13th International Conference on Applications of Statistics and Probability in Civil Engineering, ICASP13
Seoul, South Korea, May 26-30, 2019

Simplified assessment of seismic performance for RC building classes towards preliminary applications of SISMABONUS incentive at the community scale

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ABSTRACT: This paper applies a simplified approach for the attribution of seismic risk classes SRC to infilled reinforced concrete RC archetype buildings representative of existing gravity load designed GLD building typologies in Italy and investigates on the effect of possible local retrofit interventions to reduce SRC. The evaluation is based on simplified modeling of lateral seismic behavior and on the estimate of the peak ground acceleration PGA corresponding to attainment of building capacity at increasing damage limit states. The SRC is attributed as the minimum between two classes, depending on safety level (percentage of new building standard %NBS) and on expected annual loss EAL. It is shown that, due to brittle failures induced by local infill-frame interaction and consequent low seismic capacity at life safety limit state, the lower (worst) SRC is generally attained for the considered building typologies, independently from the seismic hazard at the site. The application of local retrofit interventions allows ameliorating the SRC and it is found that the most probable SRC for retrofitted building typology depends on the seismic hazard at the site; lower SRC are obtained for zones of higher hazard. Application to RC building typologies in the town of Pompei, near Naples, and cost benefit analysis CBA is performed to investigate on the convenience of alternative retrofit strategies towards risk reduction at the community level.

The Sismabonus incentive mechanism, in Italy, regulates the possibility to benefit of tax deductions after seismic strengthening interventions on buildings. Polese et al. (2018) presented a simplified approach for evaluating the effects of implementation of the Sismabonus policy at the territorial scale, evaluating SRC for RC (bare) building typologies identified in the interested area; a speed method for calculating the SRC was introduced and applied for the town of Portici, in Campania region. The evaluation is based on simplified modeling of lateral seismic behavior and on the estimate of the PGA corresponding to attainment of building capacity (PGA_c) for relevant limit states, namely damage limitation (SLD) and life safety limit state

(SLV). The effect of possible retrofit interventions was also considered, suitably modifying the building model and re-calculating the SRC after seismic upgrading. This paper applies the same approach presented in (Polese et al., 2018) but implementing it for RC building typologies with infills. Moreover, the effect of the possible implementation of the Sismabonus approach is evaluated for the town of Pompei in Campania, also evaluating the convenience of alternative retrofit strategies through the execution of CBA.

1. EVALUATION OF LATERAL SEISMIC CAPACITY

According to the guidelines for seismic risk classification of constructions (Ministerial Decree, 2017) the SRC for a building can be determined once the (PGA_c) for relevant limit states, namely damage limitation (SLD) and life safety limit state (SLV), is available. The rationale and some example applications can be found in (Cosenza et al., 2018). In (Polese et al., 2018) a simplified pushover-based approach for rapid calculation of PGA_c at the two mentioned limit states was presented referring to bare RC frames. However, the presence of infills can sensibly modify the response of RC frames, with increase of the initial stiffness and of the peak resistance of the infilled frame with respect to the bare one. If the infills are not uniformly distributed in elevation, undesired mechanisms such as soft storey could form for larger seismic intensities. Another critical aspect is frame-infill interaction for buildings not adequately designed, where due to the local forces transferred from the infill to the surrounding frame, the triggering of a number of local effects may lead to a premature collapse of the columns at a single storey (Fardis et al., 2015).

In this paper, regular GLD RC buildings constructed in Italy between 1950 and 1980 (Polese et al. 2011) are considered. This is a common typology in large part of Italian territory, that was entirely classified as seismic solely in 2003. The presence of infills in the perimeter frames is taken into account and explicitly modeled.

1.1. Nonlinear building modeling

The structural model for the generic archetype building is obtained with simulated design, with the approach introduced in (Verderame et al., 2010). Thanks to symmetry, each building is analyzed separately in both the longitudinal (X) and the transversal (Y) directions, simply assembling the contribution of the relevant frames as acting in parallel.

Concerning the structural modeling, for RC columns a tri-linear moment-rotation envelope is built with cracking and yielding as characteristic points. The infills are modeled as equivalent diagonal struts acting only in compression according to the proposal from Panagiotakos and Fardis (1996). In such a model, the quadri-linear envelope of the lateral force-displacement relationship is constructed depending on the geometry of the surrounding frame, and on both the mechanical and the geometrical characteristics of the infill masonry.

Global model is assembled considering that ends of the columns are restrained against rotation (Shear Type model), as already proposed in (Ricci, 2010). The presence of infills induces additional shear forces at the ends of beams and columns that may lead to the activation of brittle collapse mechanisms especially in non-ductile RC structures. Hence, the effect of frame-infill interaction is explicitly considered through the lateral shear-force transmitted from the infill to the surrounding columns and joints. Then, for non-ductile RC building, the possible shear failure of columns is identified by comparing the obtained column shear demand with the column shear capacity evaluated according to the Eurocode 8 (CEN, 2005). Finally, the brittle failure of unconfined beam-column joints is properly simulated adopting the principal stress failure criterion proposed in (NTC2018). More details on building modeling approach may be found in (Gaetani d'Aragona et al., 2018).

1.1.1. Local retrofit interventions

Possible effective strategies to increase global building capacity could be based on local modification of components that are inadequate in terms of strength or deformation capacity. In this paper, the strategy employing externally bonded Fiber Reinforced Polymers (FRP) is applied to columns and beam-column joints for building upgrading. Continuous uniaxial Carbon FRP (CFRP) strips with fibers perpendicular to the column longitudinal axis are adopted to increase columns shear strength, while quadriaxial CFRP fabric are adopted to strengthen the corner joints. Further, to prevent shear failure at the column joint interface due to local effects of infills, Steel reinforced Polymer (SRP) composites are disposed around the beam-column joints prior to application of CFRP quadriaxial fabric. When retrofit is applied, two increasing levels of retrofit are considered, namely R1 and R2, corresponding to the application of 1 or 2 plies of FRP for the elements (i.e. exterior beam-column joints or columns) that are not verified at the SLV limit state. The case of original structure will be indicated as "non-retrofitted" structure (NR) in the following.

1.2. Simplified pushover analysis and evaluation of PGA$_c$

The lateral seismic capacity is evaluated by means of a simplified nonlinear static pushover analysis procedure. Assuming a given lateral force distribution shape (i.e., proportional to first mode shape or with forces proportional to storey masses) the global pushover curve is obtained in closed-form through a force-controlled procedure up to the peak response. After the peak, a displacement-controlled procedure is followed, as explained in (Gaetani d'Aragona et al., 2018).

Only the attainment of SLD and SLV are detected along pushover curve and transformed in the relative PGA$_c$.

According to the Italian code (NTC 2018), in case the infills are included in the building model, the SLD is attained as the maximum interstorey drift IDR_{max} exceeds the value that refers to ordinary masonry, i.e. 2‰, or as the first elements reaches flexural yielding, whichever comes first. The SLV is attained as the first primary component (columns or beam-column joints) reaches ¾ of its ultimate displacement (ductile members) or strength capacity (brittle members). Note that the brittle failure of RC members does not influence the global pushover curve, since these failures are treated as non-simulated collapse modes.

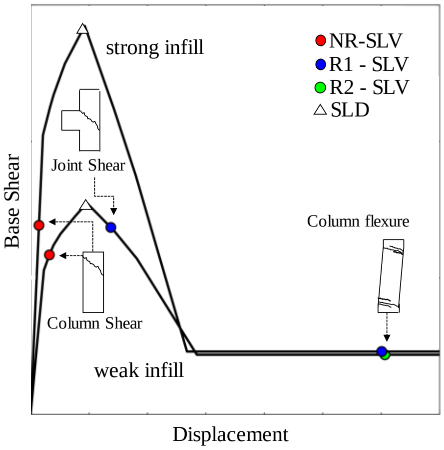


Figure 1: Pushover curve for infilled RC building with considered damage states.

Figure 1 shows an example pushover curve for infilled RC frame considering both strong and weak infills. The circle markers on the curve correspond to the attainment of SLV for NR, R1, R2 schemes, while tringle marker corresponds to SLD. Also, different brittle/ductile failures leading to SLV are evidenced.

Starting from the pushover curve, the capacity spectrum method approach, in the modified version proposed in (Dolšek and Fajfar, 2005) for infilled frames, is employed for the evaluation of the PGA$_c$ corresponding to the selected limit states.

2. EVALUATION OF SEISMIC RISK CLASS FOR RC BUILDING TYPOLOGIES

This paper aims at evaluating expected SRC for existing GLD RC building typologies with infills. The models for three archetype regular buildings of rectangular shape, representative of existing GLD RC frames of 3, 5, and 7 storeys, already introduced in (Gaetani d'Aragona et al., 2018), are considered.

The variability of lateral seismic capacity and eventually of SRC within each typology is considered by explicitly accounting for the uncertainty in infills characteristics. In particular, the infills consistency is assumed to be variable depending on the infill thickness and strength.

We assume that weak (W) and medium (M) infill panels are realized with a double layer hollow clay brick infill having (80 + 80) mm or (120 + 120) mm thickness, respectively (global thickness t_w = 160 mm for W and t_w = 240 for M), while a single layer brick infill of (300) mm thickness is assumed for strong (S) panels; these infill masonry configurations are widely used in European building practice (Hak et al., 2012). Concerning the elastic shear modulus, a lognormal distribution is assumed, with median value G_w = 1089 MPa for W and M infills and G_w = 1296 MPa for S ones and considering a COV = 30% for each typology.

Hence, the nonlinear model and associated simplified pushover analysis varies depending on infills property. In order to explicitly consider this variation in the assessment of building risk class, the modeling and subsequent analysis can be applied in an automatic loop in the framework of a Montecarlo simulation method, where relevant parameters (in this case G_w) are extracted from suitable distributions. Latin Hypercube Sampling (LHS) technique (Vořechovský and Novák, 2009) is adopted to reduce the number of simulations. Figure 2 synthesizes the methodology to derive the expected SRC for a building typology and assigned infills type (W, M or S). For each step of the simulation, the random sampling of the G_w distribution is performed first. Next, the nonlinear building model for the generic archetype building, using the obtained sampled value for G_w and associated properties of the equivalent struts is built, and simplified pushover is performed.

Given the acceleration response spectral shape, the $PGA_{c,SLD}$ and $PGA_{c,SLV}$ corresponding to the attainment of lateral seismic capacity for SLD and SLC limit states can be determined and the corresponding SRC derived.

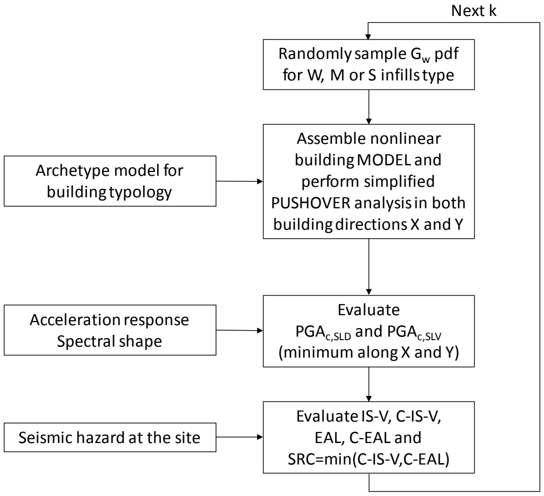
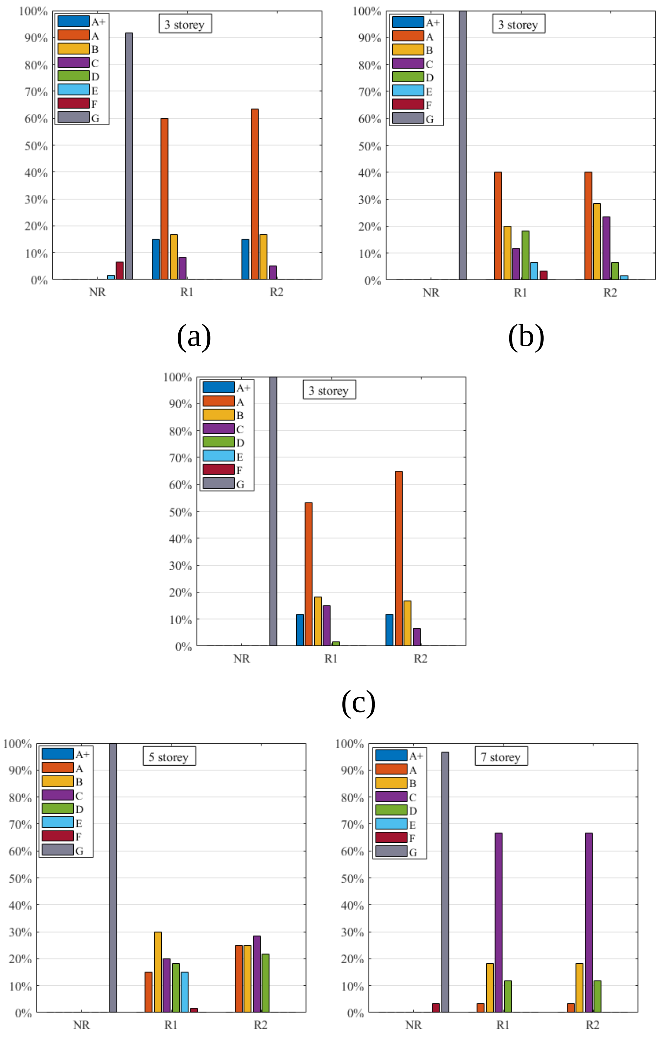


Figure 2: Methodology to derive the expected SRC for a building typology with W, M or S infills type

Adopting the illustrated procedure, the probability of attaining the different SRC for the archetype buildings of 3, 5 or 7 storeys is calculated. Equal probability of occurrence is assigned to W, M and S infills. The cases of no retrofit NR as well as R1 and R2 retrofit solutions (see § 1.1.1) are considered. A Eurocode 8 spectral shape for a subsoil B category is adopted for exemplification purposes, but other spectral shapes could be equally used. Three levels of seismic hazard are considered. Denoting with $PGA_{d,SLD}$ and $PGA_{d,SLV}$ the design level of PGA for damage limitation and life safety limit state, respectively, an increasing hazard level from z3 ($PGA_{d,SLD}$, $PGA_{d,SLV}$)=(0.075 g, 0.125 g), to z2 (0.075 g, 0.175 g) to z1 (0.1 g, 0.275 g) is considered. These PGA values correspond to increasing hazard levels for the Campania region according to (NTC 2018).

Figure 3 (a), (b) and (c) represent the results for the archetype buildings of 3 storeys for z3, z1 and z2 respectively. Figure 3 (d) and (e) represent the results for the archetype buildings of 5 and 7 storeys for z2 hazard level. Due to variability of building capacity in each building typology, that in this example application depends only on variability of infills properties, different SRC, with variable occurrence probability, are possible for each case.



(a) (b)

(c)

(d) (e)

Figure 3: SRC probability for the archetype buildings of 3 storeys for hazard levels z3 (a), z1 (b) and z2(c); and 5 (d) and 7 (e) storeys for hazard level z2

As it can be seen, the NR case corresponds to the higher probability of being in the worst class (the G). This happens because most of the analyzed building models are characterized by premature brittle failures in joints or columns. On the other hand, with application of increasing retrofit solutions a general decreasing of SRC can be observed. For the considered cases, the most beneficial effects of the retrofit are observed for 3 storey buildings, followed by 5 and lastly by 7 storey ones. Moreover, observing the SRC variation for z1, z2 and z3 hazard levels (the variation is shown only for 3 storey buildings, but analogous observations are valid also for 5 and 7 storey buildings) it can be noted that the greater SRC reduction can be obtained for lower hazard levels (i.e. for z3 in the example).

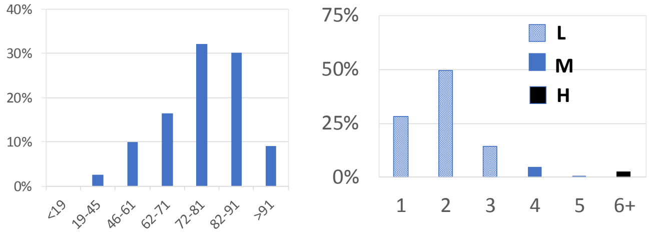
3. APPLICATION FOR THE TOWN OF POMPEI

This section presents an application for RC building typologies in the modern town of Pompei, which is at the south-east of Naples, down the slopes of Vesuvius volcano and facing the Tyrrhenian sea. The modern town of Pompei, that flanks and partly surrounds the famous Pompeii archeological site, has an approximate extension of 12.4 km^2 and a population of more than 25000 inhabitants (Censimento, 2001).

The first seismic classification for some areas in Campania region dates to 1935; however, the town of Pompei was classified as seismic (zone 2) only in 1981.

3.1. Building inventory

The inventory for RC building typologies is assembled starting from the information on buildings reported in census returns (Censimento, 2001).



(a) (b)

Figure 4: Distribution of RC buildings in age ranges (a) and height ranges (b) according to census returns (Censimento, 2001).

Figure 4 shows the distribution of RC buildings in age ranges (a) and height ranges (b) according to census. From Figure 4 (a) it can be noted that more than 60% of RC buildings were built before the seismic classification of the town, so they are designed only for gravity loads (GLD). The height ranges in Figure 4 (b) are obtained grouping the buildings with number of storeys N_s from 1 to 3 (low height class L), N_s 4 and 5 (medium height class M) and $N_s \geq 6$ (high height class H).

3.2. Variation of SRC after retrofit and CBA

The SRC for RC building typologies in Pompei is evaluated in a simplified manner, considering the archetype GLD buildings of 3, 5 and 7 storeys as representative of L, M and H height ranges for buildings. Hence, only a portion of approximately 60% of the RC building stock (the GLD buildings) is considered in this application. The z2 hazard level is considered for Pompei; hence the SRC distributions shown in Figure 3 (c), (d) and (e) can be applied for the selected building typologies. It is noted that the percentage of SRC belonging to the different SRC varies for the 3, 5 and 7 storey buildings and considering the case of no retrofit (NR) or increasing retrofit level (R1, R2). If we denote as prevalent risk class PRC the SRC having higher probability to be attained for each case, it is observed that for the 3 storey buildings, the PRC are (G, A, A) for (NR, R1, R2), with probabilities (100%, 53%, 66%). For the 5 storey buildings the PRC for (NR, R1 and R2) are (G, B, B) with probabilities (100%, 30%, 26%); for the R1 case the probability of having A or B is 45% and for R2 is 52%, with a clear global ameliorating trend from R1 to R2. For the 7 storey buildings the PRC for (NR, R1 and R2) are (G, C, C) with probabilities (97%, 67%, 67%); in this case the SRC distribution doesn't vary between R1 and R2, indicating the ineffectiveness of the further upgrading from R1 to R2. The SRC distributions for the different building typologies can give a preliminary indication on the preferable risk reduction strategies. On the other hand, the realistic evaluation of potential losses depends on the value of exposed assets, e.g. on the building stock inventory for the territory under investigation. Loss evaluation is needed, together with an estimate of the costs for alternative retrofit strategies, to perform CBA. In the present application, the CBA is applied to evaluate the efficacy of increasing retrofit measures applied to the selected building typologies in Pompei. The indirect cost benefits, including human loss and down time, are not considered, while only direct losses and the costs for the retrofit are explicitly included.

The Net Present Value NPV_L of losses over a given time frame T (e.g. 50 years) can be calculated with Equation (1):

$$NPV_L\left(S_j, R_k\right) = \sum_{i=1}^{T} \frac{SA_{tot}\left(S_j\right) \cdot C_R \cdot EAL\left(S_j, R_k\right)}{\left(1+r\right)^i} \qquad (1)$$

where (S_j,R_k) indicates building typology S_j retrofitted by the alternative R_k (R_0 corresponds to no retrofit, i.e. NR), r represents the discount rate, T is the time frame of interest, $SA_{tot}(S_j)$ represents the surface area summed over the storeys of the S_j typology, C_R is the unit reconstruction cost, including costs of nonstructural parts and systems, that is expressed in €/m^2 and $EAL(S_j,R_k)$ is the median EAL for building typology S_j with retrofit solution R_k. The EAL can be calculated in a simplified manner as a function of ($PGA_{c,SLD}$, $PGA_{c,SLV}$) at a site (Cosenza et al., 2018) and is computed in the framework of the Montecarlo simulation process ; the value of $EAL(S_j,R_k)$ considered for CBA is the median value resulting from the analyses. It is expected that, $EAL(S_j,R_0) \geq EAL(S_j,R_1) \geq EAL(S_j,R_2)$. In this study r=3% is adopted and a time frame of 50 years is considered.

The benefit of a measure R_k is determined by evaluating the reduction of losses with respect to the initial state R_0. So, the overall benefit $BN(T, S_j ,R_k)$ is given by Equation (2):

$$BN\left(T, S_j, R_k\right) = \left[NPV_L\left(T, S_j, R_0\right) - NPV_L\left(T, S_j, R_k\right)\right] \qquad (2)$$

The cost $C(S_j,R_k)$ of retrofitting measure R_k for all structures S_j is computed multiplying $SA_{tot}(S_j)$ by the unit retrofit cost for the selected measure $C_{Ret,Rk}$, also expressed in €/m^2. Assuming that the capital expenditure happens at time the analysis is performed, no discounting of the cost C is necessary.

The benefit cost ratio BCR, that is the ratio of the discounted benefits $BN(T, S_j, R_k)$ to the costs, can be used to evaluate the the attractiveness of each single alternative measure. A measure is attractive if BCR>1.

For the case of our application it is assumed that C_R=1360 €/m^2 while retrofit costs are roughly assumed $C_{Ret,Rk}$=270 and 335 €/m^2 for k=1, 2; such values are deduced from actual repair and retrofit costs that were monitored in the reconstruction process following recent Italian earthquakes (Cosenza et al., 2018). It is noted that the adopted values of $C_{Ret,Rk}$ are higher than the costs that could be estimated for the local (FRP+SRP) retrofit interventions; indeed they take into account other possible interventions (e.g. retrofit of foundations) that typically take place in the upgrading of non-conforming buildings.

The $SA_{tot}(S_j)$ for each typology, that is needed for calculation of NPV_L, is obtained considering the effective distribution of buildings into the different storey number (see Figure 4 (b)) and multiplying the number of buildings (relative to the considered Ns) for the storey number Ns and for the mean surface area.

Table 1: Results of CBA

S_j	R_k	EAL	NPV	*BN*	C	BCR
		%	M €	M €	M €	
L	R0	8.2	1578.2	0.0	0.0	n.a.
L	R1	1.3	242.0	1336.1	177.9	7.5
L	R2	1.3	240.4	1337.8	220.7	6.1
M	R0	8.2	70.5	0.0	0.0	n.a.
M	R1	2.9	25.1	137.0	24.0	5.7
M	R2	2.3	19.6	153.6	29.7	5.2
H	R0	8.2	64.7	0.0	0.0	n.a.
H	R1	2.6	20.2	134.3	22.0	6.1
H	R2	2.6	20.2	134.3	27.3	4.9

Table 1 resumes the results of the CBA for the three considered building typologies and assuming two retrofit levels R1 and R2. It can be noted that, thanks to the contribution at SLV given by the strengthening solution, a significant reduction of EAL is obtained even for the primary retrofitting solution (R1). This determines the convenience of all the retrofit strategies (BCR>1). If there are no budget constraints, the R1 strategy for the L building typology, giving the highest BCR, would be the most convenient.

4. CONCLUSIONS

This study shows the applicability of a simplified performance-based procedure for the estimation of SRC at the community scale. The paper also demonstrates its usefulness for the preliminary evaluation of the most convenient investment towards large scale risk reduction, through cost benefit analysis. The SRC is evaluated in a simplified manner depending on the PGA capacity at two relevant limit states (damage limitation $PGA_{c,SLD}$ and life safety $PGA_{c,SLV}$). The proposed performance-based approach allows to take into account for the effect of local retrofit interventions finalized to the increment of $PGA_{c,SLV}$. The local retrofit (e.g through FRP wrapping) can significantly contribute to increase the building safety in case of premature brittle failures, that often occur in nonconforming elements (e.g. columns or external unconfined joints), also due to local effects caused by frame-infill interaction. The beneficial effect of building upgrading with local interventions is also evident in the significant reduction of EAL. The probability of attaining different SRCs is determined with a Montecarlo simulation approach, varying infills properties within given pdfs for each archetype building. For future studies, the evaluation can be improved by suitably introducing other sources of variability for each building model, e.g. geometric dimensions (surface area of the buildings as well as bay lengths in longitudinal and transversal directions) and material properties (concrete strength and steel yield stress). Previous applications for bare RC buildings showed the feasibility to consider intra-building variability in each typology by using a simulated design approach (Polese et al., 2015a,b; 2017). The SRC distributions for the different building typologies can give a preliminary indication on the preferable risk reduction strategy. A more complete assessment for evaluation of the most convenient risk reduction strategy at the territorial scale can be obtained applying cost benefit analysis. The evaluation of SRC and subsequent application of CBA to selected building typologies for the town of Pompei, in Campania, Italy, showed that the largest cost benefits can be attained even with a minimum retrofit level. However, the criterion to maximize the economic benefits does not take into account other aspects such as safety levels of buildings and occupants; these critical issues should be properly evaluated when taking decisions at the community scale.

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ACKNOWLEDGEMENTS

This study was performed in the framework of PE 2019-2021 joint program DPC-Reluis – WP2 – Typology building inventory (Cartis) and WP4 – Risk maps and seismic damage scenarios