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SIMPLIFIED LOSS ESTIMATION IN INFILLED RC BUILDINGS: MECHANICAL METHOD AND VALIDATION

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Abstract

In this study a dedicated framework for seismic losses estimation in Reinforced Concrete buildings is presented, taking advantage of a simplified analytical structural analysis, a dedicated drift-based fragility curves and a specific repair cost analysis. To this aim, the mechanically based "Pushover on Shear Type model" (POST)-method, already know in the literature [1] for simplified structural analysis, has been integrated herein to obtain expected losses due to earthquakes for infilled RC buildings. On the other hand, the thoroughly cost analysis dedicated to only masonry infill panels and services (electric and plumbing system, sanitary equipment, floors, etc.) restoration presented in [2] has been used to develop an integrated formulation for loss estimation in Reinforced Concrete buildings.
The application to a wide dataset of buildings struck by L'Aquila (Italy) 2009-earthquake is used as testbed for large-scale applications. In fact, the comparison with actual damage distribution and repair cost provides a useful validation of the whole framework, from structural analysis to loss prediction.

Keywords: Seismic risk, infilled RC buildings, mechanical methodology, loss prediction, validation.

1 INTRODUCTION

The unfavorable combination of high exposure of artistic, monumental and residential assets, together with the high seismic hazard and the high vulnerability of the major part of building stock makes seismic risk in Italy and, generally in the Mediterranean area, a pivotal issue. Thus, several methodologies for losses assessment of built inventory have been developed in Italy since the end of '80 ([3]; [4]; [5]; [6]; [7]), belonging to the first generation of approaches making use of empirical Damage Probability Matrix (DPMs) and damage factor (DF) to

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determine repair cost as a function of the complete replacement cost. The second generation of methods ([8]; [9]; [10]) makes use of fragility curves for different building classes ([11]; [12]; [13];[14];[15];[16]) to evaluate seismic risk maps of Italy. The last generation of methods ([17]; [18]; [19]; [20]; [21]; [22]) estimates seismic losses through a component level approaches, thus requiring the use of specific component fragility functions and consequence data.

In this study, a mechanical method for regional loss estimation is presented, taking advantage of structural analyses performed through the simplified mechanical method POST ([1]) (Push-Over on Shear Type models). POST method originally developed for fragility analysis of building portfolio ([23]; [24]; [25]; [26]), has been slightly adapted to properly determine damage distribution and resultant losses within a component-based approach for economic (direct) loss estimation.

To this aim, specific drift-based fragility curves and repair cost analysis have been defined and used for three damage states (light cracking - DS1, extensive damage - DS2, severe damage - DS3), describing the evolution of damage to the masonry infills and partitions in a RC building.

The application to a wide dataset of buildings (5095 RC buildings) struck by L'Aquila (Italy) 2009-earthquake is used as testbed for large-scale applications. In fact, the comparison with actual damage distribution and repair cost provides a useful validation of the whole framework, from structural analysis to loss prediction.

2 A REGIONAL LOSS ESTIMATION FRAMEWORK VIA POST METHOD

A novel methodology for regional loss estimation at the component-level is presented herein based on structural analyses performed through the simplified mechanical method "POST" ([1]; [23]; [24]; [25]; [26]) (Push-Over on Shear Type models).

POST method is a simplified mechanical methodology for vulnerability and fragility assessment at regional scale of RC buildings, which can be applied both at single building level ([1]; [23]; [24]; [26]) or at building class level ([25]).

The mechanical framework stated above is used to evaluate repair cost for a given building considering the contribution of all its N-components:

$$E[L|IM = im] = \sum_{i=1}^{N} a_i \cdot E[L_i|IM = im] \tag{1}$$

The conceptual derivation of the adopted procedure is briefly recalled in Figure 1, which shows: *(i)* the evaluation of IM value from ground motion characterization; *(ii)* the assessment of spectral displacement and resultant roof displacement through IDA curves; *(iii)* the consequent interstorey drift ratio (IDR) profile assessment throughout the height of building by means of pushover analysis results; and (iv) lastly the definition of damage and resultant cost through their comparison with capacity values related to specific damage levels.

The seismic hazard phase can be done both with results of Probabilistic Seismic Hazard Analysis (PSHA) or from the results of ShakeMap scenario earthquakes, depending on the objective to be pursued, namely if an unconditional risk analysis (considering the seismic events could occur in a given area and in a given time interval and their mean annual frequency of exceedance) or a conditional risk analysis (referred to a specific scenario) should be performed.

The structural response phase is accomplished with the aid of POST method, which allows to relate an engineering demand parameters (edp), i.e. roof displacement, and a resultant displacement profile, given an intensity measure (IM) value, trough the use of simplified Incremental Dynamic Analysis (IDA) curves within the SPO2IDA framework ([27]). The Static Pushover (SPO) analysis is carried out in closed form based on a software package on Matlab code thanks to the simplified assumption of shear-type behaviour for RC frames. In fact, the

POST method starts generating geometrical and mechanical models of buildings based on a simulated design procedure, accounting for the technical codes in force at the age of construction and the relevant seismic classification of the site. Then, the nonlinear behaviour of RC structural components is reproduced by means of a tri-linear response, with two linear ascending branches up to yielding (defined in agreement with [28]) and perfectly plastic thereafter. Note that eventual shear critical elements are not explicitly modelled (with modified plastic hinges or explicit shear springs), but their damage due to seismic loading can be detected as reported in [24].

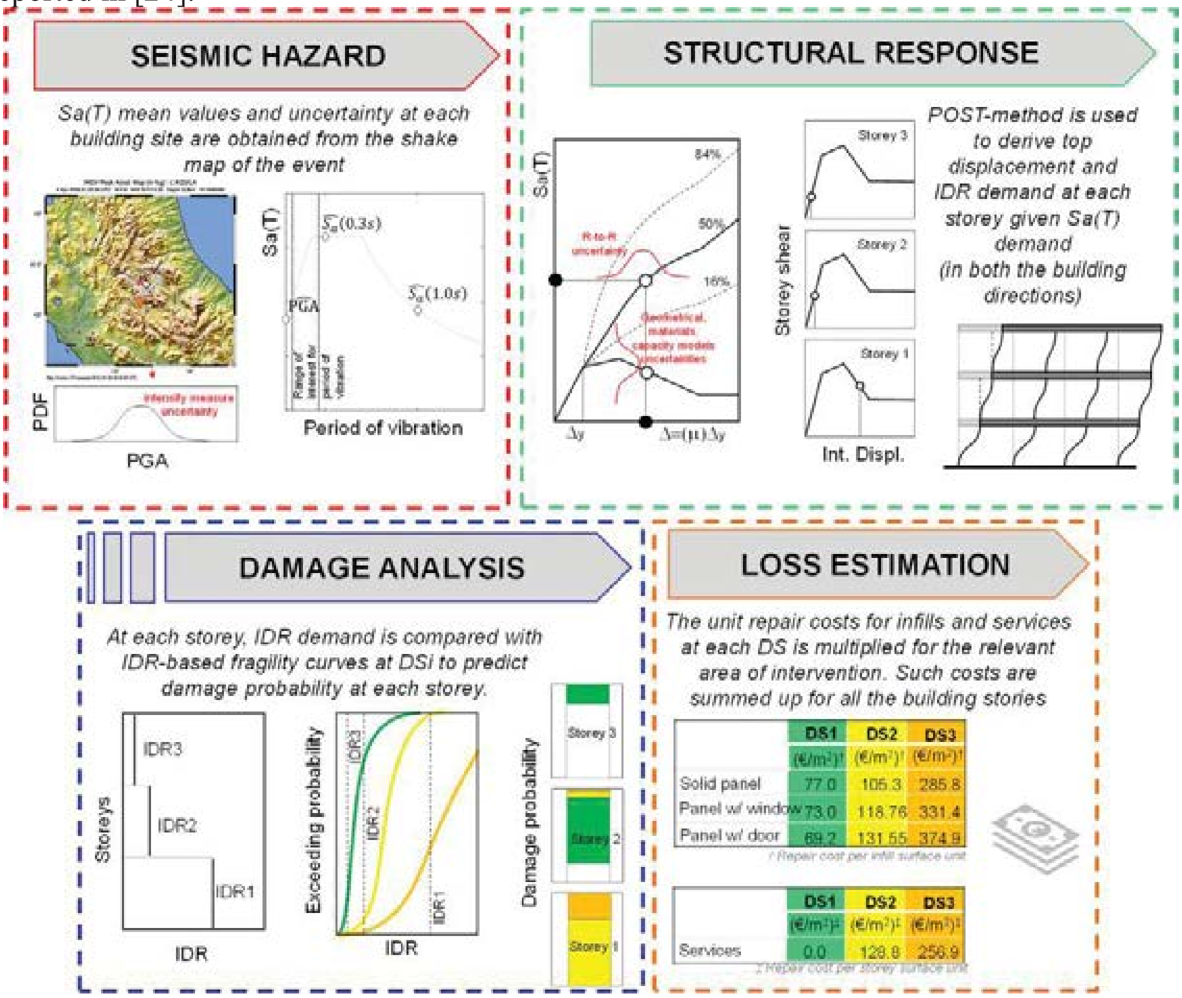

Figure 1: Flow-chart of the procedure applied in this study for loss assessment

Infills have been explicitly included in the structural models, by means of a four-branch force-displacement curve ([29]). The influence of the openings on infills' lateral force-displacement relationship is also considered, by means of the modifying behaviour parameters based on [30].

The simplified assumption of shear-type behaviour for RC frames allows obtaining a multi-linear storey shear -vs-interstorey displacement relationship at each storey by simply adding up the lateral shear-displacement relationships of all the RC columns and infill panels along longitudinal and transverse direction, separately. In such a way, seismic response via a static push-over curve is obtained in a closed-form procedure, which is force-controlled up to peak response and displacement-controlled thereafter, once the distribution of lateral forces has been set.

Therefore, the structural response estimation is entirely evaluated via POST method, which returns the evolution of the lateral displacement profile increasing the IM value through the results of static SPO analysis for each main direction of the building. The relation between IM values and EDPs is given by the IDA curves related to the quadri-linear simplification of SPO curve.

The damage estimation phase is performed by means of specific component fragility curve, returning the probability of exceeding a discrete Damage State, DS, given the EDP.

It has to be noted, that due to the peculiarity of the building dataset considere in this work (see later), resulting to be "lightly damaged" to infills only after the 2009 Abruzzi earthquake, vertical structures will be neglected from damage and loss computation. Moreover, IDR thresholds and resultant uncertainties for infills/partitions and services have been assumed in this study from [31]'s proposal, which finds its background in [32]. In fact, the construction practices in Mediterranean region for residential RC buildings entail that services are generally allocated within building enclosure, the latter typically made up of hollow clay bricks. In this case, cascading effects could occur, such that damage to one, i.e. infills, could cause the fracture of the other one, i.e. a water or electric distribution pipes or a sanitary equipment. Thus, damage for both infill panels and services is strictly related to each other due to their firm interaction, as it will be better shown in the following application.

The comparison between IDR demand and fragility curves allows determining DS for the considered component. In such a way, the number of components suffering a given DS_i can be determined, thus evaluating its relative extension also considering the possibility of experiencing different co-existing DSs along the building height (namely at different stories).

Finally, the loss estimation phase is fulfilled taking advantage of proper repair cost analysis reproducing detailed quantity surveying considering a list of elementary actions to be performed for an area of intervention given DM = dm, through the use of specific unit costs from a price list (e.g., that for Public Works in Abruzzi Region - [33], as applied in the following section). Thus, the values of repair costs for infills and services per square meters of storey surface for 3 DSs reported in [2] and [22] (briefly reported in table 1 and table 2) are used.

	$\bar{C}^{IP}_{DS1}$ (€/m^2)	$\bar{C}^{IP}_{DS2}$ (€/m^2)	$\bar{C}^{IP}_{DS3}$ (€/m^2)
solid panel (w/o openings)	77.0	105.3	285.8
panel with window	73.0	118.76	331.4
panel with door	69.2	131.55	374.9
interior partition	51.3	73.5	199.9

Table 1. Repair costs for double leaf hollow clay bricks for infills/partitions (IP) at each DS per infill panel unit (from [2] and [22])

	$C^{Services}_{DS1}$ (€/m^2)	$C^{Services}_{DS2}$ (€/m^2)	$C^{Services}_{DS3}$ (€/m^2)
All Services	0.0	128.8 ± 28.2*	258.9 ± 32.8*

(*) mean ± standard deviation

Table 2. Repair costs for services at each DS per plan surface unit (from [2] and [22])

Obviously, the damage and loss estimation steps have to be repeatedly calculated for all building components and for all DSs. Nonetheless, a realistic definition of losses should consider the fact that some activities should be carried out simultaneously for all the components of a given portion of the building ("minimum area of intervention") higher than that strictly necessary for practical or aesthetic reasons which is assumed in this study as the whole storey. In other words, it is assumed that all the (structural and non-structural) components located in a given storey are characterized by the maximum damage therein experienced, thus resultant losses are consequently evaluated, favoring an intervention that meets practical and aesthetic criteria.

3 APPLICATION OF REGIONAL LOSS ESTIMATION METHOD TO SLIGTHLY DAMAGED RC BUILDINGS AFTER L'AQUILA EARTHQUAKE

A large-scale application of the mechanical method for regional loss estimation via POST method is performed in this section, considering a building stock struck by the L'Aquila (Italy) earthquake (April 6th, 2009) and damaged to only infills, which incidence represented, for RC buildings, almost the entirety of actual losses after the most recent earthquakes occurred in Italy [34].

The main features of the event and of the analysed building stock are completely treated in previous works and briefly recalled in what follows. For further analysis the reader is referred to [2].

The seismic event investigated for this application struck the Abruzzi region, with a magnitude Mw equal to 6.3, resulting in IX-X grade of the Mercalli-Cancani-Sieberg scale.

For this application, the IM characterization is fulfilled by means of the shake map of the seismic event which struck the Abruzzi region on 6th April 2009, with a magnitude M_W equal to 6.3, resulting in IX-X grade of the Mercalli-Cancani-Sieberg scale. The latter is derived following the procedure reported in [35].

3.1 Building stock description

Building stock characterization is made available from post-earthquake reconnaissance filed trips carried out in the aftermath of L'Aquila earthquake with the supervision and coordination of Department of Civil Protection (DPC), and recently made available on the Da.D.O platform ([36]). These inspections collected data for each building about location, typology, geometry, age of construction, and suffered damage for structural components (including vertical structures, horizontal structures, stairs, roofs and infills) and non-structural components, by means of the so-called AeDES forms ([37]). Additionally, for each component damage, its severity and its extent have been recorded.

Overall, out of a total of about 7500 residential RC buildings listed in the Da.D.O. platform, only a subset of 5095 buildings have been selected, hereinafter defined as "lightly damaged buildings", since they are characterized to be damaged only to infills.

Their main geometrical properties (number of stories, Ns, and average plan surface, A), are thoroughly analyzed in ([2]), where it has been shown that a major part of considered building stock is characterized by three or four stories (about 75% of the whole database), that 92% of the building stock has been built after 1972 and that the most common average plan surfaces range between 70 and 230m^2 (about 80% of the building stock).

3.2 Building class definition for loss analysis via POST-method

The case study (large-scale) application is performed through a class-oriented approach to reduce the computational burden required by the derivation of structural analysis for an extensive (5095 units) building stock. In particular, 15 building classes have been considered herein as a function of number of storeys, N_s, and average plan area, A, such that their statistical characterization well reproduces data collected from post-earthquake AeDES survey forms. Thus, for each class of storey (from 1 to 5), three further sub-classes (low, medium and high) of plan area are defined.

Moreover, in order to explicitly consider the uncertainties related to seismic risk estimation, different kind of uncertainties are considered within a Monte Carlo simulation procedure approach, dealing with:

(i) **geometrical-typological parameters**, i.e. building plan ratio, infills thickness, the type of opening (no opening; window opening; door opening).

(ii) **material properties**, i.e. compressive strength of concrete (f_c), steel yield strength (f_y), mechanical characteristics of infill panels (shear strength - τ_{cr}, shear modulus - G_w).

(iii) **capacity models**, both for the non-linear behaviour of both RC columns and infill panels.

(iv) **intensity measure**, from INGV ShakeMap in terms of PGA (mean and logarithmic standard deviation values at each site);

(v) **record to record variability**.

A summary of all the considered random variables (RV) and the parameters for their characterization are briefly reported in Table 3.

Type of R.V.	R.V.	Reference	Distribution	Median value	CoV [-]
Geometry	Building area	survey data	uniform	from survey	-
	Building plan ratio	[1]; [24]	uniform	median([1.0-2.5])	-
	Infill: Type of opening	-	discrete	[solid; window opening; door opening]	-
Material properties	f_c	[38]	lognormal	25 MPa	31%
	f_y	[39]	lognormal	Calculated	Calculated
	τ_{cr}	[40]; [41]	lognormal	[0.23-0.53] MPa**	30%
Modelling parameters	θ_y	[28]	lognormal	0.95·Calculated	28%
	$k_{elastic,infill}$*	[29]	lognormal	1.09·Calculated	32%
	$k_{peak,infill}$*		lognormal	1.63·Calculated	70%
	F_{cr}*		lognormal	0.93·Calculated	19%
	F_{max}*		lognormal	0.93·Calculated	25%
PGA	PGA value from ShakeMap	http://shakemap.rm.ingv.it [35]	lognormal	from ShakeMap	from ShakeMap
Record-to-record variability	Record-to-record variability	[27]	lognormal	Calculated	Eq. (2)

**: sampled through the simulated annealing procedure according to (Vorechovský and Novák, 2009)*
***: modified depending on the age of construction*

Table 3: Summary of the considered random variables.

4 EVALUATION OF PREDICTED DAMAGE AND LOSSES FROM STRUCTURAL ANLYSIS

Maximum damage (DS_{max}) can be easily determined from results of structural analysis as the most severe DS_i suffered in all stories and in both directions. Contrarily, mean damage gathers information on both severity and damage extension – DE_i related to DS_i. To this aim, DE_i is evaluated from results of POST method as:

$$DE_i = \frac{\sum_{j=1}^{n_s} 1_i \cdot \left(\sum_{s=1}^{n_{t,x}} A_{j,s}^{inf} + \sum_{k=1}^{n_{t,y}} A_{j,k}^{inf}\right)}{\sum_{j=1}^{n_s}\left(\sum_{s=1}^{n_{t,x}} A_{j,s}^{inf} + \sum_{k=1}^{n_{t,y}} A_{j,k}^{inf}\right)} \quad (2)$$

where 1_i is the indicator function which is 1 if infill panels at that storey are characterized by DS_i at least in one (longitudinal or transversal) direction and 0 vice-versa. Previous equation is derived referring to the minimum area of intervention (the whole storey surface), thus assuming that all the (structural and non-structural) components located in a given storey are characterized by the maximum damage therein (i.e. at that storey) experienced in both (longitudinal and transversal) directions. In Eq.2 A_j^{in} is the area of j^{th} infill panel in s^{th}- or k^{th}-direction.

Obviously, since the damage distribution of infills can be characterized by the attainment of different DSs along the height of building, a synthetic information about the co-existing DSi and its extent is represented by the “mean damage” level (hereinafter referred to as $\overline{DS}$), calculated as follows:

$$\overline{DS} = \sum_{i=0}^{3} i \cdot DE_i \tag{3}$$

Therefore $\overline{DS}$ is always lower than or equal to DS_{max}, and it can range between 0 and 3, since the maximum possible average damage is achieved when the maximum possible damage state (DS3) is reached in the whole building (DE_3=1).
Finally, the total repair cost for unit surface area (*trc*) is evaluated for each building as a function of specific repair costs for infills and services reported in Tables 1 and 2:

$$trc = \sum_{i=1}^{3} \left\{ \sum_{j=1}^{N_s} 1_i \cdot \left[\overline{C}_{DSi}^{IP} \left(\sum_{s=1}^{n_x} A_{j,s}^{in} + \sum_{k=1}^{n_y} A_{j,k}^{in} \right) / A + C_{DSi}^{S} \right] \right\} \tag{4}$$

The *trc* is evaluated by summing up the relative repair costs for each storey. The latter is determined given the maximum DS (DS_{max}) suffered by at least one infill panel in one of the two directions and extended to all the remaining one, in addition to services (plumbing systems, radiators, electrical system, floor/wall tiles), too. This circumstance is given in Eq. (6) through the indicator function (1i) which is equal to 1 when at least one infill panel suffers DSi at that storey and 0 vice-versa. Obviously, the repair costs of infills are first multiplied by the panel area (A^{in}) and then divided by the floor area (A) to obtain the total repair cost for unit surface area.

5 PREDICTED-TO-OBSERVED COMPARISON OF DAMAGE AND LOSSES

Predicted damage and loss estimation presented in the section 4 are here compared with damage actually observed for the investigated buildings population (section 5.1) and with repair costs directly obtained from this damage (section 5.2) (hereinafter referred to as “observed damage” and “observed losses”, respectively). Note that all details about “observed damage” and “observed losses” can be found in [2] and [22].

5.1 Comparison between Observed and Predicted damage

The actual data about damage suffered by the collected building stock (“observed damage”) represents the anchorage to reality against which predicted data should be compared. Such a comparison will be shown in this section to “validate” the mechanical based procedure presented in this work.

The observed-versus-predicted agreement in terms of maximum achieved DS, reported in Figure 2, results very satisfying, considering the simplification of the method and its large-scale application. A slight underestimation of no-damaged (DS_{max}=DS0) buildings can be noted, along with an overestimation of DS3-buildings.

"Predicted" damage well reproduces the "observed" damage, independently on the number of stories, as shown in Figure 3, where "predicted" and "observed" DSmax scenarios are reported depending on the number of stories, Ns, for the most frequent classes of Ns, namely from 1 to 5 stories.

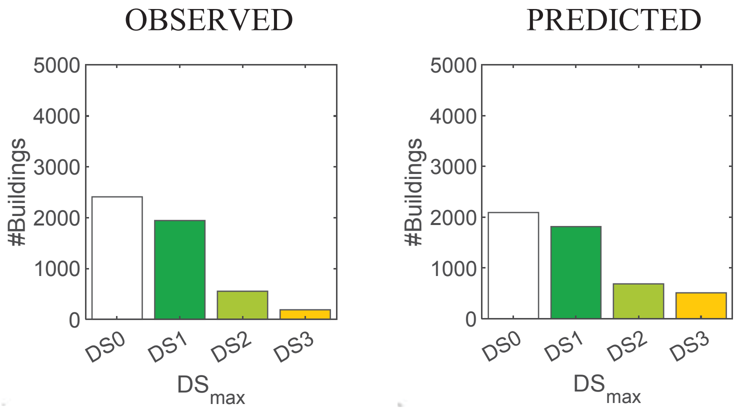

Figure 2. Comparison between observed and predicted damage scenario in terms of DSmax

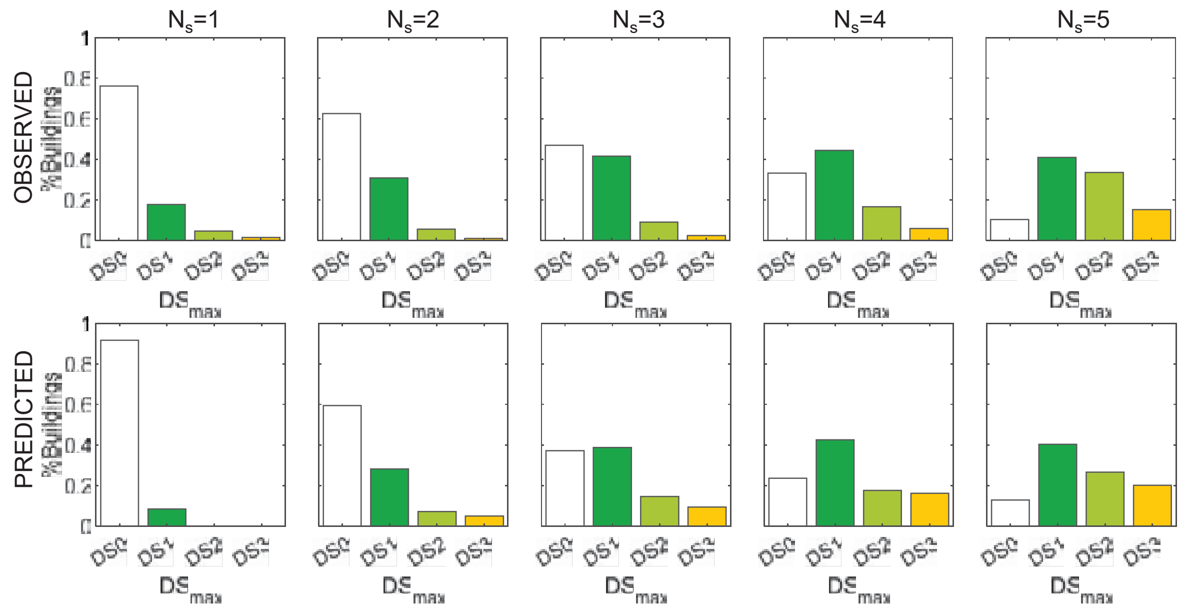

Figure 3. Comparison between observed and predicted damage scenario in terms of DSmax depending on the number of stories (Ns)

Figure 4 reports the comparison between observed and predicted mean damage given the maximum achieved DS, where the 16th, the 50th and the 84th percentiles are also reported. A quite good agreement between mean "predicted" and "observed" mean damage can be generally observed.

Additionally, when median values of "observed" mean damage are considered, a clear trend exists depending on the number of stories, as in Figure 5, where buildings are grouped depending on the maximum achieved DS. When DS_{max} is equal to DS1 or DS2, the average damage tends to decrease when N_s increases from 1 to 3 stories, then keeping a pseudo-constant value for taller buildings. At DS3, such a decreasing trend is observed from 1 to 5 stories. The predicted damage successes in reproducing such a trend.

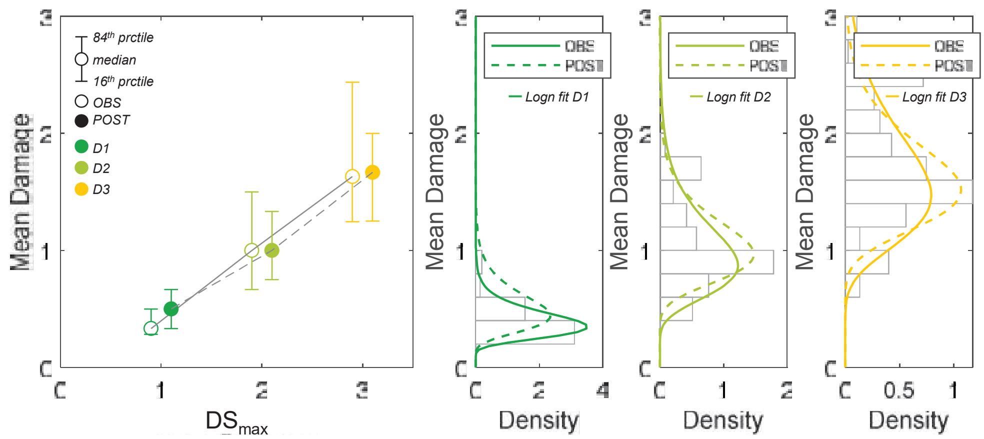

Figure 4. Predicted (POST)-versus-observed (OBS) comparison: mean damage-versus-maximum achieved DS (DSmax); 16th, 50th and 84th percentiles.

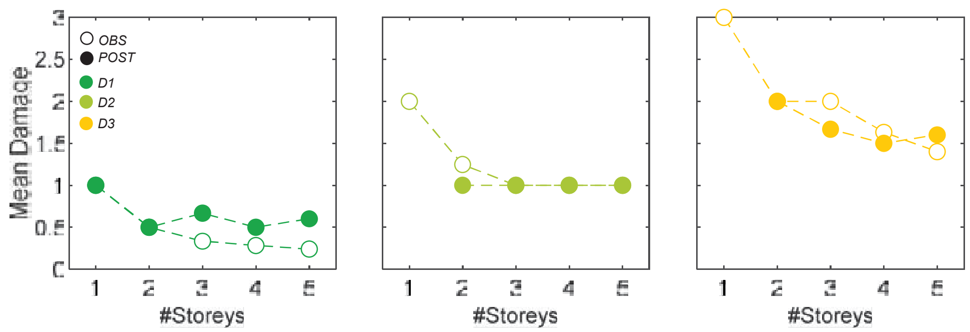

Figure 5. Predicted (POST)-versus-observed (OBS) comparison, given DSmax: trend of mean damage depending on the number of stories.

5.2 Comparison between Observed and Predicted losses

In this section, the comparison between observed and predicted losses (in terms of *trc*) is shown. In Figure 6, the 16^{th}, 50^{th} and 84^{th} percentiles of observed and predicted *trc* are reported, showing a very good agreement, on average, especially when DS_{max} is equal to DS2 (-11%) or DS3 (-3%). A sligth overestimation of the “observed” losses is obtained at DS1.

In Figure 7, the trends between the trc and Ns, given DS_{max}, are reported. It can be noted that both “observed” and “predicted” trc decrease, on average, when Ns varies from 1 to 3 when the maximum achieved damage is DS1 or DS2, then keeping an almost constant value for higher Ns. At DS3, a decreasing trend of trc is observed, on average, for Ns varying from 1 to 5, for both “observed” and “predicted” trc.

As for the “predicted” trc, “observed” trc can be also shown as a function of mean damage (Figure 8). A clear linear trend exists between the average mean damage and *trc*, with an increasing slope for increasing maximum damage severity. Obviously, when the average damage is exactly equal to a given maximum DSi (with i=1,2,3), *trc* can be very easily computed as the sum of the repair costs per floor unit related to infills and services at that DS_i, equal to respectively: 142.1 €/ m2 for DS1; 352.9 €/ m2 for DS2 and 744.4 €/m2 for DS3. It can be easily verified that the ratio between *trc* and average mean damage (=DSi) is very close to the slope of the linear fitting plotted in Figure 8, for the “observed” *trc*.

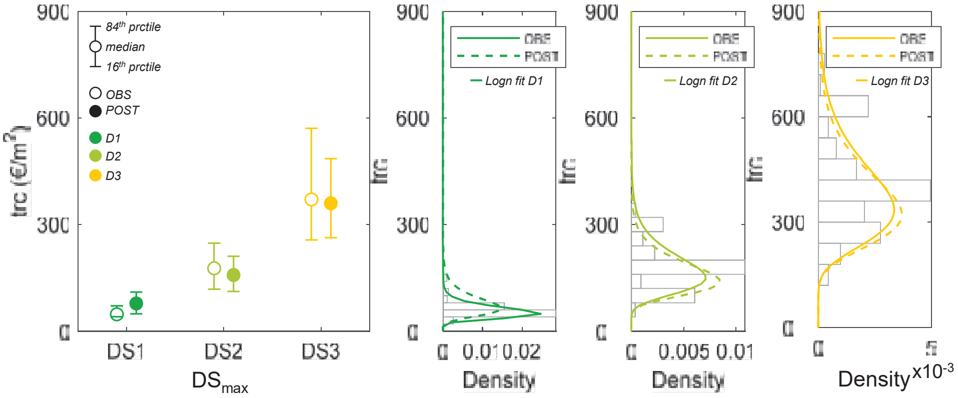

Figure 6. *trc* percentiles depending on DSmax: predicted (POST)-versus-observed (OBS) comparison.

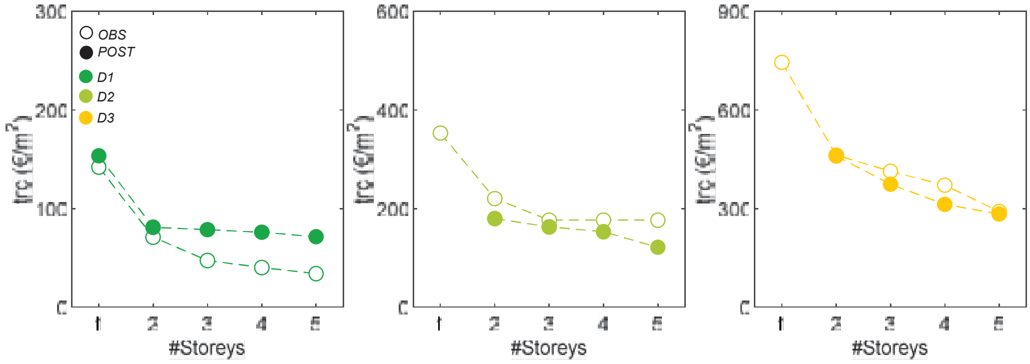

Figure 7. Predicted (POST)-versus-observed (OBS) comparison, given DSmax: trend of trc depending on the number of stories.

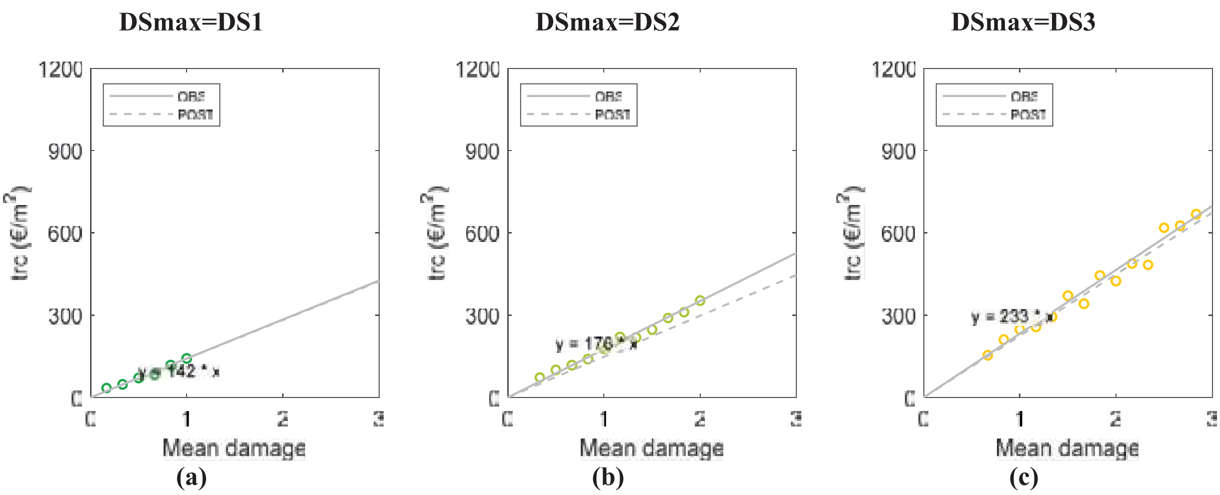

Figure 8. Predicted-versus-experimental comparison: trc depending on average damage level. Along x- and y-axis the distributions of mean damage and trc are reported.

6 CONCLUSIONS

In this work provides a regional loss estimation framework via the "Pushover on Shear Type model" (POST)-method ([1]) for residential Reinforced Concrete (RC) buildings has been shown. The proposed component-based procedure accounts for the contribution of infills/partitions and services to the buildings seismic repair costs, using dedicated drift-based fragility curves and specific repair cost analysis for masonry infills and partitions and for three damage states (DSs) proposed in [31].

The methodology has been applied to a wide dataset of real buildings, struck by L'Aquila (Italy) 2009-earthquake and resulted damaged to infills or partitions only, as testbed for its reliability and robustness.

A generally satisfying agreement between observed and predicted results was shown. In fact, predicted damage successes in well reproducing the general observed trend in terms of maximum achieved DS, also catching their trend with the number of stories, namely, the higher the number of stories, the higher the percentage of buildings with more severe damage. The mechanical method allowed to well reproduce the damage distribution observed over the buildings, beyond their maximum value; in fact, the predicted mean damage index – combining damage severity and its extent –well replicates the "observed" outcomes, along with their trends depending on the number of storeys and on maximum achieved DS. Finally, a good agreement can be found also between predicted and observed total repair costs, capable of also capturing the observed trend of loss as a function of number of storeys and mean damage values.

In conclusion, the comparison between numerically predicted and actually observed damage scenario and seismic losses allowed the validation of the implemented procedure, showing its potential for large-scale applications.

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