Observed and predicted earthquake damage scenarios: the case study of L'Aquila municipality

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Abstract

A simplified analytical method for the seismic vulnerability assessment of reinforced concrete buildings on a large scale is presented. The approach followed is based on the capacity spectrum method (CSM) to evaluate seismic capacity and approximate IDA curves to define PGA capacity starting from damage states' characteristic displacement capacity for structural and non-structural elements. Damage states are defined according to the observational-based damage states provided by the European Macroseismic Scale EMS-98.

A database consisting of 131 reinforced concrete buildings located at the Municipality of L'Aquila is presented, which after the earthquake of 2009 have been charged to post-earthquake usability assessment procedure. The specific interpretation of damage data allowed carrying out fragility curves for slight, moderate, and heavy damage, (i.e., DS1, DS2, and DS3), defined according to EMS 98 macroseismic scale.

The damage scenario deriving from the application of such a procedure is compared with that collected from the post-earthquake usability assessment procedure.
Keywords: RC buildings, infills, large scale, seismic fragility assessment.

1 Introduction

In the following, a simplified analytical method for the seismic fragility assessment of reinforced concrete buildings at large scale is presented. The proposed method is based on a simulated design procedure to define the structural model and on non-linear static analysis of a simplified structural model based on shear-type assumption to evaluate seismic capacity. Damage states are defined

WIT Transactions on The Built Environment, Vol 152, © 2015 WIT Press
www.witpress.com, ISSN 1743-3509 (on-line)
doi:10.2495/ERES150151

according to the observational-based damage states provided by the European Macroseismic Scale (EMS-98). Presence of infills is considered, both taking into account their influence on the structural response and evaluating the damage to such non-structural elements.

Hence, the methodology has been used for the assessment of a damage scenario for a sample of 131 buildings located in L'Aquila Municipality. Uncertainties in seismic demand, material characteristics, and capacity models are taken into account through a Monte Carlo simulation technique. Fragility curves are obtained for each building, leading to the evaluation of damage scenario through the values of the PGA from the shake map of the event provided by INGV.

In fact, a database of 131 reinforced concrete (RC) buildings collected after 2009 L'Aquila earthquake, in the neighbourhood of Pettino, has been derived. For each building, the outcomes of official usability and damage inspections collected by Italian National Civil Protection right after the event are available. Furthermore, additional data about the location and plan dimensions of buildings collected during independent field surveys (Polidoro [11]) have allowed the construction of a geo-referencing database.

The comparison in terms of damage scenario has allowed on one side the validation of the methodology, especially for what concerns the correspondence between the displacement thresholds and the relative damage observed on the individual element, columns and infill panels, on the other side the validation of the results obtained by the application of the methodology.

2 Damage database

The database considered in this study is made of 131 infilled RC MRF frames located in Pettino neighborhood in L'Aquila. Pettino area was very close to the epicenter of the mainshock event of L'Aquila 2009 earthquake.

Just after the earthquake survey campaigns of the damage, emergency response and usability of buildings were performed, through the damage inspections form derived from the Italian National Civil Protection (Baggio *et al*. [1]).

The inspection form is divided into operative sections. The first two sections give general information regarding geometrical, typological and morphological characteristics of buildings. Sections 3 and 4 supply information respectively about the vulnerability and apparent damage observed on the structural and non-structural components of building due to the earthquake (Figure 1).

The inspection form provides information both on extent and extension of damage, the latter evaluating the percentage of the building affected by each of damage grade (Figure 1). The definition of the observed damage grades is based on the European Macroseismic Scale EMS98 (Grünthal [6]). The EMS98 scale includes six possible damage grades (from D0 – no damage to D5 – destruction) referred to the whole building, based on the level and on the extension of structural and non-structural damage in the building. Despite that, the inspection form reports 3 damage levels, combining level D2 with D3 and D4 with D5.

Level / Extension / Component		DAMAGE									
		D4-D5 Very heavy or collapse			D2-D3 Medium or heavy			D1 Slight			D0 Null
		> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	> 2/3	1/3 - 2/3	< 1/3	
		A	B	C	D	E	F	G	H	I	L
1	Vertical structures	□	□	□	□	□	□	□	□	□	○
2	Horizontal structures	□	□	□	□	□	□	□	□	□	○
3	Stairs	□	□	□	□	□	□	□	□	□	○
4	Roof	□	□	□	□	□	□	□	□	□	○
5	URM Infill walls	□	□	□	□	□	□	□	□	□	○
6	Pre-existing damage	□	□	□	□	□	□	□	□	□	○

Figure 1: Damage classification in AEDES survey form (Baggio *et al*. [1]).

Statistics about geometrical, typological and morphological characteristics, as well as for what concerning the damage of the buildings object of this study. The 131 buildings selected are all regular in plan and elevation and fully infilled according to data reported in post-earthquake inspection forms by Italian National Civil Protection (Polidoro [11], De Luca *et al*. [4]).

In Figure 2 a general overview of Pettino area in the Municipality of L'Aquila is shown. In Figure 3 buildings plane shape is shown in addition to Peak Ground Acceleration data ac-cording to the evaluation provided by Istituto Nazionale di Geofisica e Vulcanologia (http://shakemap.rm.ingv.it/shake/index.html).

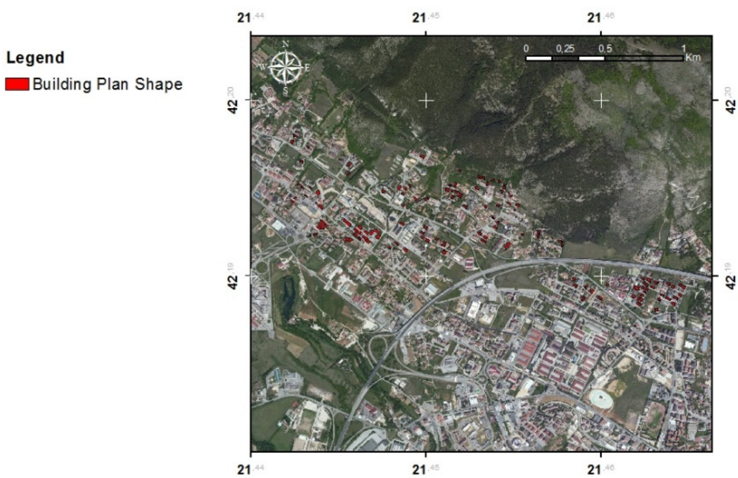


Figure 2: Overview of Pettino area in the Municipality of L'Aquila.

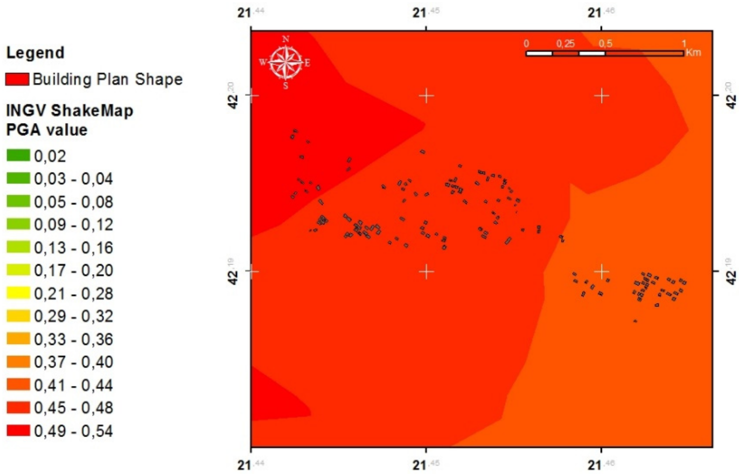
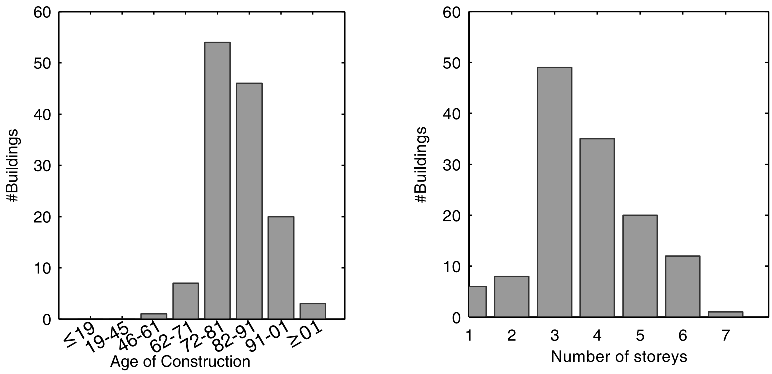


Figure 3: Peak Ground Acceleration data according to the evaluation provided by Istituto Nazionale di Geofisica e Vulcanologia.

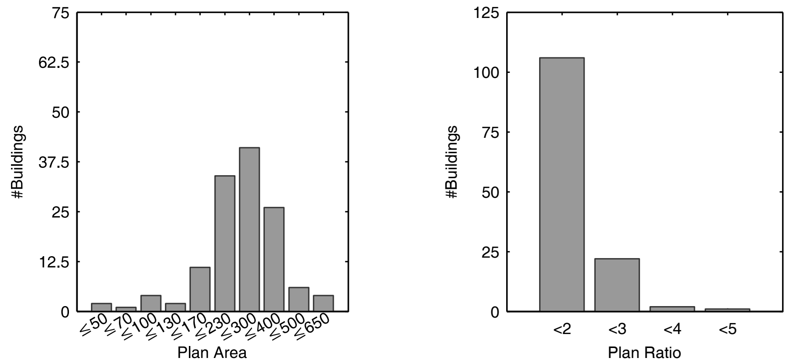


(a) (b)

Figure 4: Distribution of age of construction and number of storeys within the database.

The 131 RC buildings are located in the Pettino area in the Municipality of L'Aquila, and are mainly built in the twenty years at the turn of the 70s and 90s (about 75%), have a regular and compact plan and are characterized mainly by a number of floors between 3 and 4 (in about 65% of cases) as shown in Figure 4.

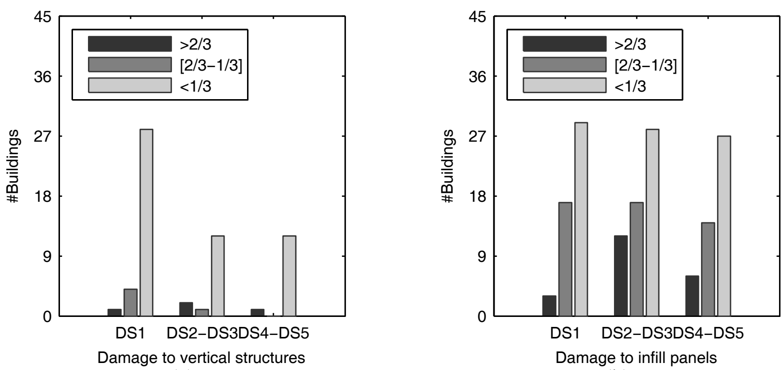
The major part of the buildings has a plan area between 200 and 300 m^2 and a plan ratio lower than 2 (see Figure 5).



(a) (b)

Figure 5: Distribution of plan area and plan ratio within the database.

Moreover, from figure 6 it can noted that in 50% of the buildings no damage is detected to vertical structures, whereas in the remaining cases slight damage limited to less than one third of the elements is surveyed. Notwithstanding a mainly severe and widespread damage to infill panels can be observed.



(a) (b)

Figure 6: Distribution of damage to vertical structure (a) and to infills (b).

Hence, it is possible to interpret a posteriori the results of inspection form, regarding damage to RC columns and infill panels, in order to derive damage grade for the building, according to what is reported in Table 1.

Therefore, for each building, namely, for each inspection form, a different grade for RC columns and infill panels can be obtained. The heaviest grade between the two represents the grade for the whole building.

In Figure 7 damage grades outcomes for the 131 buildings are reported. It is to be noted that most of the buildings subject to damage lie between Grade 1 and Grade 3 (83%), while only a small percentage in Grade 1 (7%) and Grade 4 (9%) and a negligible percentage in Grade 5 (1%).

Table 1: Correspondence between damage states and damage described in AEDES survey form (Baggio *et al.* [1]).

EMS-98	AEDES inspection form	
	Infills	RC columns
Grade 1	DS1 <⅓ DS1 ⅓-⅔ DS1 >⅔	DS1 <⅓ DS1 ⅓-⅔ DS1 >⅔
Grade 2	DS2-DS3 <⅓ DS2-DS3 ⅓-⅔ DS2-DS3 >⅔	DS2-DS3 <⅓
Grade 3	DS4-DS5<⅓ DS4-DS5⅓-⅔ DS4-DS5>⅔	DS2-DS3 ⅓-⅔ DS2-DS3 >⅔
Grade 4		DS4-DS5<⅓ DS4-DS5⅓-⅔
Grade 5		DS4-DS5>⅔

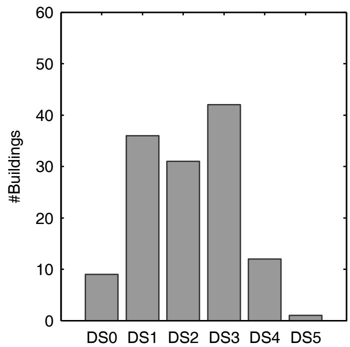


Figure 7: Distribution of damage states (DS) within the database.

3 Simplified methodology for vulnerability assessment (post)

In the following a simplified methodology for seismic vulnerability assessment of building stocks, which have been implemented in POST (PushOver on Shear Type models), a software based on MATLAB® code (Ricci [12], Del Gaudio *et al.* [5]) – is synthetically described. The methodology is based on the following steps:

- a simulated design procedure to evaluate the building structural characteristics based on few data such as number of storeys, global dimensions and type of de-sign (Verderame *et al.* [14]);
- the assumption of a shear type behaviour to evaluate in closed form the non-linear static response (Ricci [12]);
- the assessment of the seismic capacity is evaluated within the framework SPO to IDA (Vamvatsikos and Cornell [13]), leading to the construction of fragility curves, based on the mechanical interpretation of the DSs described by the EMS-98.

The reference unit of the procedure is the building.

The procedure is based on few geometrical data that allow to define a geometrical-structural model of the building, based on design code prescriptions, professional practice and seismic classification of the area of interest at the time of construction, according to (Verderame *et al.* [14]).

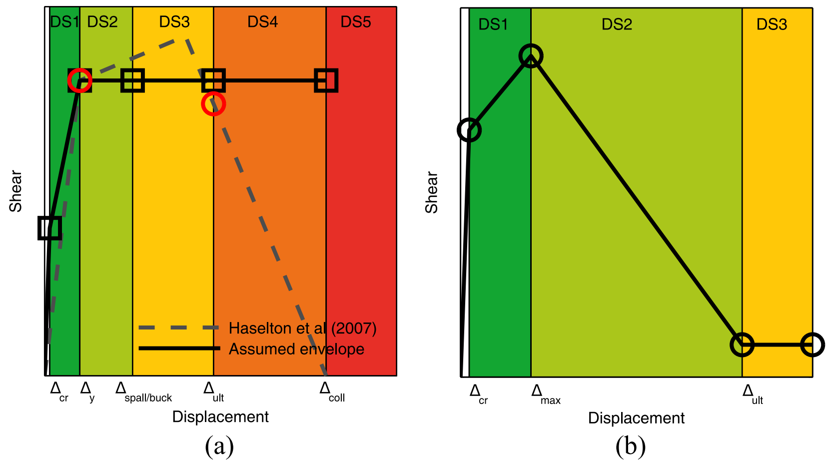


Figure 8: Distribution of age of construction and number of storeys within the database.

The evaluation of the non-linear static response of the building is performed through a simplified model: (i) definition of behaviour for RC columns and infill panels, (ii) evaluation of interstorey shear-displacement relationships at each storey, (iii) evaluation of building response. First of all, a tri-linear envelope is assumed for the moment-rotation model, with cracking and yielding as characteristic points. Behaviour is linear elastic up to cracking and perfectly-plastic after yielding (see Figure 8(a)). Moment at yielding (M_y) is calculated in closed form by means of the first principles-based simplified formulations proposed in (Biskinis and Fardis [2]). Rotation at yielding (θ_y) is univocally identified by M_y and the secant stiffness to yield provided by (Haselton *et al.* [7]).

Lateral force-displacement relationships for infill panels (see Figure 8(b)) are evaluated according to the model proposed by Panagiotakos and Fardis [10], for further details see (Del Gaudio *et al.* [5]).

RC buildings have usually external and internal partitions, to ensure first acoustic comfort and thermo-hygrometric, in addition to the definition of the external envelope of the building and the partitioning of the space. Typically, such perimetral infill panels have openings to ensure adequate natural light and to guarantee health conditions related to air circulation.

In the present work opening in infill panels are explicitly considered. In particular, non-linear behavior of the infills is modified according to the model presented in (Kakaletsis and Karayannis [8]). In this work control parameters to derive non-linear behaviour of panel with opening from corresponding solid panel as a function of window and door opening sizes are introduced. Furthermore, it is assumed that for each building facade the presence of the three types of panel (solid, panel with window and balcony) is equally probable. Moreover, the size of opening is assumed equal to 25% of bay length.

Secondly, besides perimetral panels, also internal infill panels for each direction are considered to derive building response. In particular, for each internal frame the thickness of infill panels is evaluated assuming a ratio between the internal infill area and the building area equal to 50% of that corresponding the external infill.

The relationship between the interstorey displacement and the corresponding interstorey shear is then evaluated considering all the RC columns and infill elements (if present) acting in parallel. In this way, a multi-linear interstorey shear-displacement relationship is obtained at each storey by adding up the lateral shear-displacement relationships of all the RC columns and infill panels along longitudinal and transverse direction, respectively.

A distribution of lateral forces is assumed, proportional to a linear, uniform or 1st mode de-formed shape. Once the shape of the applied distribution of lateral forces is given, the shape of the corresponding distribution of interstorey shear demand can be determined, too. The sum of interstorey displacements represents the top displacement associated to the assigned base shear at each step of the closed-form procedure; then the pushover curve is obtained, as reported in Figure 9. The illustrated plan analysis is carried out in both building directions X and Y.

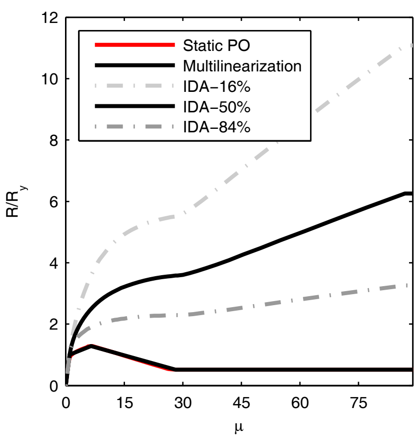


Figure 9: Static pushover curve and IDA-curves for 4-storeys building.

Once the multi-linearization from the pushover curve is carried out, simplified IDA curves are derived from (Vamvatsikos and Cornell [13]), which allow to obtain a relationship between a seismic intensity measure (spectral ordinate) and an Engineering Demand Parameter (ductility) and to assess the variability of the intensity (R\Ry) given the value of ductility, as it will be seen in the following. Damage states adopted in the proposed analytical methodology are defined according to the damage scale proposed by EMS-98. To this aim, analytical displacement thresholds corresponding to the damage to structural and non-structural elements described by EMS-98, based on the mechanical interpretation of the reported description of damage are assumed.

Table 2 reports, for each one of the five EMS-98 damage grades, key sentences describing the damage to infills and RC members, respectively, and the corresponding assumed analytical displacement threshold. Note that, due to the assumed shear-type behaviour, the interstorey displacement leading to the attainment of each damage state is the minimum between the values reported in Table 2 for infill panels and RC columns.

Table 2: Displacement thresholds at the assumed damage states, based on the mechanical interpretation of the damage grades described by EMS-98.

Damage States		Infill panels		RC columns	
		EMS 98 description	Displ. threshold	EMS 98 description	Displ. threshold
DS1	GRADE 1: Negligible to slight damage	*Fine cracks in partitions and infills*	Δ^{inf}_{cr}	*Fine cracks in plaster over frame members*	Δ^{RC}_{cr}
DS2	GRADE 2: Moderate damage	*Cracks in partition and infill walls.*	Δ^{inf}_{max}	*Cracks in columns*	Δ^{RC}_{y}
DS3	GRADE 3: Substantial to heavy damage	*Large cracks in partition and infill walls, failure of individual infill panels*	Δ^{inf}_{ult}	*Spalling of concrete cover, buckling of reinforced rods*	$\Delta^{RC}_{spalling}$ $\Delta^{RC}_{buckling}$
DS4	GRADE 4: Very heavy damage	-	-	*Large cracks in structural elements with compression failure of concrete and fracture of rebars*	First attainment of $\Delta^{RC}_{collapse}$
DS5	GRADE 5: Destruction	-	-	*Collapse of ground floor or parts of buildings*	Last attainment of $\Delta^{RC}_{collapse}$

Once displacement capacity for each DS is determined, the relative spectral ordinate is evaluated from IDA curve (see Figure 9) and finally Peak Ground Acceleration, as a function of EC8 spectrum shape.

Hence, a Monte Carlo simulation is used, and sampling of Random Variables is carried out through the efficient stratified Latin Hypercube Sampling (LHS) technique (McKay *et al.* [9]), adopting the "median" sampling scheme (Vorechovsky and Novak [15]). In this way, a population of buildings is generated, each one corresponding to a different set of values of the defined Random Variables (for further details see Del Gaudio *et al.* [5]), regarding: (i) material properties, (ii) capacity models and (iii) displacement threshold for infill panel.

Finally, record-to-record variability can be estimated directly through the dispersion of IM given EDP (Vamvatsikos and Cornell [13]). Thus, the effect of aleatory randomness can be estimated through SPO2IDA, evaluating IDA-curve-84% and IDA-curve-16% (see Figure 9). Therefore, if PGA capacity, at a given DS, is calculated for all the generated buildings, the corresponding cumulative frequency distributions of the obtained PGA capacity values provide the fragility curves in X and Y directions and at each DS.

In the same way fragility curves independent of the direction can be obtained, through the evaluation of the cumulative frequency distribution of the minimum PGA capacities be-tween longitudinal and transversal direction for each sampling.

4 Comparison between observed and predicted earthquake damage scenarios

Damage scenarios are derived from fragility curves and from the shake map of the seismic event, which struck the area on 6/4/2009 provided by INGV.

Damage scenario is compared with observed damage resulting from post-earthquake survey through inspection form. Note that fragility curves derived herein are for single buildings.

Seismic fragility evaluated on horizontal soil type B is used. Indeed soil type of a station of the National Accelerometric Network (Rete Accelerometrica Nazionale, RAN) in the area was classified according to cross-hole test results as type B, see (De Luca *et al.* [4], Chioccarelli *et al.* [3]) for more details.

Then a distribution of damage for each building from each DS fragility curve and the value of PGA, evaluated for each building from shake map of the event, can be derived. This distribution detect the probability of building to show each DS used to derive fragility curves, or similarly the percent of building of the population of building characterized by each DS, generated through the set of values of the defined Random Variables used to derive the fragility curve. Figure 10 shows the damage distribution for the whole database derived summing up all damage distributions for the 131 buildings. This scenario is compared in figure with that derived from observed damage resulting from post-earthquake survey.

A good agreement between the observed and predicted results, at the different damage states, is observed.

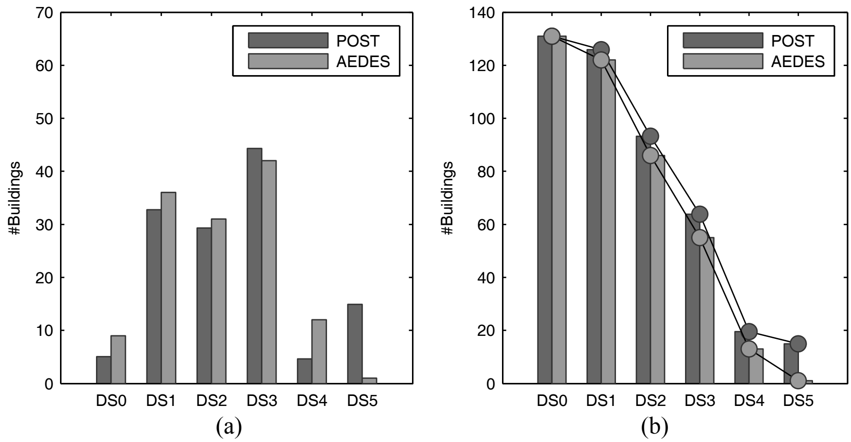


Figure 10: Comparison between predicted and observed damage.

5 Conclusions

In this paper, a simplified analytical methodology for large scale seismic fragility assessment of RC buildings is illustrated. The methodology accounts explicitly for the damage to structural and non-structural (infill) elements. Then, a database reporting the damage to 131 buildings in the area of L'Aquila collected after the 2009 earthquake is reported and discussed. The illustrated methodology is applied to the database and a comparison between predicted and observed damage is shown. A good agreement is generally observed. Such a kind of comparison is of fundamental importance in validation of an analytical methodology aimed at large scale applications.

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