses and energy efficiency-related annual costs.

5 CONCLUSIONS

DLBD allows for the design of structures that can achieve - rather than being limited by it- a given loss-related metric under the specific seismic hazard of a site. The term "direct" refers to the designer's ability to input a loss target before any analysis is carried out and to achieve it virtually without design iterations.

This paper presents the DLBD procedure and its recent applications in designing RC frame and wall buildings, both monolithic and base-isolated, and retrofitting existing buildings using various strategies and techniques. The available validation studies involve benchmarking the target loss of several case-study buildings against refined loss estimations based on non-linear time-history analysis of refined numerical models. The errors recorded are considered acceptable for the preliminary/conceptual design phase, indicating the reliability of DLBD for existing applications.

However, there is still a need for more research to enhance the DLBD methodology and scope to meet modern structural design requirements. The paper provides a research outlook highlighting potential areas for future investigation.

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