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Displacement-Based Framework for Simplified Seismic Loss Assessment

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ABSTRACT

Loss assessment methodologies have been introduced to assess the seismic performance of buildings using more meaningful metrics like direct monetary losses. Different approaches exist, each with varying degrees of complexity and requiring different levels of detail, regarding structural behaviour characterisation or damage and loss estimation, for example. With these developments, loss assessment is increasingly becoming a more commonplace instrument in the seismic evaluation and retrofitting of existing buildings. Despite these developments, there is arguably still a need to provide practising engineers with simplified tools with which to conduct building-specific loss assessment. Displacement-based methodologies have been developed over the past number of years with a particular focus on design. The extension of this approach to loss assessment via displacement-based assessment (DBA) is the subject of this article, where a general framework for its implementation to different structural typologies is outlined and illustrated. This forms a general overview of a recently-concluded 5-year research project on the topic in Italy, where different research groups from various universities focused on specific building typologies as part of a coordinated effort to develop DBA for simplified loss assessment. An overview of the DBA method employed is presented here in addition to an overall description of the results of each working group. A summary of the developments for each typology examined is presented along with an illustration of the potential benefits of different retrofitting techniques in reducing monetary losses, whose details are found in the different typology-specific contributions to the special issue in which this paper is presented. To conclude, a comparative implementation of these simplified methodologies is described for three school buildings in Italy.

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Seismic assessment; displacement-based; simplified; retrofitting; seismic risk

1. Introduction

Since the early 1990s, displacement-based design (DBD) procedures have emerged in an effort to address the so-called "myths and fallacies" of force-based design (FBD) procedures discussed in Priestley (1993, 2003). Sullivan et al. (2003) provided a critical review into many different DBD approaches, with the most notable of these methodologies being that comprehensively described in the recent textbook by Priestley, Calvi, and Kowalsky (2007). These developments in DBD approaches have undoubtedly improved the

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appreciation and understanding of how structures behave under seismic loading and how critical mechanisms may be identified and mitigated. Similar advancements are still being made to the displacement-based assessment (DBA) methodology, whose basic formulation appears in Priestley (1997) with a more updated outline in Priestley, Calvi, and Kowalsky (2007). While the initial developments of DBA were relatively simple, since they essentially applied the DBD approach in reverse, its application to older structures designed before the introduction of modern design codes requires further development.

Recently, in Italy, a research line (Line 7) focused on the development of a simplified loss assessment methodology that utilises the DBA procedure was funded between 2014 and 2018 by the research consortium *Rete dei laboratori universitari di Ingegneria Sismica* (ReLUIS, www.reluis.it). This consortium was founded in 2003, as an inter-university consortium with the purpose of coordinating and funding University laboratories in Italy that are active in the field of earthquake engineering. The aim of this article is to present a general overview of the common framework followed by each working group of the aforementioned DBA research line to study a series of structural archetypes typically found throughout Italy. Each working group focused therefore on a specific building typology and the findings for typical values of expected annual loss (EAL) and, in some cases, the expected benefits of considering different retrofitting solutions, are presented here in a summarised format. Further details of the specific implementation are available in the additional specific articles contained in this special issue. Furthermore, an independent application of the simplified methodology to three school buildings is also included here to further illustrate the method's versatility.

2. Simplified Assessment of Existing Structures

2.1. *Displacement-based Assessment*

Figure 1 shows a basic overview of the DBA methodology, where one uses the substitute structure concept (Shibata and Sozen 1976) to get an equivalent single degree of freedom (SDOF) system with effective properties at the limit state displacement capacity, Δ_{cap}.

In order to convert the multi degree of freedom (MDOF) structure to its equivalent SDOF system, one must be able to assess the likely mechanism that would form in the structure and determine the displaced shape. Furthermore, limit states other than that leading to a lateral collapse of the structure may be considered, provided the displacement profile is adequately characterised. For example, a recent development by Sullivan et al. (2018) described a simplified method to characterise the evolution of a frame structure's displaced shape as it passes from elastic response to a fully inelastic mechanism. Knowing the mass, m_i, and expected floor displacement, Δ_i, at each level i for a given limit state, the equivalent SDOF properties are found from the expressions in Equations 1–5,

$$\Delta_{cap} = \frac{\sum m_i \Delta_i^2}{\sum m_i \Delta_i} \tag{1}$$

$$m_e = \frac{\left(\sum m_i \Delta_i\right)^2}{\sum m_i \Delta_i^2} \tag{2}$$

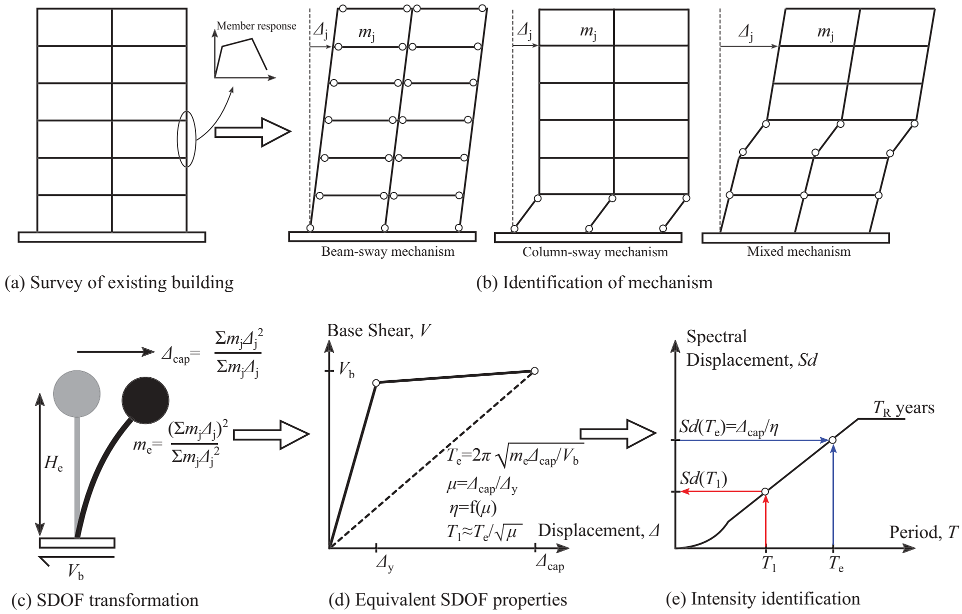


Figure 1. Overview of the DBA methodology (After Priestley, Calvi, and Kowalsky 2007).

$$H_e = \frac{\Sigma m_i \Delta_i H_i}{\Sigma m_i \Delta_i} \tag{3}$$

$$K_e = \frac{V_b}{\Delta_{cap}} \tag{4}$$

$$T_e = 2\pi\sqrt{\frac{m_e}{K_e}} \tag{5}$$

where V_b is the expected base shear to be developed by the structure for the given limit state, and K_e and T_e are the effective stiffness and period of the equivalent system shown in Fig. 1d, respectively.

Another aspect relates to the handling of P-Delta effects, which refer to the additional overturning effect of the gravity loads acting at each level of the building. To account for this, Priestley, Calvi, and Kowalsky (2007) describe how the total base shear resistance, V_b, can be adjusted by reducing the base shear computed from the governing mechanism, V_0, by the term in Equation 6:

$$V_b = V_0 - V_{P\Delta} = V_0 - C\frac{m_e g\Delta_{cap}}{H_e} \tag{6}$$

where C depends on the structural system being considered. For reinforced concrete (RC) frames, Priestley, Calvi, and Kowalsky (2007) proposed the use of C = 0.5 and C = 1.0 for steel frame structures, for example.

The effects of inelastic behaviour are typically accounted for by using an equivalent viscous damping approach, which is determined as a function of ductility and type of structural system. Using an appropriate spectral reduction factor, η, spectral displacement can be determined as:

$$Sd(T_e) = \frac{\Delta_{cap}}{\eta} \tag{7}$$

which corresponds to the elastic spectral displacement of the system at the effective period, $Sd(T_e)$, shown in Fig. 1e. From the overall system ductility demand, μ, the initial period T_1 can be estimated and the corresponding spectral demands at the initial period, $Sa(T_1)$ can also be found following the approach of O'Reilly and Calvi (2020).

2.2. Displacement-based Loss Assessment

The previous section showed how DBA can be used to estimate the response parameters at various limit states of a building. Using this procedure, two distinct parameters can be determined: the intensity at which each limit state is expected to occur and the structural demands (i.e. storey drifts and the floor accelerations) at that intensity. Using these two pieces of information, one can perform what is termed displacement-based loss assessment (DBLA) to estimate the monetary losses with respect to intensity and compute other performance metrics such as the EAL. Figure 2 illustrates the basic idea of this approach, where the mean annual frequency of exceedance (MAFE) of each limit state is estimated, as per Cornell et al. (2002), from the site hazard curve using the intensity computed from DBA along with appropriate considerations of dispersion. To relate the structural demands to an expected loss ratio, the storey loss function approach developed by Ramirez and Miranda (2009) may be employed, although these specific functions were developed using Californian costs and may require further consideration to be used in the present context. This approach therefore allows a simplified estimate of the structure's EAL by using just DBA and some other simplified considerations regarding the computation of expected monetary losses due to damage to the structural and non-structural elements.

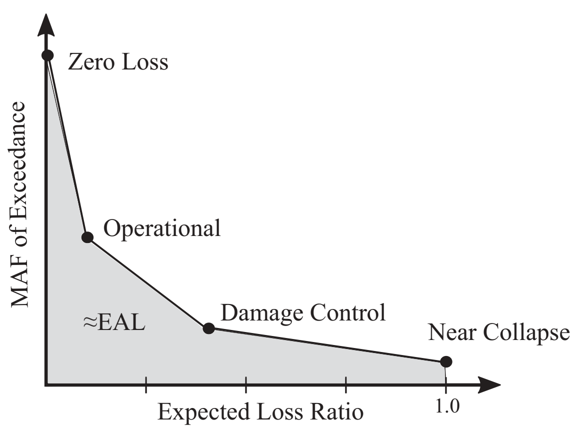


Figure 2. Illustration of the fundamental aspects of DBLA (After Welch, Sullivan, and Calvi 2014).

3. Overview of the ReLUIS DBLA Project

3.1. *Motivation*

Since its conception in the early 2000s, loss assessment in general has been developed as part of a large coordinated effort in the US under the premise of the then recently revamped performance-based earthquake engineering (PBEE) philosophy outlined by Cornell and Krawinkler (2000). It focused on construction typologies typically encountered in the US and led to significant research on the topic (e.g. Haselton and Deierlein 2007; Jalayer 2003; Liel 2008; Mitrani Reiser 2007; Vamvatsikos 2002). This research effort came to fruition in the early 2010s with the conclusion of the FEMA P-58 guidelines (FEMA 2012) and the development of the performance assessment calculation tool (PACT). With FEMA P-58, loss assessment was described in a step-by-step set of guidelines for practitioners to follow and implement. The provision of PACT meant that this process could also be implemented with relative ease, given that much of fragility and consequence information required by the procedure was included in the provided libraries. The procedure relies heavily on data from experimental testing in order to develop fragility functions and estimate damage, in addition to costing information to estimate the expected cost of repair associated with each damageable component in a building.

Large efforts to make this kind of information available in PACT were made, but oftentimes some limitations arose. These usually related to the lack of available data for certain components meaning that expert judgement was required to provide some placeholder values. Some of these values have been refined over the years and the databases updated, but some other issues remain. The first is that the developed procedure is largely US-oriented with costing and component typologies corresponding to those typically found in California. Simply adopting this data for other parts of the world is not so straightforward and recent studies, such as the one by Silva, Castro, and Monteiro (2020), have highlighted these relative differences in costs between the US and European countries. Similarly, Giordano, Mosalam, and Günay (2019) have pointed out the limitations and discussed possible remedies for the FEMA P-58 approach when applied to existing unreinforced masonry buildings. Another pertinent issue is which components to include in the damageable inventory implemented in PACT, since the accurate quantification of losses in a building depends heavily on how exhaustive and accurate the assumed database of damageable components is. This uncertainty can give rise to different estimates of loss that vary by orders of magnitude between different analysts, as has been seen in past studies (Krawinkler 2005; Porter, Beck, and Shaikhutdinov 2004). Removing this ambiguity in loss assessment in order to make it a more robust tool with which to make informed decisions regarding retrofitting etc. is an issue that still needs to be addressed. A very convenient development in this regard was the development of storey loss functions by Ramirez and Miranda (2009). For a predefined set of damageable components and associated repair costs, the expected losses can be directly estimated from the structural demands. This meant that much of the difficulties or ambiguities arising from the implementation of PACT are overcome via a set of representative storey loss functions that have essentially made an important number of the decisions on the analyst's behalf.

The above discussion operates on the presumption that structural demands can be accurately quantified across the full range of structural response (i.e. from initial elastic behaviour right up to collapse). This may be quantified using complex numerical models that capture the different potential mechanisms and particularities associated with a given structural typology. Given the sheer volume of analysis often required with these models and the desire to have a complete, but simple, understanding of structural behaviour, the mechanism's development and its progression, simplified procedures have also found their place in loss assessment. FEMA P-58 outlined one method largely oriented on force-based design considerations to estimate demands on structures for different levels of intensity – an assessment philosophy criticised by Priestley, Calvi, and Kowalsky (2007) and a main reason for the initial development of DBA. Welch, Sullivan, and Calvi (2014) extended DBA for the simplified loss assessment of ductile RC bare frame structures, as previously discussed in Section 2.2. A side by side comparison of these so-called *extensive* and *simplified* loss assessment procedures is illustrated in Fig. 3. It is noted that the illustration shown in Fig. 3 for the extensive approach differs slightly from classic depictions of the FEMA P-58 approach discussed by Gunay and Mosalam (2013), for example. Here, the damage and loss analysis have been described together in Step 3 since this is typically carried out by dedicated programs, such as PACT. The overall process remains exactly the same, with more focus given to the decision variables like EAL in Step 4, which is the focus of this work.

The application of such a loss assessment framework in the Italian context required development on a number of fronts. The first was because the specific nature of construction typologies found in Italy, and in the Southern Mediterranean in general, significantly differs to those typically encountered in the US, meaning that a lot of work previously developed in the US was not necessarily applicable in the Italian context (O'Reilly 2016; O'Reilly et al. 2018; O'Reilly and Sullivan 2018). For example, the majority of Italian RC frames possess masonry infills and have been constructed prior to the introduction of modern seismic design provisions. Another aspect is related to the high prevalence of unreinforced masonry structures, which are typically not encountered in the US. Furthermore, more specific details relating to the behaviour of precast and steel frame buildings typical of Italian industrial facilities that were seen to be particularly vulnerable following the 2012 Emilia-Romagna earthquake (Casotto et al. 2015; Magliulo et al. 2014), for example, needed to be considered in further detail.

The aforementioned aspects were the main aims of line 7 of the ReLUIS project, initiated in 2014 and concluded at the end of 2018. Both simplified and extensive methods of assessing construction typologies usually found throughout Italy were examined in detail. This was to conclude with at a set of recommendations on the implementation of loss assessment using simplified approaches that returned EAL estimates consistent with those found via more extensive analysis. The following sections provide an overview of the different working groups involved in this five-year project and the typologies considered. To provide sufficient and consistent case study implementations of the methods developed, a site location was chosen in Italy, its seismic hazard characterised via PSHA and the outputs subsequently used by each working group. Finally, each working group's results are presented and collective commentary is then provided.

3.2. *Working Groups and Typologies Considered*

The aim of this study was to develop an assessment framework for direct monetary losses relevant to structural and non-structural components using DBA. To this end, five structural typologies were selected as most prevalent in the Italian building stock: unreinforced masonry

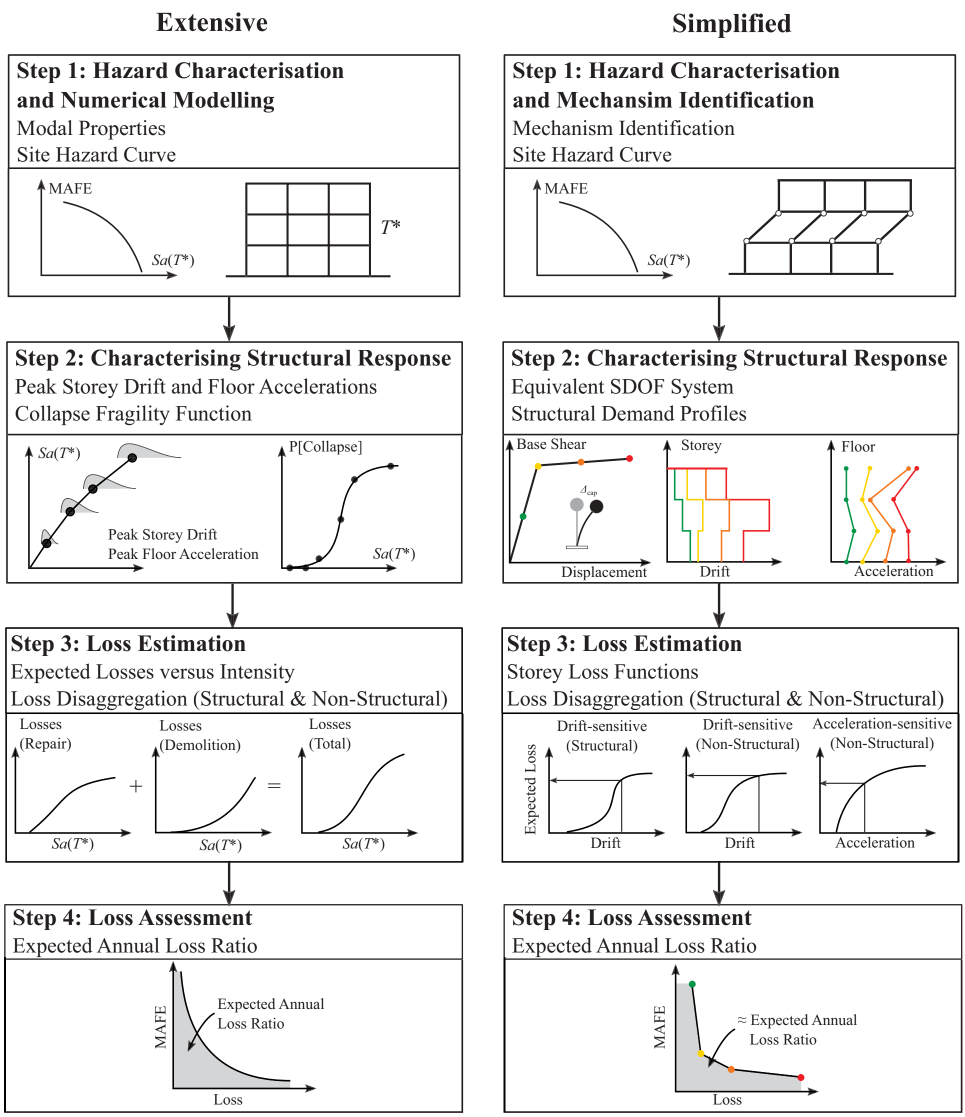


Figure 3. Comparison of extensive and simplified loss assessment methodologies prescribed by FEMA *P*-58 and DBLA, respectively.

(URM) examined by the *Università degli Studi di Genova* (Ottonelli, Cattari, and Lagomarsino 2020); pre-1970s and post-1970s RC frame buildings with masonry infills studied by the *Università degli Studi della Basilicata* (Cardone, Perrone, and Flora 2020) and the *Università di Bologna* (Landi et al. 2020), respectively; steel structures examined by the *Università degli Studi di Napoli Federico II* (Cantisani et al. 2020) and precast concrete (PC) systems studied by the *Università degli Studi di Bergamo* (Bosio et al. 2020). The choice of separating RC structures into two periods of construction was due to the fact that modern seismic provisions were not imposed in most parts of Italy until the early 1970s, where previously the majority of the buildings were largely designed to carry gravity loading only, disregarding seismic design considerations. The five selected building typologies refer to older and modern constructions and are illustrative of Italian public, residential and industrial structures. Moreover, because assessment procedures and applicability differ for each structural typology, the displacement-based approach was adapted for each. The typology-specific DBLA methods pertaining to the considered typologies are presented in detailed in the other contributions to this special issue.

3.3. *Seismic Hazard Characterisation and Ground Motion Record Sets*

The PBEE framework as outlined in FEMA P-58 for EAL computation was utilised as the benchmark to which the results of the emerging simplified DBLA approaches were compared. Most applications of the methodology incorporate the use of extensive non-linear time history analyses applied to numerical models such as multiple-stripe analysis (Jalayer and Cornell 2009) or incremental dynamic analysis (Vamvatsikos and Cornell 2002) using sets of ground motion records scaled to represent different return period intensities. Thus, in order to utilise non-linear dynamic analyses, the identification of site hazard-compatible ground motion sets was essential. The conditional spectrum approach (Baker 2011) was used, where the expected response spectrum is first identified and defined in terms of mean and variance and then conditioned on the exceedance of a target spectral acceleration value for a period of interest, $Sa(T^*)$. Seismic hazard information for Italy was available and adopted for nine return periods of shaking, T_R, corresponding to: 30, 50, 72, 101, 140, 201, 475, 975 and 2475 years. The conditioning periods, T^*, were selected to be: 0.3, 0.4, 0.5, 0.75, 1.0, 1.5 and 2.0 seconds so as to cover the full range of expected first mode periods encountered in each of the typologies considered. Seismic hazard disaggregation information was taken from Barani, Spallarossa, and Bazzurro (2009) for period of values up to 2.0 seconds. Using this hazard disaggregation information, ground motion sets were selected for a site in L'Aquila, Italy, whose hazard curves are shown in Fig. 4. For each combination of T^* and T_R, 10 earthquake records were selected and matched to the conditional mean spectrum using the algorithm outlined in Jayaram, Lin, and Baker (2011). Figure 5 presents an excerpt of the ground motion sets selected, which are further discussed in Ay, Fox, and Sullivan (2017).

3.4. *Summary of Results Obtained by Each Working Group*

As explained previously in Section 3.2, each working group dealt with a specific typology and the results are summarised here. Figure 6 illustrates an overview of the results expressed in terms of EAL for each case study building and potential retrofitting schemes examined (where applicable) while

Table 1 presents a partial summary of the work carried out by the individual work-groups. A brief summary of the workgroups' findings is described as follows:

(1) **Pre-1970s RC Buildings**: a total of fourteen case-study buildings were examined (7 representing real existing buildings and 7 simulated archetype designs). The EAL of the 3 real existing buildings (1-a: 3 storey, 1-b: 4 storey, 1-c: 8 storey) is presented herein for the sake of brevity and the EAL obtained from simplified analyses was reported to be 1.57%, 1.45% and 0.47%, respectively, while refined computations for these cases yielded EAL values of 1.38%, 1.49% and 0.44%. Further details on the

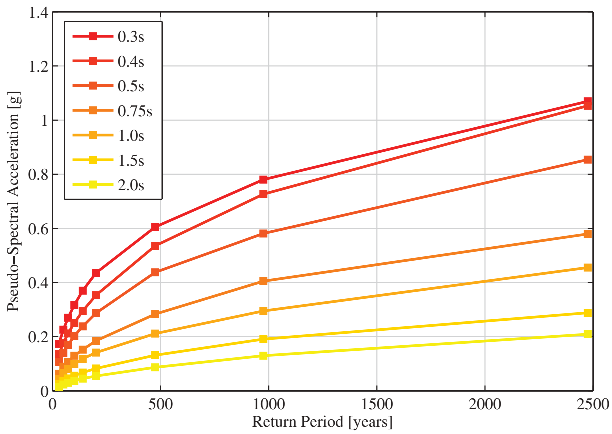


Figure 4. (a) Hazard curve (Spectral acceleration, $Sa(T^*)$ vs. return period, T_R) for case study site in L'Aquila.

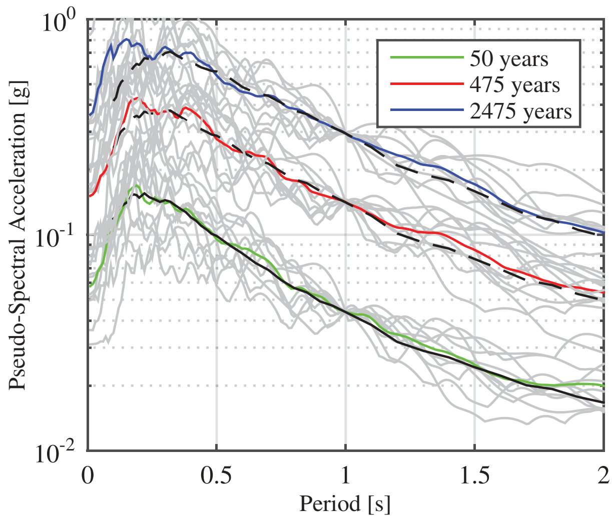


Figure 5. Illustration of the selected ground motion sets for case study site in L'Aquila with return periods T_R = 50, 475 and 2475 conditioned at T^* = 1.0s to the target conditional mean spectrum shown in dashed black for each case.

numerical analysis and DBLA methodology employed for the full set of fourteen case study buildings are given in Cardone, Perrone, and Flora (2020).

(2) **Post-1970s RC Buildings**: one real case study building representative of post-1970s construction techniques along with 3 proposed retrofitting schemes were presented (2-a: addition of viscous damping; 2-b: addition of hysteretic damping; and 2-c: addition of shear walls). The results are illustrated in Fig. 6 along with the EAL after retrofitting when adopting the aforementioned retrofitting techniques, which were reduced to 48%, 60% and 67% of the original EAL value, respectively. A detailed overview of the refined and simplified analysis is outlined in Landi et al. (2020).

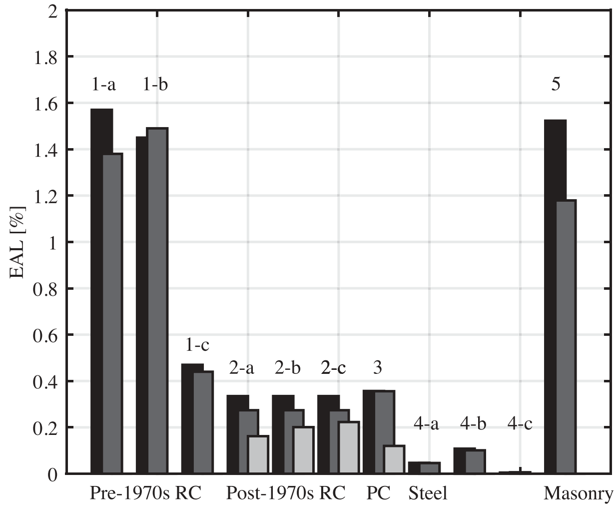


Figure 6. Overview of the EAL per specific typology, number of case-study buildings and adopted retrofitting schemes (black: EAL value from DBLA, dark grey: EAL value from refined analyses, light grey: EAL after retrofitting and intervention measures).

Table 1. Overview of the case-study typologies and proposed retrofitting schemes per building typology.

Typology	Label	Case study buildings	Refined EAL before retrofit [%]	DBLA EAL before retrofit [%]	DBLA EAL after retrofit [%]
Pre-1970s RC	1-a	3-storey real building	1.38	1.57	No proposed retrofitting schemes
	1-b	4-storey real building	1.49	1.45	
	1-c	8-storey real building	0.44	0.47	
Post-1970s RC	2-a	6-storey RC building with masonry infills	0.274	0.335	0.162 (VD)
	2-b				0.201 (SD)
	2-c				0.223 (SW)
Precast Concrete	3	Single-storey PC structure	0.356	0.357	0.121 (retrofitting of cladding)
Steel	4-a	Single-storey with sandwich panels	0.046	0.054	No proposed retrofitting schemes.
	4-b	Single-storey with trapezoidal sheeting	0.107	0.119	
	4-c	8-storey office building	0.0054	0.005	
Masonry	5	3-storey building with spandrels coupled with tie-rods	1.179	1.523	No proposed retrofitting schemes.

(3) **PC Buildings**: one archetype PC case-study building, representative of typical industrial structures was included with and without the retrofitting of the cladding system for a noticeable EAL after retrofitting of approximately 34% the non-retrofitted EAL value. Further details on the numerical analysis and DBLA are detailed in Bosio et al. (2020).

(4) **Steel Buildings**: two archetype case-study buildings were examined, with 4-a and 4-b (highlighted in Fig. 6) corresponding to the same single-storey structure, but constructed with sandwich panels and trapezoidal sheeting, respectively, whereas the second archetype case study building, 4-c, was a multi-storey office building

comprising a moment frame. Given the different construction technique, the EALs of 4-a and 4-b were computed to be 0.054% and 0.119% respectively. The observed EAL value for the multi-storey building (4-c) was noted as 0.005% of the total replacement cost. When compared with other typologies, steel buildings exhibited lower values of monetary losses which may be a consequence of their inherent flexibility and need to resist wind loads, resulting in a quasi-linear response. A detailed overview of the applied methodology for steel structures is presented in Cantisani et al. (2020).

(5) **Masonry Buildings**: one case-study building with rigid floors and roof associated with spandrels coupled with tie-rods was investigated. The simplified DBLA yielded an EAL value of 1.52%, when compared to the refined methodology yielding an EAL value of 1.179%. Further details on the adopted framework and methodology are presented in Ottonelli, Cattari, and Lagomarsino (2020).

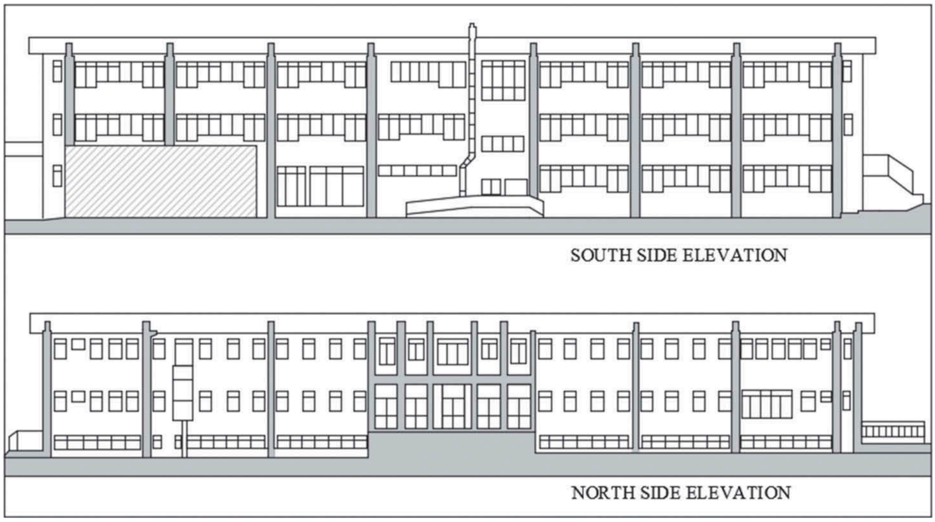
4. Application to Italian School Buildings

Following the 2002 Molise earthquake in Southern Italy, L'Aquila earthquake of 2009 and the Emilia Romagna seismic event of 2012, the seismic vulnerability and loss assessment of school buildings gained a heightened interest due to the damaging consequences of ground-shaking events in terms of fatalities and monetary losses. In the subsequent sections, the implementation of DBLA is illustrated and its results are compared with the results of refined structural analysis and loss assessment results for three representative typologies of the Italian building stock: an infilled RC frame building, a PC building and a URM building (Perrone et al. 2020). Using the structural configuration and information of material properties gathered throughout the building surveys (O'Reilly et al. 2019; 2018), a non-linear numerical model was developed for each typology for a refined loss assessment presented in O'Reilly et al. (2018), which will be used to evaluate the DBLA results.

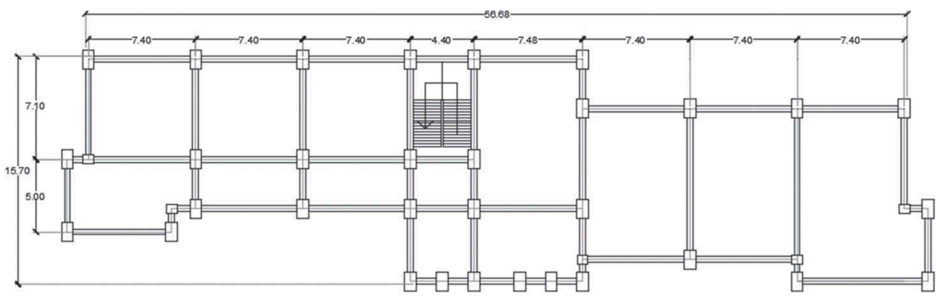
4.1. *Infilled RC Frame Building*

The majority of RC school buildings were constructed in the pre-1970s period, prior to any national-scale enforcement or consideration of contemporary seismic provisions in the Italian building code. These buildings were usually designed to withstand gravity loading only with the consideration of allowable stress methods prescribed in Regio Decreto 2229/1939 (Regio Decreto 1939). The case study infilled RC frame structure, presented in Fig. 7, is a 3-storey building whose considerations for numerical modelling follow the recommendations of O'Reilly and Sullivan (2019). The exterior masonry infill wall consists of a double-leaf hollow clay brick with "medium" strength properties as highlighted in (Hak et al. 2012).

The DBLA employed herein utilises the general framework described briefly in Section 2 and detailed in Welch, Sullivan, and Calvi (2014) with the consideration of the infill and stairs contribution highlighted in Cardone and Flora (2017). The DBA procedure was performed for all frames of the building in both directions. The first step of the proposed approach involved the identification of the likely inelastic mechanisms through the use of a sway index, S_i, and sway-demand index, SD_i, computed at each storey i (Priestley, Calvi, and Kowalsky 2007). The displacement profile and the corresponding intensity measure, IM, were evaluated at yielding



(a) South-side and north-side elevations



(b) Plan layout

Figure 7. Layout of the case study infilled RC school building.

by computing the yield drift, $\theta_{y,i}$, at each storey *i*. This was computed with reference to Glaister and Pinho (2003) for RC frames experiencing column-sway mechanism and the developments of Sullivan et al. (2018). Once the storey shear demand and displacement profiles at yield were identified, the equivalent SDOF system characteristics were derived, as described in Fig. 1. With the equivalent SDOF characteristics determined (i.e. T_e, Δ_y and ξ_{eq}), the intensity measure, Sa_y, was evaluated by entering the response spectrum for the building site (see Fig. 1e). Similarly, the displacement profile and IM at collapse were computed by adding the plastic displacement component to the yield component at first yield. The plastic displacement can be evaluated by considering the effect of each potential soft-storey mechanism. For the estimation of the structural response at different intensity measures, an iterative procedure has been proposed in Cardone and Flora (2017) for two cases: $T_R^*<T_{R,y}$ and $T_R^*>T_{R,y}$. For non-structural elements, the peak floor acceleration profiles are computed using empirical approximation described in FEMA P-58 (2012), although recent studies (Perrone and Filiatrault 2018) have noted that the estimation of peak floor accelerations in infilled buildings may require closer attention. The capacity curves extracted using both static pushover analysis and DBA are compared and presented in Fig. 8.

As observed in Fig. 8, the ultimate limit states illustrated for both directions do not capture the loss of strength due to the failure of masonry infills and strength degradation in the RC frames, as opposed to the three prior limit states, successfully characterising the behaviour of the examined case study. However, the MAFE values obtained for higher limit states are generally very low, thus, the impact of properly capturing the rupture of infills in Fig. 8 is not as significant as characterising earlier stages along the pushover curve, where losses due to progressive damage start appearing for more frequent events (i.e. higher MAFE values).

Following DBA, the MAFE, λ, for each limit state was computed using the SAC/FEMA approach (Cornell et al. 2002). The computation of losses at each considered limit state and the combination of loss contributions from the collapse and non-collapse cases to estimate the EAL was performed. The direct losses due to repairs were determined using storey loss functions outlined in Ramirez and Miranda (2009). The EAL was thus determined as the area under the MAFE-Loss Ratio curve (see Fig. 2). Results using extensive nonlinear analysis and the simplified framework were then compared.

The results displayed in Fig. 9 illustrate the loss curve of the RC school building, where the EAL value is computed as the integral of the trilinear curve and the respective values of EAL using the two methods: refined and simplified, where the refined results correspond to those computed in O'Reilly et al. (2018). The EAL computed via DBLA was determined to be 0.37% as opposed to 0.35% using extensive analysis, which suggests a slight overestimation on behalf of the simplified analysis of only 5.4%. Nevertheless, the observed values remain within the reasonable range of EAL for this given typology (Caruso, Bento, and Castro 2019; O'Reilly and Sullivan 2018; Sousa and Monteiro 2018). It is noted that some of the values reported from the pre-1970s RC buildings in Cardone, Perrone, and Flora (2020) were somewhat higher than typical values found in other aforementioned studies in the literature. While there may be a number of reasons for this, it is noted that these cases represented the upper bound repair costing cases in that study. The DBLA framework has shown to be conservative in the

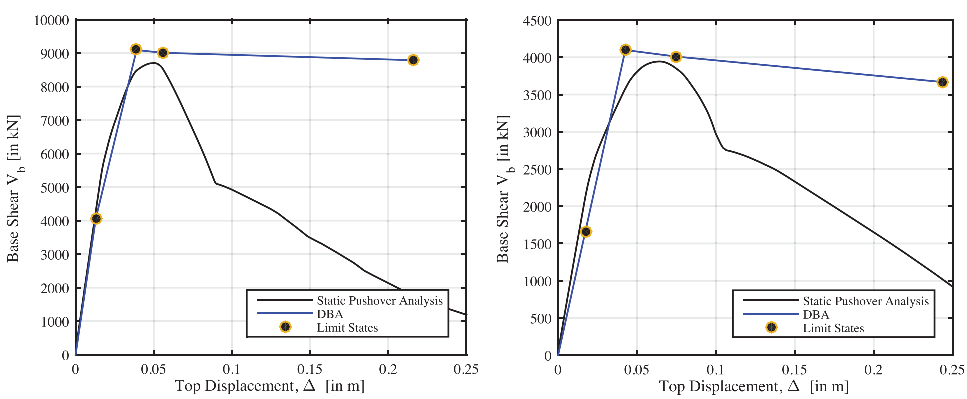


Figure 8. Static pushover curves showing base shear versus top or roof displacement of the infilled RC case study building, extracted from static pushover analysis and DBA procedure in the (a) longitudinal direction and (b) transverse direction.

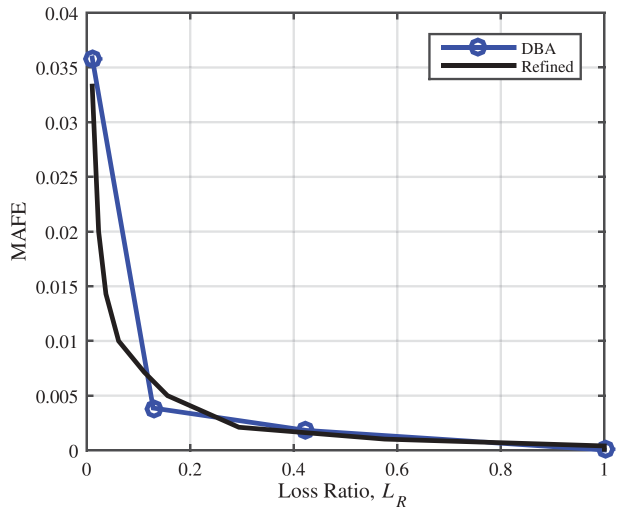


Figure 9. Normalised expected losses and MAFE of each limit state considered (zero-loss, two intermediate limit states and collapse) for the infilled RC case study building.

calculation of losses but beneficial in terms of time and computational effort as no extensive computational model was needed. Nevertheless, differences may present themselves when adopting the DBLA scheme due to: the overestimation of the losses at specified limit states obtained via DBA when quantifying the structural capacity; the adoption of a trilinear fit instead of a smoothing function between limit state points (e.g. O'Reilly and Calvi 2019); an error in the estimation of the MAFE using the hazard curve (Bradley and Dhakal 2008) and the quantification of the dispersion.

4.2. *Precast Concrete Building*

PC structures have been generally employed for industrial buildings in Italy. The seismic vulnerability of this typology has been observed in numerous events which caused substantial economic losses and in terms of casualties (Magliulo et al. 2014). The damage in PC structures is usually related to the loss of vertical support of horizontal elements or the collapse of cladding panels, with both cases being associated with poor connection detailing and a consequence of proper seismic provisions for PC typology not being fully enforced in Italy until 1987 (Magliulo et al. 2014). The case study PC school building consists of a two-storey building, constructed in the 1980s and the structural system comprises precast beams supported by precast columns in the longitudinal direction only. The beams are seated on column corbels without any additional restraint (i.e. no dowel connections or neoprene pads). The plan view of the precast concrete school building is shown in Fig. 10. The numerical model used for the comparison between refined analysis and DBLA is described in O'Reilly et al. (2018).

The DBLA methodology for PC structures employs the basic framework with certain adaptations presented in Torquati, Belleri, and Riva (2018) by employing the equivalent column simplified method (ECSM). This approach considers lateral displacement profiles of the building as the governing parameter in the seismic loss

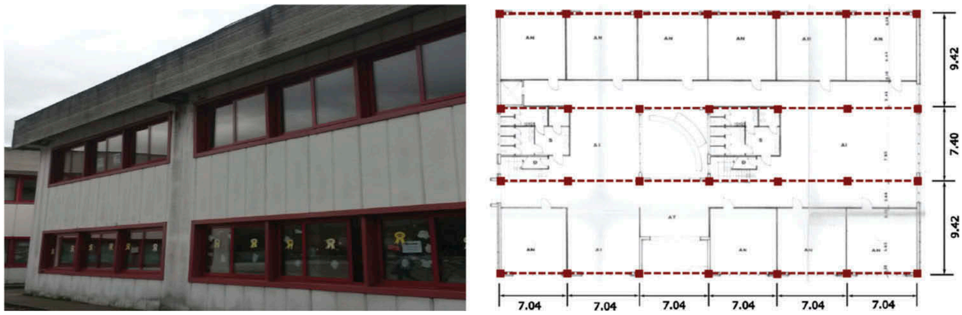


Figure 10. (left) Photograph of the precast case study school building and (right) the plan layout of the case study precast building highlighting the location of beams in red.

assessment. Thus, for the case of PC structures, the assessment required the identification of the inelastic deflected shape by referring to the ECSM (Torquati, Belleri, and Riva 2018). The definition of the force-displacement relationship was then derived from the obtained inelastic deformation. Subsequently, the displacement was computed for a predefined limit state, trialled by the identification of the equivalent SDOF characteristics for each limit state. The equivalent viscous damping (EVD) was evaluated along with the displacement spectrum reduction factor (Fig. 1). The computation was concluded by obtaining the damped displacement spectrum and the corresponding MAFE for each limit state. The outcome of the static pushover analysis is shown in Fig. 11, in which it can be seen how the DBA capacity curve tends to overestimate the nonlinear static analysis response.

Subsequent to the DBA, the damage states and repair costs were identified from Bosio et al. (2020). The collected information was used by integrating the outcome of the structural analysis, the site's hazard and the attributed losses at each limit state, expressed as a fraction of the construction cost. Using the expected loss and MAFE, it was then possible to establish the loss curve and evaluate the EAL, as shown in Fig. 12.

The EAL estimates for the PC school building are reported in Fig. 12 computed using the two methodologies mentioned previously; DBA yields an EAL value of 0.39%, which is a conservative estimate when compared to the value of 0.20% obtained using refined analysis. The difference in EAL is due to the overestimation in the coordinates of the loss curve between the first and second limit states when using a trilinear fit. The results of the DBLA framework may thus be improved through the use of a smoothing curve when connecting all limit states obtained, such as that outlined in O'Reilly and Calvi (2019). Nonetheless, the implemented DBA methodology examined herein produces conservative but sufficiently accurate estimates of the EAL.

4.3. *Unreinforced Masonry Building*

URM buildings represent a substantial share of the building stock in Italy. Structures of this type range from cultural and historical landmarks to residential dwellings where masonry is a cost-effective building material for housing construction. Unfortunately, the poor performance of these structures in seismic events has often been disastrous, as

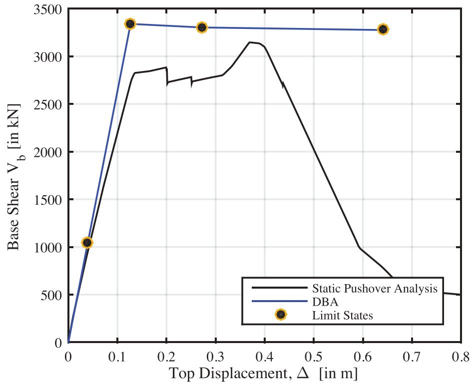


Figure 11. Static pushover curves showing base shear versus top or roof displacement of the precast concrete case study building, extracted from static pushover analysis and DBA procedure in the (a) longitudinal direction and (b) transverse direction.

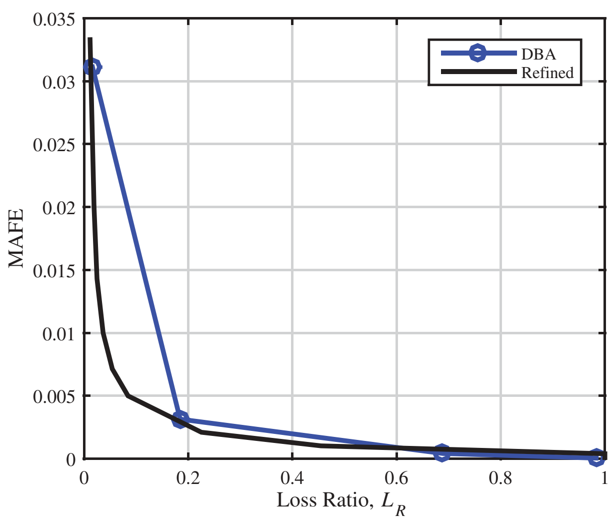


Figure 12. Expected loss ratios given MAFE of each performance level (zero-loss, two intermediate limit states and collapse) for the PC concrete building.

seen following the Emilia-Romagna event in 2012 (Penna et al. 2014) and the damage observed after the L'Aquila earthquake in 2009 (Cimellaro 2009). The URM case study school building consists of two storeys and was constructed in the early 1900s. Piers and spandrels span along the longitudinal direction of the building while simple wall systems comprise the transverse direction. The comprehensive modelling procedure of said building in TreMuri (Lagomarsino et al. 2013) is presented in O'Reilly et al. (2018) and the model of the structure itself is shown in Fig. 13.

Simplified loss assessment was conducted with reference to the DBLA approach proposed by Lagomarsino and Cattari (2015). The displacement-based vulnerability of masonry structures depends on an adequate capacity curve definition along with appropriate displacement

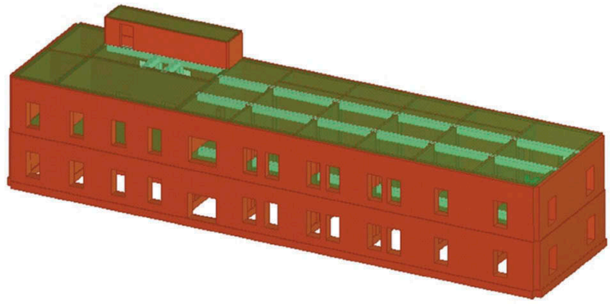


Figure 13. Isometric view of the URM building (Adapted from O'Reilly et al. 2018).

thresholds describing each limit state. Lagomarsino and Cattari (2015) proposed that the loss curve should be defined as a quadrilinear curve consisting of 5 points portraying the following limit states: zero-loss, operational; damage limitation; life safety and near collapse. The suggested bilinear capacity curve is defined by a yielding base shear capacity whose properties depend mainly on input parameters such as geometric features, modal shapes, material mechanical properties, seismic floor loads and expected failure mechanisms. The computation of the ultimate capacity comprises correction factors to account for the main prevailing mode of failure, influence of the non-homogeneous size of the masonry piers, geometric and shape irregularities and the effectiveness of spandrels influencing the global failure mechanism of the studied building. Quantifying these for the case study building examined here, the structural capacities were then calculated and are shown in Figure 14 with respect to that obtained from the numerical model built in TreMuri.

Subsequently, the displacement thresholds were determined for each limit state. The yield displacement was identified as a function of the maximum base shear and the effective stiffness. Then, the thresholds corresponding to the second and third limit states were determined linearly with respect to the yield displacement expression proposed by Lagomarsino and Cattari (2015). The displacement consistent with the fourth limit state

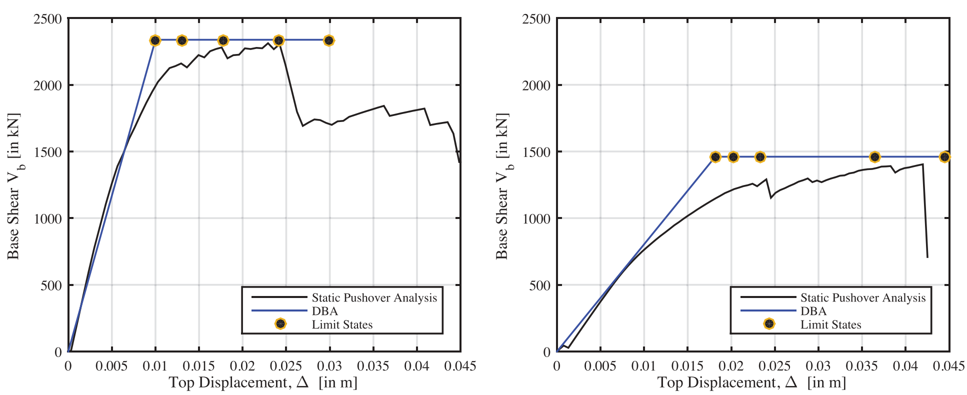


Figure 14. Static pushover curves showing base shear versus top or roof displacement of the URM case study building, extracted from static pushover analysis and DBA procedure in the (a) longitudinal direction and (b) transverse direction.

was determined as the combination between the prevalent failure mechanism (i.e. strong spandrel weak pier, weak spandrel strong pier) and the adequate storey drift ratio proposed by Lagomarsino and Cattari (2015). The ultimate displacement corresponded to a combination of both failure modes.

After characterising the force-displacement relationship, the computation of the fragility curves using an analytical formulation was performed. The intensity measure related to each limit state, IM_{LS}, was deduced using overdamped spectra (Freeman 1998). The dispersion, β_{LS}, depends on the uncertainties in the seismic demand, the definition of the limit states thresholds and the variability of the capacity. Consequence functions specific for Italy and for URM typologies were introduced in Lagomarsino and Cattari (2015) and were utilised to convert the component and building damage states into repair costs. Once defined, the MAFE of the different limit states, λ_{LS}, were computed using the SAC/FEMA approach (Cornell et al. 2002). The results are presented in Fig. 15 and compared with refined analysis.

The EAL was computed as 0.48% using refined analysis and 0.57% after the application of DBLA for the URM typology. As such, DBLA remains consistent in providing conservative values for the expected losses at each of the limit states. The MAFE-loss ratio values observed from both methods seem to converge more at intermediate limit states. However, the MAFE corresponding to the first limit state obtained via DBA is slightly overestimated.

5. Summary

This article described the main aspects of a five-year research project aiming to define and further develop a displacement-based seismic loss assessment (DBLA) framework for existing buildings. Research groups focused on and examined the most prevalent typologies of the Italian building stock to further develop displacement-based procedures as part of

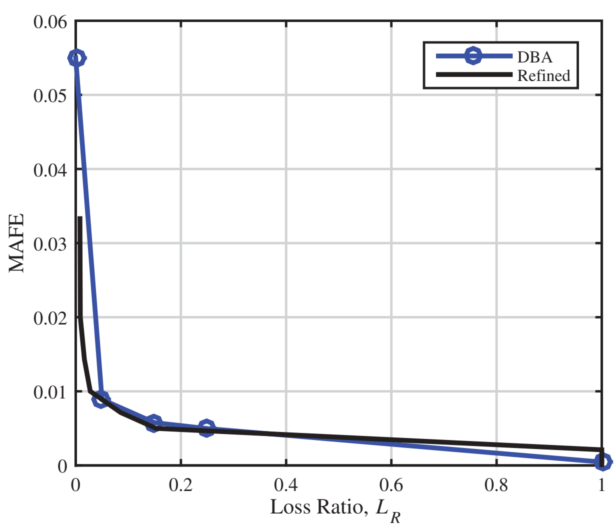


Figure 15. Expected losses given MAFE of each limit state (zero-loss, two intermediate limit states and collapse) for the URM case study building.

a coordinated effort. Thus, DBLA was developed as a simplified methodology for the quantification of the seismic performance of the most common typologies of the Italian building stock in an attempt to quantify direct monetary losses presented as the expected annual loss value (EAL). The effort of this research line was consolidated to promote DBLA as an instrument for practitioners and stakeholders to conduct building-specific loss assessment, as well as offering an alternative to the computational effort and time-demanding tools typically available via detailed numerical software.

The main findings corresponding to each typology were presented and summarised, demonstrating the promising potential of the prescribed framework. Generally, reinforced concrete (RC) structures of the pre-1970s era and masonry buildings demonstrated a higher percentage of EAL due to the damageable inventory and structural criteria pertaining to such typologies. However, RC structures constructed after the 1970s and precast (PC) buildings showed lower monetary losses when compared to the total replacement cost. This is due to the fact that seismic provisions began to be introduced after the 1970s, therefore the structures themselves, when conforming to seismic codes, are more resilient to seismic damage. The loss assessment of steel structures exhibited low EAL values when compared to other typologies mainly because of the integrity of the structural elements and design considerations leading to a linear behaviour when subjected to seismic loading. When comparing DBLA with the results of refined analyses, it was found that DBLA yields conservative, yet close, estimates of the direct monetary losses.

Some possible retrofitting techniques were briefly examined for some typologies, together with the evaluation of their impact on the reduction of the EAL of those building typologies. A comparative application of DBLA and other numerically exhaustive methods was described and illustrated in this article for three Italian school buildings to further demonstrate the opportunity of the simplified method. Considering the different developments and results of the various involved research groups, as well as the results of the three applications described here, DBLA has been shown to be simplistic, yet promisingly efficient, in quantifying structural seismic performance levels and quantifying EAL in existing Italian buildings. Further research will aim at taking the DBLA implementation to a large-scale level with the purpose of further validating the approach but also with a view to its future use within seismic risk assessment guidelines, such as those recently introduced in Italy via the Ministerial Decree No. 58/2017 (Decreto Ministeriale 2017).

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