Illustrative application of direct loss-based seismic design for reinforced concrete buildings

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Abstract: A direct loss-based design (DLBD) procedure for reinforced concrete buildings has been recently proposed by the authors. It allows achieving a target acceptable level of earthquake-induced loss (e.g. deaths, dollars, downtime) under a specified site hazard profile. The procedure is called "direct" since the target loss level (e.g. defined based on client preferences) is specified at the first step of the procedure, and it generally requires two or three design iterations. The foundation of DLBD is a simplified loss assessment employing surrogate probabilistic seismic demand models and building-level damage-to-loss models for both direct and indirect losses. For a given target loss level, and structural geometry, the procedure provides the force-displacement curve of an equivalent single degree of freedom system. Such force-displacement curve becomes the target of the structural detailing phase, which is carried out using the principles of displacement-based design, thus allowing to design beams, columns, and walls accordingly. This paper illustrates the effectiveness of DLBD in designing a realistic RC case study building that achieves a 0.5% expected annual loss.

Keywords: risk-targeted design approach; earthquake economic losses; direct/indirect losses; expected annual loss; tail value at risk.

1. Introduction

Provisions in seismic design codes generally focus on collapse prevention and/or life safety for major, rare earthquakes while damage prevention for minor, frequent ones. After the 1994 Northridge (USA) earthquake, new research led to performance based earthquake engineering (PBEE), a fully-probabilistic earthquake loss assessment approach (Cornell and Krawinkler 2000). For a fully-specified building, the PBEE approach returns the mean annual frequency (MAF) of exceeding economic losses (among other loss measures) considering: a hazard curve; a fragility model (which depends on non-linear time-history analyses); a damage-to-loss model. The PBEE approach is considered a standard for assessment purposes, but is less practical for design, due to the required amount and refinement of input data.

For this reason, most of the available loss-related design procedures are iterative, involving repeated applications of the PBEE assessment formula, while revising a guess design candidate until the target loss is achieved. Some of those refined yet time-consuming approaches employ non-linear optimisation methods and/or trial-and-error (Krawinkler et al. 2006; Mackie and Stojadinović 2007; Pei and van de Lindt 2009; Dhakal and Saha 2017; Shahnazaryan and O'Reilly 2021). Other approaches involve pre-computing the PBEE formula for many structural configurations within a class (Esmaili and Zareian 2019; Takahashi et al. 2020).

A direct loss-based design (DLBD) procedure, arguably more appropriate for preliminary design, has been recently proposed in Gentile and Calvi 2022. It was initially proposed by Gentile and Galasso 2022, and it is consistent with the conceptual guidance in Calvi et al. 2021. DLBD aims at 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 (Priestley et al. 2007)). The adjective "direct" since the target loss level (e.g. defined based on client preferences) is specified at the first step of the procedure, and it generally requires two or three design iterations.

This paper discusses the rationale behind DLBD, and briefly describes its steps (Section 2). Most importantly, Section 3 shows the application of DLBD to a realistic case-study reinforced concrete building with a frame lateral resisting system in one direction and a wall system in the perpendicular direction. Section 4 briefly discusses the conclusions.

2. Methodology

DLBD is briefly summarised in this Section, while the relevant details are provided in Gentile and Calvi 2022. The steps of the procedure can be summarised as follows:

- Provide a set of preliminary inputs, including:
  - A site-specific hazard model composed of hazard curves in terms of spectral acceleration for a set of vibration periods;
  - A structure-specific damage state (DS) thresholds, defined relatively to the ductility capacity at peak strength (μ), which is an intermediate design parameter. For example, $\mu_{DSi} = [0.5\ 1\ 0.75\mu_{cap}\ \mu_{cap}]$;
  - The typology of losses to consider and a selected loss metric (e.g. the expected annual loss, EAL, of the direct economic losses);
  - A building-level set of damage-to-loss ratios. For example, $DLR_{DSi} = [7\ 15\ 50\ 100]\%$ of the total reconstruction cost;
  - The basic material and geometrical properties, such as the yield stress of steel, the number of storeys, the inter-storey height, the seismic storey mass.
- Select a target loss L_{target} (e.g. EAL equal to 0.5% of the total reconstruction cost);
- Select a number of *seed single-degree-of-freedom (SDoF) systems* by defining combinations of four parameters: the hysteresis type ($hyst$), the fundamental vibration period (T), the yield strength (f_y), the hardening ratio (h), and the seed ductility capacity μ_{cap}. The range for such parameters must be compatible with the surrogate probabilistic seismic demand model by Gentile and Galasso 2022. The number of considered combinations is a choice of the user;
- Apply the simplified loss assessment procedure summarised in Figure 1 to each seed SDoF system, and calculate the selected loss metric. The simplified loss assessment (described in detail in Gentile and Calvi 2022) is based on the above surrogate model for the seismic demand (i.e. probability distribution of peak horizontal deformation given ground-motion intensity), and simplified building-level damage-to-loss models for both direct and indirect losses;
- Select all the SDoF seeds that meet the target loss metric and, for each of them, run the capacity spectrum method using code-based spectra for each DS demand. The seed SDoFs meeting both the target EAL and the code-based seismic demand for all DSs are called *candidate design SDoFs*. The designer is free to arbitrarily choose one of those as the final *design SDoF*;

- The last step of the procedure, i.e. structural detailing, involves designing each structural member in the lateral resisting system such that the considered structure complies with the design SDoF's backbone. Any analysis method to achieve this goal (including trial and error) is equally valid, although it is herein suggested to adopt the principles of displacement-based design (Priestley et al. 2007).

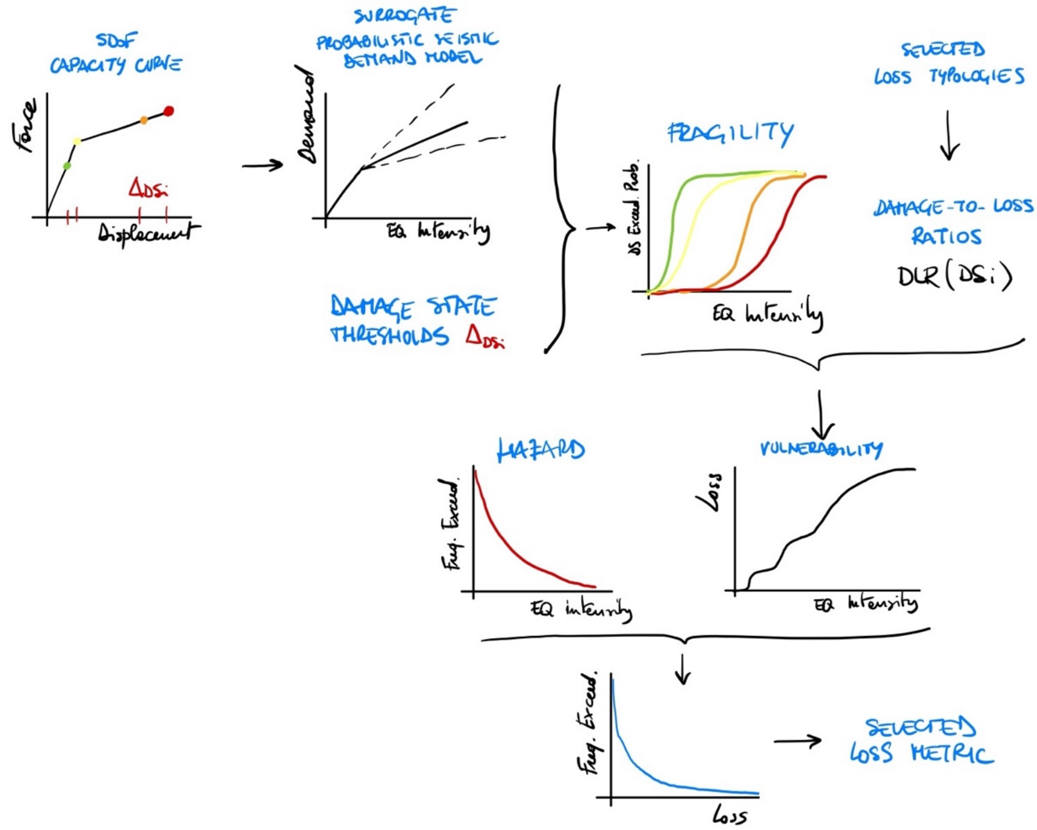

Fig. 1 – Simplified loss assessment method at the basis of DLBD.

3. Illustrative application

DLBD is demonstrated for a three-storey, three-by-three-bay RC case-study building in the city of Napoli, Italy. The lateral resisting system is composed of four frames in the longitudinal direction and two walls in the transverse. The building is designed to achieve a 0.5% EAL in both directions (only direct losses are considered, for simplicity). It is worth mentioning that no torsional behaviour is considered and the two building directions are designed independently.

To avoid performing an *ad hoc* site-specific probabilistic seismic hazard analysis, the code-based Italian seismic hazard model is adopted (Stucchi et al. 2011). Among other variables, the model provides hazard curves for 10 periods between 0.1s and 2.0s. Linear interpolation is adopted for the seed SDoFs having different vibration periods. The damage states (relative to the unknown building ductility capacity) are defined as $\mu_{DSi} = [0.5\ 1\ 0.75\mu_{cap}\ \mu_{cap}]$, while the adopted damage-to-loss ratios are $DLR_{DSi} = [7\ 15\ 50\ 100]\%$ of the total reconstruction cost, consistently with those proposed in (Cosenza et al. 2018) for Italian concrete buildings. The basic material properties of the building involve: concrete strength equal to $f_c = 30MPa$, steel yield stress equal to $f_{sy} = 450MPa$. The basic geometry properties involve: beam length equal to $l_b = 5.5m$, inter-storey height equal to $H_{int} = 3.3m$, beam depth equal to $h_b = 0.5m$, column width equal to $h_c = 0.6m$. According to the parameter definitions in Gentile and

Galasso 2022, the frame is characterised by the modified Takeda "fat" hysteresis model, while modified Takeda "thin" is used for the wall. The total storey mass is equal to $205Ton$.

Figure 2a shows the mapping of the EAL for 10000 SDoF seeds related to the frame building direction. On the other hand, Figure 2b shows the selected candidate design SDoFs, together with the code-based uniform hazard spectra used for the displacement-based checks at 30y, 50y, 475y, and 975y mean return periods. The selected design SDoFs for the frame and wall building directions are also shown. For both directions, the principles of direct displacement-based design are used for the structural detailing of the members. Full details about the resulting member detailing can be found in Gentile and Calvi 2022.

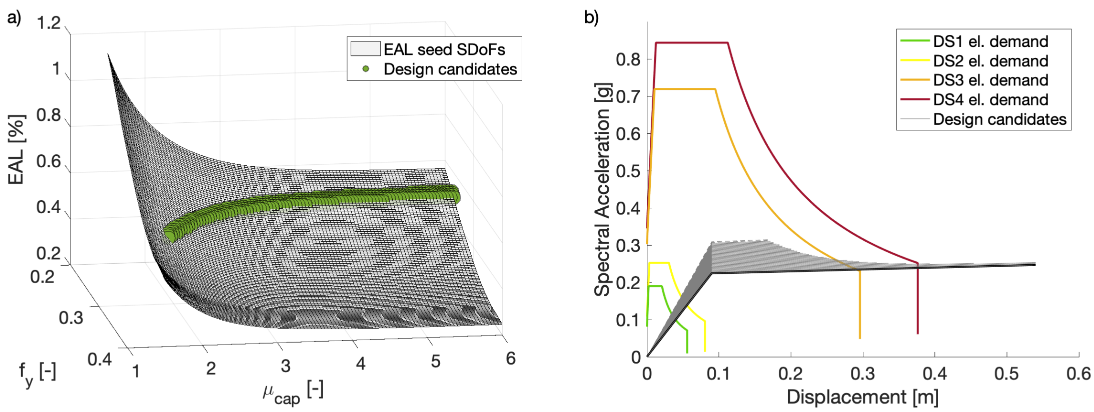

Fig. 2 – a) Expected annual loss map for the case study (frame direction). b) Capacity curves for the candidate SDoFs (frame direction).

The DLBD results, for both the frame and the wall directions, are compared to a refined loss assessment procedure based on non-linear time history analysis, herein simply referred to as time history (TH). Although the overall methodology is consistent with Figure 1, there are some fundamental methodological differences to consider within the discussion: the building fundamental period is estimated from the bilinear representation of the numerical pushover curve; the member-level DSs are quantified using numerical pushover results; the response analysis is based on refined non-linear time-history analyses (instead of the surrogate model). The details of the adopted numerical modelling strategy, ground-motions for the time history analyses, fragility and vulnerability derivation are provided in Gentile and Calvi 2022.

Figures 3 and 4 respectively show a summary of the results for the frame and wall lateral resisting systems. In particular, Figures 3a and 4a show a comparison of the pushover-based capacity curves with the capacity curves resulting from DLBD. The observed discrepancy is satisfactory, and it is almost negligible for the wall case study. The same applies for the comparison of the DS thresholds, which are below 7% for DS2 and below 25% for DS4. By propagating such discrepancies to the PSDM definition (Figures 3b and 4b), while adding the errors caused by the surrogate modelling within DLBD, returns PSDMs almost superimposable to the time-history based ones, with the highest discrepancies observed for the wall system in the non-linear response range. This is directly, and trivially, reflected on the derivation of fragility curves (Figures 3c and 4c). Finally, Figures 3d and 4d show that the hazard curves adopted for the refined and simplified loss assessment are essentially superimposed, thus confirming that the period-estimation errors are acceptable. The same figure panels show that the discrepancy between the vulnerability curves is particularly small, and it increases for higher values of the intensity measure, which are associated with particularly low values of the mean annual frequency of being exceeded.

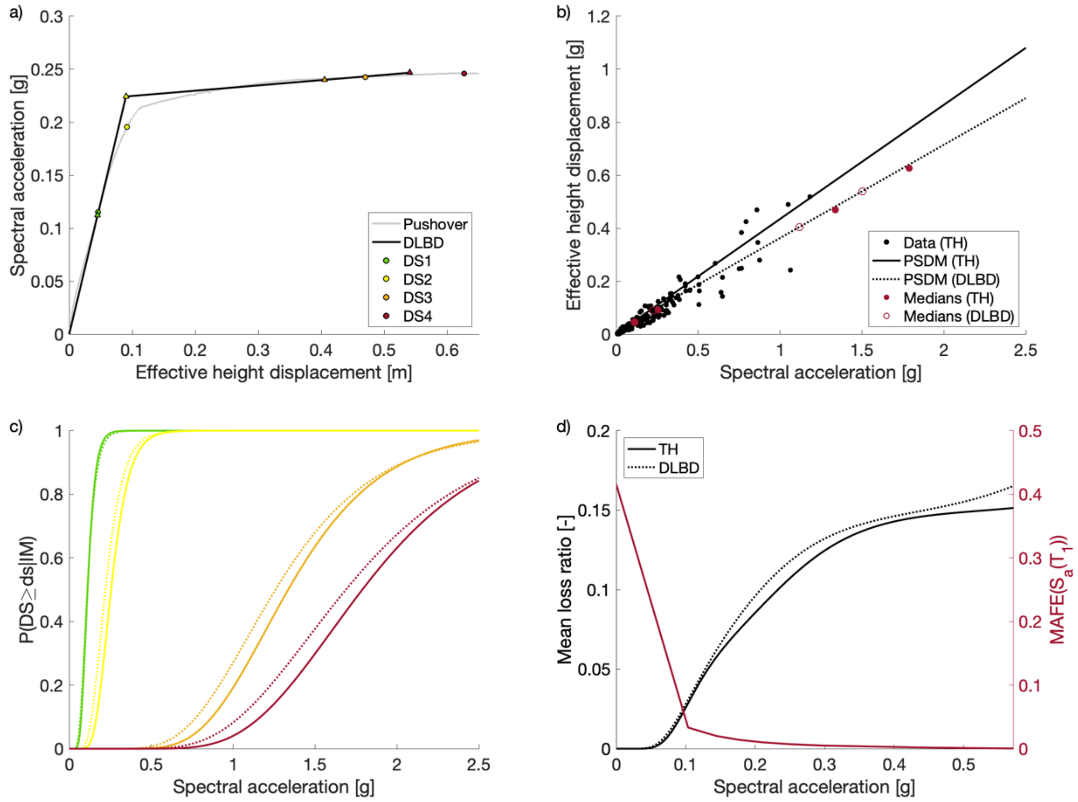

Fig. 3 – DLBD vs. time-history based loss assessment for the frame case study: a) force-displacement curves; b) probabilistic seismic demand models (PSDM); c) fragility curves; d) vulnerability curves.

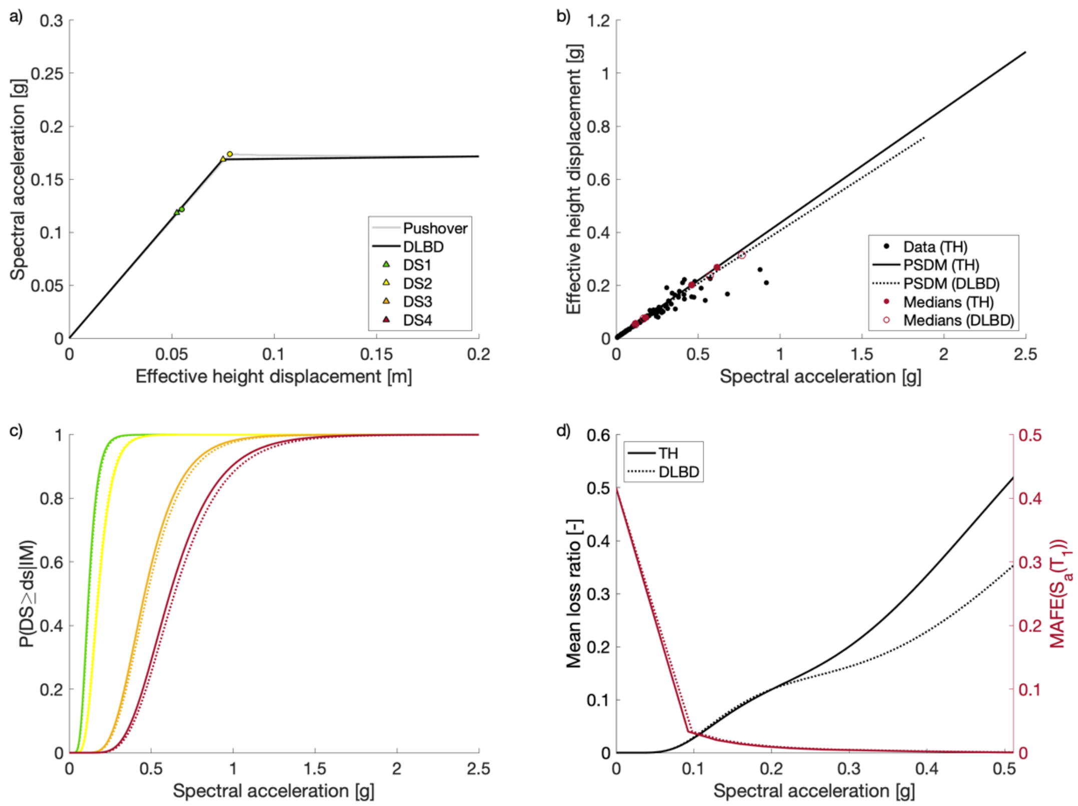

Fig. 4 – DLBD vs. time-history based loss assessment for the wall case study: a) force-displacement curves; b) probabilistic seismic demand models (PSDM); c) fragility curves; d) vulnerability curves.

Therefore, the EAL discrepancy, $(EAL_{NLTHA} - EAL_{target})/EAL_{target}$, are respectively equal to -13% and -10%, for the frame and the wall directions. Those are deemed satisfactory, since they correspond to an EAL anomaly respectively equal to -0.06% and -0.045% of the total reconstruction cost. It is worth mentioning that a detailed discussion of these results, together with 15 more building case-studies, is provided in Gentile and Calvi 2022.

4. Conclusions

This paper briefly reports an illustrative application of a direct loss-based design (DLBD) procedure for seismic actions, described in Gentile and Calvi 2022, and initially proposed by Gentile and Galasso 2022. It allows achieving a target acceptable level of earthquake-induced loss (e.g. deaths, dollars, downtime) under a specified site hazard profile, virtually with no design iteration (practically, two or three iterations are sufficient).

DLBD is herein showcased for a three-storey, three-by-three-bay RC case-study building in the city of Napoli, Italy. The lateral resisting system is composed of four frames in the longitudinal direction and two walls in the transverse. The building is designed to achieve a 0.5% EAL in both directions. The results showed that DLBD provides a rational and practice-oriented way to achieve a risk-based seismic design. By comparison with a refined non-linear time-history based loss estimation procedure, DLBD shows an expected annual loss discrepancy equal to 13% for the frame, and 10% for the wall direction of the case-study building. This corresponds to an expected annual loss anomaly equal to 0.06% and 0.045% of the total reconstruction cost, respectively.

Acknowledgements

This study was partially funded by the European Union's Horizon 2020 research and innovation program under grant agreement No. 843794 (Marie Sk1odowska-Curie Research Grants Scheme MSCA-IF-2018: Multi-level Framework to Enhance Seismic Resilience of RC buildings - MULTIRES).

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