12th National Conference on Earthquake Engineering
Salt Lake City, Utah
27 June - 1 July 2022
Hosted by the Earthquake Engineering Research Institute

Calibration of Damage-to-loss Ratios for a Case-study Structure

K. Aljawhari[1], R. Gentile[2], and C. Galasso[1,2]

ABSTRACT

This study illustrates a simulation-based procedure for calibrating structure-specific damage-to-loss ratios (DLRs), which link the earthquake-induced global damage states (DSs) of a structure with the resulting loss ratios (repair costs normalized by replacement costs). A non-ductile reinforced-concrete frame representative of those built in Italy before the 1970s is selected as a case study. An advanced numerical non-linear model is developed to simulate its dynamic response and failure modes, including flexure, shear, and joint mechanisms. The calibration procedure starts by defining structure-specific DSs describing the increasing structural/nonstructural damage levels and their story-drift thresholds using pushover analysis. Building-level fragility functions are subsequently developed to quantify the probabilities of exceeding each DS given any ground-shaking intensity level. Component-based seismic loss assessment is then performed following the FEMA P-58 approach, which adopts simulation to quantify such losses at multiple ground-shaking intensities. Next, each DLR is statistically characterized by fitting a beta distribution to the component-based loss results upon being conditioned on the corresponding global DS. It is finally shown that the simplified losses obtained by combining the derived DLRs with the building-level fragility functions are highly consistent with their component-based counterparts. This indicates that such DLRs can be easily utilized in seismic risk assessment, particularly for building portfolios, offering a trade-off between accuracy and computational time/effort.

Introduction

Performance-based earthquake engineering (PBEE) has been widely implemented in the past few decades to provide stakeholders/decision-makers with an improved characterization of seismic performance with respect to specific objectives and decision variables (*e.g.* losses, casualties, downtime). PBEE integrates four different phases to evaluate seismic risk, including hazard, structural, damage, and loss analyses, while considering the uncertainties of each phase. The concepts of PBEE have been subsequently refined by FEMA P-58 [1] through introducing a rigorous building-specific seismic risk assessment approach, which quantifies the overall loss in a building by aggregating losses incurred by its individual components. The FEMA P-58 approach, however, is more applicable to loss assessment and (re-)insurance applications for individual structures rather than large-scale building portfolios. This is mainly attributed to the fact that it requires the definition of a comprehensive inventory of all damageable structural/nonstructural components with their fragility/repair models, in addition to conducting site-specific hazard-consistent record selection to be used in non-linear analysis. Such complex requirements could make it infeasible/impractical to implement the FEMA P-58 component-based approach for building portfolios, especially under limited time and/or budget. The availability of fragility and repair models for each building component is another challenge that could hinder this approach's applicability.

[1] Centre for Training and Research on Reduction of Seismic Risk (ROSE Centre), University School for Advanced Studies (IUSS) Pavia, Piazza della Vittoria, Pavia 27100, Italy (email: karim.aljawhari@iusspavia.it)

[2] Department of Civil, Environmental, and Geomatic Engineering (CEGE) and the Institute of Disaster Risk Reduction (IRDR), University College London (UCL), Gower St., London WC1E 6BT, United Kingdom

Aljawhari K, Gentile R, and Galasso C. Calibration of damage-to-loss ratios for a case-study structure. *Proceedings of the 12th National Conference in Earthquake Engineering*, Earthquake Engineering Research Institute, Salt Lake City, UT. 2022.

To tackle this issue, more simplified approaches offering a trade-off between accuracy and computational time/effort are usually implemented for assessing building-portfolio seismic losses. For instance, losses can be computed at the building- rather than component-level by means of damage-to-loss ratios (DLRs), aka consequence models, which are used in combination with building-level fragility relationships via the total probability theorem [2,3]. Those DLRs represent the link between different damage states (DSs) a structure can incur due to ground shaking and their respective loss ratio defined as the repair cost normalized by the replacement cost of a building. Despite the simplicity of using DLRs in risk assessment, they remain a major, probably the largest, source of uncertainty due to the difficulties in correlating damage to loss [4]. Therefore, care must be exercised while selecting DLRs for loss estimation to ensure the reliability of results. DLRs are commonly derived based on expert judgment and/or field observations of buildings following strong seismic events [5–8]. While this method appears to be the most reliable, many DLRs in the literature are deterministic and/or derived based on a limited amount of empirical data [4,9]. Therefore, numerical (*i.e.* simulation-based) derivation of such ratios is a useful alternative that has gained more popularity in the past few decades [9]. Accordingly, this study demonstrates a simulation-based procedure to derive the statistical distribution of DLRs for a case-study reinforced concrete (RC) frame, which can be used to provide quick loss estimates that are highly consistent with those evaluated via the more rigorous FEMA P-58 component-based approach.

Methodology

The derivation of DLRs in this study incorporates the following steps: 1) select a case-study archetype structure and develop a non-linear model to simulate its response; 2) define structure-specific DSs and their story-drift thresholds; 3) select hazard-consistent ground motions at different levels of shaking intensity (stripes) and then run non-linear time-history analysis (NLTHA); 4) derive building-level fragility relationships; 5) define an inventory of all damageable structural/nonstructural elements and run component-based loss analysis; and 6) for each DS, fit a distribution to the resulting loss realizations upon being conditioned on the global DS to characterize the statistical DLR|DSi distributions. More details are provided in the sections below.

Case-study Structure and Modeling Strategy

A five-story infilled RC frame located in L'Aquila (42.3498 N°, 13.3995 E°), which was designed to sustain gravity loads only, is adopted as a case study. This frame represents those built in Italy before the 1970s. Its non-linear response is modeled using OpenSees [10]. All structural elements are modeled as beam-column components with finite-length plastic hinges addressing the non-linear flexural response via moment-curvature relationships [11]. Shear springs are added in series to the beam-column components to address potential shear mechanisms [12–14]. Joint failure is also considered through additional springs assigned in beam-column joint zones [15]. The reader is referred to [16,17] for detailed information about the case-study structure's design, material properties, and modeling strategy. It should be noted that masonry infills are modeled as equivalent diagonal double struts [18,19]. Figure 1(a) illustrates the geometric layout of the case-study structure with cross-section dimensions, whereas Figure 1(b) presents the modeling strategy of beam-column components.

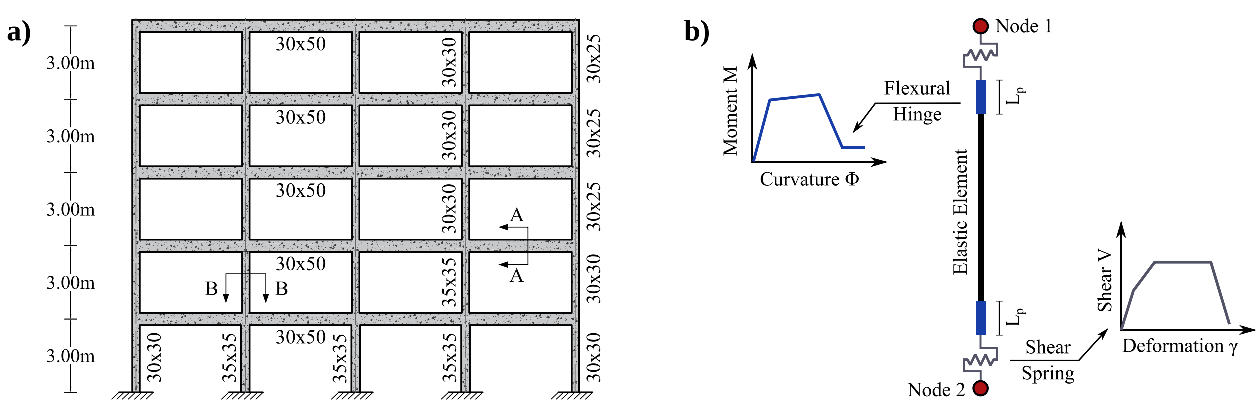

Figure 1. (a) Layout of the case-study frame (cross-sections are in cm x cm); and (b) beam-column modeling.

Ground-motion Selection and Intensity Measure (IM)

The response of the case-study frame is assessed by running NLTHAs using the multiple-stripe analysis (MSA) procedure [20], in which a structure is subjected to ground motions with discrete IM levels (stripes). In this study, 12 stripes reflecting IMs with return periods ranging from 30 to 4975 years are selected. Each stripe has 35 hazard-consistent records that are selected from the NGA-West2 database [21] using the EzGM tool [22]. The considered IM is the geometric mean of pseudo-spectral acceleration (avgSa) evaluated over periods ranging from $0.2T_1$ to $1.5T_1$, where T_1 is the first-mode period [23–25]. L'Aquila's seismic hazard is assessed by using the European Seismic Hazard Model (ESHM13) platform [26,27].

Damage States and Fragility Relationships

Four different DSs are considered to describe the global damage levels sustained by the case-study structure, which are slight, moderate, extensive, and near collapse DSs. Those DSs are quantified by estimating the maximum interstorey drift ratio (MIDR) among all floors. The MIDR threshold of each DSs is calibrated by assessing the multiple measurable criteria defined in [3,16,28] via pushover analysis. The pushover curve of the case-study structure, in addition to the DS thresholds are shown in Figure 2(a). The next step constitutes performing NLTHA using the selected records to characterize the non-linear response of the case-study frame. This process's outcome can be used to derive fragility relationships that describe the probabilities of exceeding each DS over a range of IM values. Such relationships are derived as per the maximum likelihood approach suggested by [29] and they are reported by Figure 2(b).

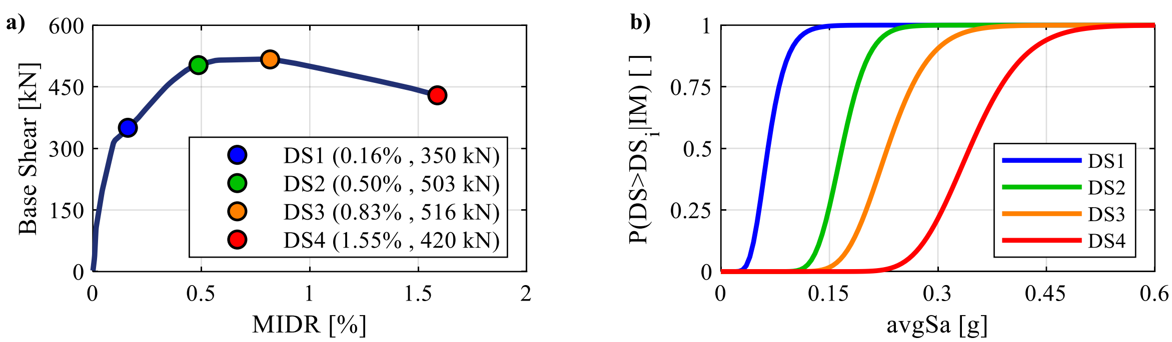

Figure 2. (a) Pushover curve with DS thresholds; and (b) fragility relationships for all DSs.

Component-based Seismic Loss Assessment

The simulation-based derivation of DLRs requires first computing the component-based seismic losses as per the FEMA P-58 approach. This is performed using the PACT tool [1], which characterizes the seismic loss distribution by generating a number of loss realizations at several IM levels via a Monte Carlo approach. PACT requires three inputs: 1) hazard information; 2) results of MSA for generating statistically consistent sets of simulated demands at each IM; 3) a full inventory of damageable structural and nonstructural components with their quantities and fragility/consequence models. Such components, including structural elements, infills, and services (*e.g.* plumbing, heating) are defined as per [30–32] for residential occupancies. The number of loss realizations produced by PACT at each IM level is equal to 1000, which needed a runtime of 30 minutes. This number of realizations is selected upon a sensitivity check to ensure that loss results will not change if analyses are re-run. To facilitate deriving the DLRs, the loss results must be first conditioned on the corresponding global DS, which is achieved by investigating the simulated MIDR value for each realization and assigning an appropriate DS based on the thresholds in Figure 2(a). This process produces four sets of loss realizations, each one conditioned on a specific DS. An empirical cumulative distribution function (ECDF) is assembled for each set, and a beta distribution is then fitted to that ECDF to statistically characterize the DLR for each DS. Such a distribution type has been implemented to characterize DLRs in several past studies [*e.g.* 6,7]. The parameters of the fitted distributions, including the mean (μ) and coefficient of variation (CoV), are reported in Table 1. The shape parameters of the beta distribution, *i.e.* a and b, can be estimated based on μ and CoV [33].

Figure 3(a) shows the ECDFs and fitted beta distributions. The goodness-of-fit of the distributions is tested with a Kolmogorov-Smirnov (K-S) test [34], which verified, at 95% confidence, that the empirical and fitted data can be referred to the same distribution. For the sake of comparison, Figure 3(b) displays the actual loss realizations provided by PACT including their mean and ±1 standard deviation (σ) values, together with the loss ratio (LR) vs. avgSa function (both the mean and ±1σ) obtained by combining the DLRs with the fragility relationships. It can be noticed that the mean LR vs. avgSa function is almost identical to the mean losses estimated by PACT at each IM stripe with only a slight deviation not exceeding 7% in the last stripe. Similar observations can be also noticed regarding the losses with a ±1σ around the mean values. This demonstrates that the proposed DLRs can provide simplified loss estimates that are quite consistent with their component-based counterparts, but with significantly less computational time/effort, *i.e.*, within a few seconds only if fragility relationships are readily available. Lastly, it is worth mentioning that the derived DLRs are compared to those proposed in other studies [*e.g.* 4,5] for validation purposes, and found to be highly consistent.

Table 1. Mean and variance values of the beta distributions fitted for the DLRs.

DS/Parameter	**DS1 (slight)**	**DS2 (moderate)**	**DS3 (extensive)**	**DS4 (near-collapse)**
Mean μ [ ]	0.09	0.34	0.62	0.86
CoV [ ]	0.556	0.244	0.192	0.117

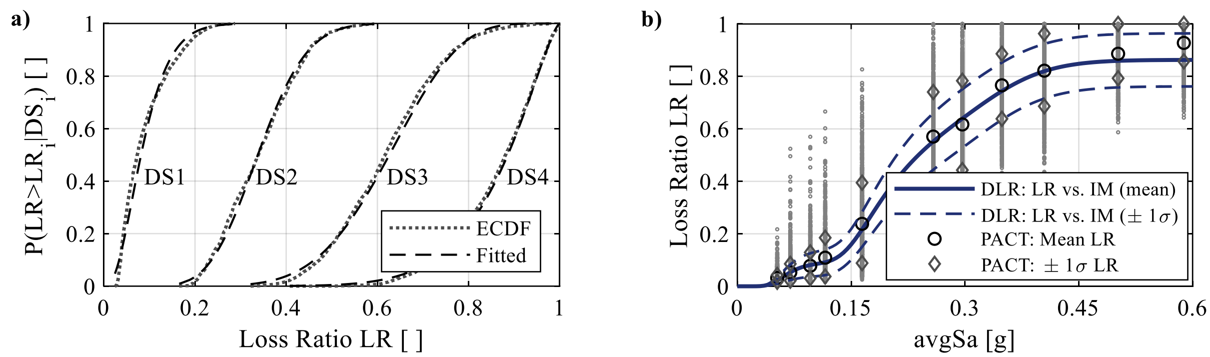

Figure 3. (a) ECDFs and beta distributions of the DLRs; and (b) LR vs. avgSa function evaluated using the derived DLRs in comparison with the real loss realizations produced by PACT.

Conclusions

This paper demonstrated a simulation-based procedure for the calibration of building-level DLRs based on the results of component-based loss analysis. An older five-story infilled frame was considered as a case study. Four different DSs, ranging from slight damage to near-collapse, were considered. The non-linear response of the case-study structure was investigated using the MSA, adopting hazard-consistent record sets at different IM levels. Next, component-based loss analyses were performed using PACT to evaluate the loss distribution at each stripe. The DLRs were finally derived by fitting beta distributions to the loss realizations upon being conditioned on the corresponding DS. The resulting DLRs were consistent with those found in other studies [6,7]. It was also shown that the LR vs. avgSa function evaluated by combining the DLRs with the building-level fragility relationships is highly consistent with the component-based losses evaluated by PACT at each stripe. This indicates that the considered calibration procedure yields DLRs that can be adopted in simplified risk analysis for providing quick loss estimates that are quite close to the detailed component-based losses. This, in turn, constitutes a useful compromise between accuracy and time/effort, especially in risk assessment of building portfolios, where conducting component-based loss analysis for all assets is usually beyond the timeframe and resources. As the proposed simulation-based approach is generic, future developments might include deriving DLRs for other building types and occupancy categories. Alternative statistical distributions, other than the beta, can be investigated as well with respect to their goodness-of-fit. It is also worth developing methodologies that rely on the LR|IM data rather than LR|DS, which can allow calibrating separate damage-to-loss models for direct and indirect losses for different building occupancy categories.

References

1. FEMA. Seismic Performance Assessment of Buildings: Volume 1 - Methodology. 2nd edit. Washington, DC: 2018.
2. Gentile R, Galasso C. Simplified seismic loss assessment for optimal structural retrofit of RC buildings. *Earthq. Spectra*. 2021; **37** (1): 346–365. doi:10.1177/8755293020952441.
3. Aljawhari K, Gentile R, Freddi F, Galasso C. Effects of ground-motion sequences on fragility and vulnerability of case-study reinforced concrete frames. *Bull. Earthq. Eng.* 2020; . doi:10.1007/s10518-020-01006-8.
4. Martins L, Silva V, Marques M, Crowley H, Delgado R. Development and assessment of damage-to-loss models for moment-frame reinforced concrete buildings. *Earthq. Eng. Struct. Dyn.* 2016; **45** (5): 797–817. doi:10.1002/eqe.2687.
5. Di Pasquale G, Orsini G, Romeo RW. New developments in seismic risk assessment in Italy. *Bull. Earthq. Eng.* 2005; **3** (1): 101–128. doi:10.1007/s10518-005-0202-1.
6. Dolce M, Kappos A, Masi A, Penelis G, Vona M. Vulnerability assessment and earthquake damage scenarios of the building stock of Potenza (Southern Italy) using Italian and Greek methodologies. *Eng. Struct.* 2006; **28** (3): 357–371. doi:10.1016/j.engstruct.2005.08.009.
7. Kappos AJ, Panagopoulos G, Panagiotopoulos C, Penelis G. A hybrid method for the vulnerability assessment of R/C and URM buildings. *Bull. Earthq. Eng.* 2006; **4** (4): 391–413. doi:10.1007/s10518-006-9023-0.
8. FEMA. Hazus ®-MH 2.1 Technical Manual. Washington D.C.: 2012.
9. Odabaşi Ö, Kohrangi M, Fagà E, Bazzurro P. Consequence Functions for Seismic Risk Assessment Consequence Functions for Seismic Risk Assessment A review of consequence modelling state-of-practice for ERM-CH - Module D. 2020;
10. McKenna F. OpenSees: A framework for earthquake engineering simulation. *Comput. Sci. Eng.* 2011; **13** (4): 58–66. doi:10.1109/MCSE.2011.66.
11. Priestley MJN, Calvi GM, Kowalsky MJ. Displacement-Based Seismic Design of Structures. Pavia: Fondazione EUCENTRE, IUSS Press; 2007.
12. Mergos PE, Kappos AJ. A gradual spread inelasticity model for R/C beam-columns, accounting for flexure, shear and anchorage slip. *Eng. Struct.* 2012; **44** : 94–106. doi:10.1016/j.engstruct.2012.05.035.
13. Zimos DK, Mergos PE, Kappos AJ. Shear hysteresis model for reinforced concrete elements including the post-peak range. *COMPDYN 2015 - 5th ECCOMAS Themat. Conf. Comput. Methods Struct. Dyn. Earthq. Eng.* 2015; (May): 2640–2658. doi:10.7712/120115.3565.1184.
14. Sezen H, Moehle JP. Shear strength model for lightly reinforced concrete columns. *J. Struct. Eng.* 2004; **130** (11): 1692–1703. doi:10.1061/(ASCE)0733-9445(2004)130:11(1692).
15. O'Reilly GJ, Sullivan TJ. Modeling Techniques for the Seismic Assessment of the Existing Italian RC Frame Structures. *J. Earthq. Eng.* 2019; **23** (8): 1262–1296. doi:10.1080/13632469.2017.1360224.
16. Aljawhari K, Gentile R, Galasso C. A fragility-oriented approach for seismic retrofit design. *Earthq. Spectra*. 2022; . doi:10.1177/87552930221078324.
17. Aljawhari K, Gentile R, Galasso C. Mapping performance-targeted retrofitting to seismic fragility reduction. In: COMPDYN Proceedings, 8th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, Athens, June 28-30. 2021. p. 1301–1321. (vol 2021-June).
18. Liberatore L, Decanini LD. Effect of infills on the seismic response of high-rise RC buildings designed as bare according to Eurocode 8 [Infl uenza della tamponatura sulla risposta sismica di edifi ci in c.a. alti progettati come nudi con l'Eurocodice 8]. *Ing. Sismica*. 2011; **28** (3): 7–23.
19. Burton H, Deierlein G. Simulation of seismic collapse in nonductile reinforced concrete frame buildings with masonry infills. *J. Struct. Eng. (United States)*. 2014; **140** (8): 1–10. doi:10.1061/(ASCE)ST.1943-541X.0000921.
20. Jalayer F, Cornell CA. Alternative non-linear demand estimation methods for probability-based seismic assessments. *Earthq. Eng. Struct. Dyn.* 2009; **38** : 951–972. doi:10.1002/eqe.876.
21. Ancheta TD, Darragh RB, Stewart JP, Seyhan E, Silva WJ, Chiou BS-J, et al. NGA-West 2 database. *Earthq. Spectra*. 2014;
22. Ozsarac V, Monteiro R, Calvi GM. Probabilistic seismic assessment of reinforced concrete bridges using simulated

records. *Struct. Infrastruct. Eng.* 2021; . doi:10.1080/15732479.2021.1956551.

23. Kazantzi AK, Vamvatsikos D. Intensity measure selection for vulnerability studies of building classes. *Earthq. Eng. Struct. Dyn.* 2015; **44** (15): 2677–2694. doi:10.1002/eqe.2603.

24. Kohrangi M, Bazzurro P, Vamvatsikos D, Spillatura A. Conditional spectrum-based ground motion record selection using average spectral acceleration. *Earthq. Eng. Struct. Dyn.* 2017; **46** (10): 1667–1685. doi:10.1002/eqe.2876.

25. O'Reilly GJ. Limitations of Sa(T 1) as an intensity measure when assessing non-ductile infilled RC frame structures (Bulletin of Earthquake Engineering, (2021), 19, 6, (2389-2417), 10.1007/s10518-021-01071-7). *Bull. Earthq. Eng.* 2021; **19** : 2389–2417. doi:10.1007/s10518-021-01071-7.

26. Woessner J, Laurentiu D, Giardini D, Crowley H, Cotton F, Grünthal G, et al. The 2013 European Seismic Hazard Model: key components and results. *Bull. Earthq. Eng.* 2015; **13** (12): 3553–3596. doi:10.1007/s10518-015-9795-1.

27. Giardini D, Wossner J, Danciu L. Mapping Europe's Seismic Hazard. *Eos (Washington. DC).* 2014; **95** (29).

28. Aljawhari K, Freddi F, Galasso C. State-dependent vulnerability of case-study reinforced concrete frames. In: 7th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering, COMPDYN 2019; Crete, Greece; June 24-26. 2019. p. 2677–2689.

29. Baker JW. Efficient analytical fragility function fitting using dynamic structural analysis. *Earthq. Spectra*. 2015; **31** (1): 579–599. doi:10.1193/021113EQS025M.

30. De Risi MT, Del Gaudio C, Verderame GM. A component-level methodology to evaluate the seismic repair costs of infills and services for Italian RC buildings. Springer Netherlands; 2020. (vol 18).

31. Cardone D. Fragility curves and loss functions for RC structural components with smooth rebars. *Earthq. Struct.* 2016; **10** (5): 1181–1212. doi:10.12989/eas.2016.10.5.1181.

32. Del Gaudio C, De Risi MT, Ricci P, Verderame GM. Empirical drift-fragility functions and loss estimation for infills in reinforced concrete frames under seismic loading. Springer Netherlands; 2019. (vol 17).

33. Hahn GJ, Shapiro SS. Statistical Models in Engineering. 1994.

34. Massey FJ. The Kolmogorov-Smirnov Test for Goodness of Fit. *J. Am. Stat. Assoc.* 1951; **46** (253): 68–78. doi:10.1080/01621459.1951.10500769.