# Mitigation Analyses for the Selection of Effective Seismic Retrofit Strategies at a Territorial Scale

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**ABSTRACT:** Recent developments of viable and low-cost retrofit solutions within a multi-level retrofit approach, suggest the possibility to implement “standardized” solutions at a urban or territorial scale. However, due to the limited funds available, alternative strategies should be considered and analyzed in order to define the most effective action plan able to minimise the overall risk. Such mitigation analyses, although not yet codified, are expected to become in the near future a fundamental decision making tool for the allocation of funds by local authorities, as already happening overseas. In this paper the efficiency of different structural mitigation strategies will be investigated within the framework of a seismic risk analysis approach. Alternative mitigations strategies will be examined by combining: 1) alternative retrofit solutions based on different techniques and targeting various performance objectives; 2) spatial distributions of the intervention for targeted typologies. The effectiveness of the aforementioned alternative mitigation strategies will be assessed with reference to a case study area using different mitigation analysis methods, based on a single- or multi-criteria approach within either a deterministic or a stochastic evaluation.

## 1 INTRODUCTION

Valuable and efficient seismic strengthening/upgrading techniques have been developed in the recent past and implemented on real buildings. A balance between structural requirements and associated benefits versus the costs associated to the intervention is typically sought, at a case-by-case basis, and drives the final choice of the solution.

Recent developments of viable and low-cost retrofit solutions within a multi-level retrofit approach, suggest the possibility to implement “standardized” solutions at a urban or territorial scale.

However, when expanding the scale of the intervention (and analysis) to a territorial level (city, region, country), more complex criteria and intervention strategies should be considered and evaluated in order to define the most effective action plan to minimize the overall risk. In particular, the actual limits of available resources, including budget, material, human and technical resources, logistics and supporting infrastructures, can represent the critical constraints for a large scale intervention.

Mitigation analyses, although not yet codified, are expected to become in the near future a fundamental decision making tool for the allocation of funds by local authorities, as already observed in some part of the world . As an example, the FEMA act of 2000 mandates that states and local governments conduct mitigations analyses as a fundamental condition to receive Hazard Mitigation Grant Programme (HMGP) funds. Mitigation analyses should describe: 1) the prioritizing mitigation actions and 2) how the overall mitigation strategy is cost-effective and maximizes the overall wealth; in other words which one amongst the possible alternatives shall be funded to minimise the overall risk.

In a previous contribution by the authors (Giovinazzi et al., 2006), the efficiency of targeting partial or total retrofit intervention (thus aiming at different targeted performance) as part of a territorial scale retrofit strategy has been demonstrated on a case-study area. In these studies, given the different scope of the investigations, a crude cost-benefit analysis has been adopted within a deterministic approach referred to a scenario earthquake. No constraints to the available budget, or, more generally, resources were assumed.

In this contribution, the effectiveness of implementing such retrofit solutions at a territorial scale will be assessed with reference to a case-study area using different mitigation analyses methods, based on a single- or multi-criteria approach within either a deterministic or a stochastic evaluation. The implications in terms of mitigation analysis and overall decision-making process when planning a retrofit intervention at territorial scale instead of on a single buildings will be evident

## 2 ALTERNATIVE RISK MITIGATION ANALYSIS AND DECISION CRITERIA

### 2.1 *Benefit-Cost Analysis*

A Benefit-Cost Analysis approach (BCA) provides a means of economically evaluating a project that involves seismic mitigation decisions, supplying decision makers with preferred policy alternatives, including the alternative of "no action" (doing nothing).

In order to determine the most economically-efficient mitigation option, BCAs are performed by: 1) assessing the cost of implementing each alternative, 2) assessing the benefit (in terms of losses avoided), 3) comparing alternative according to a decision criteria i.e. benefit/cost ratio, benefit minus cost, deterministic net present value (maximization of net revenues).

As highlighted by Zerbe and Falit-Baiamonte (2001) BCAs should be implemented within a national perspective, taking into account that the benefits and the costs associated with performance-based earthquake engineering decisions will differentially affect a wide variety of parties, or stakeholders: such as the owner(s) of the buildings, the user(s)/tenant(s) of the buildings, the local economy, the regional economy, and the "society". For this reason, societal indicators of damage should be added to the analysis, (such as the liability resulting from injuries and casualties), and should be quantified in monetary terms (translating, if necessary, qualitative terms into crisp numbers). Being such an approach often criticized on moral grounds, an alternative approach typically consist of evaluating and accounting for such societal indicators, separately, without expressing them in monetary terms. The benefits associated to the mitigation strategies would thus comprise of "monetary" figures as well as non-monetary translated social indicators.

After clarifying which target parameters should be more emphasised as analyses outcomes depending on the expected audience, the main assumptions of the analyses to be clarified are: 1) who are the interested parties, stake-holders, and what type and extent of costs and benefits should be included; 3) the level of discount rate adopted; 4) the robustness of the results with respect to other assumptions; 5) the evaluation criteria implemented (i.e. Benefit/Cost ratio, Benefit minus Costs, Net Present Value), 6) the treatment of inflation rate and other uncertainties.

Clearly, when operating at a territorial scale, the evaluation of the overall (city council, region, country as well as inter-country) economical impact of an earthquake event and associated benefits if a pre-damage strengthening intervention is carried out, become a much more complex task. The reconstruction/repairing costs and time, for example, of the single building after a major event shall be evaluated considering the whole picture. The limited amount of operational funds, lack of material, human and technical resources to implement the repairing/strengthening operations, as well as the delay due to production and transportation difficulties (due to damage to critical infrastructures), will play a major role either in the case of a pre-event retrofit intervention and/or in the case of a post-disaster reconstruction. In the latter scenario, the overall resilience of the society will determine the capacity and speed of recovery.

#### 2.1.1 *Stochastic Benefit-Cost Analysis*

When the earthquake hazard is generated stochastically or according to a PSHA (Probabilistic Seismic Hazard Analysis), a stochastic Benefit-Cost Analysis, herein referred to as SBCA, should be implemented, by evaluating the probability density functions associated to the benefits. Results of a SBCA might be expressed as exceedance probability curves showing the probability that any given level of loss will be equalled or exceeded. Exceedance probability curves can be summarised in terms of Expected Annualised Loss, EAL. EAL, which measures the average yearly amount of loss when accounting for the frequency and severity of various levels of losses, is one of the most common parameter adopted to present the results of a SBCA. However, as underlined by Smith and Vignaux (2006), in spite of being widely adopted by insurance companies, the EAL it is a very limited measure, not always applicable in some areas of risk management, as annualised risks may appear small and give the wrong impression of risk due to a single event.

### 2.1.2 *Life-cycle Cost Analysis*

It is worth noting that a Life-cycle cost analysis (LCCA), commonly used in the evaluation of seismic mitigation strategies, may be properly viewed as a subcategory of the broader group of BCAs, with simply a different way of presenting the results.

### 2.1.3 *Cost-effectiveness analysis*

A further subcategory of the BCAs is a cost-effectiveness analysis. Cost-effectiveness analysis presumes that a policy decision regarding the main goals/objectives driving the implementation of action-plan has already been made (i.e. targeted budget, maximum acceptable downtime) and that the only matter to resolve is the best way of meeting the specific targets. Figure 1 shows, for instance, some performance targets adopted within a performance assessment framework (Performance-Based Earthquake Engineering PBEE) developed at PEER by Cornell and Krawinkler (2000). According to a cost-effectiveness approach, the PBEE methodology has been implemented targeting either the minimisation of the expected annual loss, EAL (Hamburger 2004), or ensuring that the probability of exceeding structural limit states, or other socio-economical parameters, is lower than a specific acceptable value (Krawinkler et al. 2004) as in Fig. 1.

| Performance Targets | Decision Variables DV | Damage Measures DM | Engineering Demands EDP | Seismic Hazard IM |
|---|---|---|---|---|
| • Collapse & Life safety $P_f < y$<br>• Losses < x<br>• Downtime < z | • Collapse<br>• Number of casualties<br>• $ losses<br>• Length of downtime | • Fragilities for failure states<br>–Structural<br>–Nonstructural<br>–Content | • Engrg. analysis (story drift, floor acc.)<br>–Soil–foundation –structure system | • Hazard analysis<br>• Ground motions |
| $\lambda$(DV) | G(DV/DM) | G(DM/EDP) | G(EDP/IM) | $\lambda$(IM) |

**Figure 1: Identified performance targets within the framework of PBEE (after Krawinkler et al. 2004)**

## 2.2 *Use of a functional and optimization process*

When multiple performance targets are defined within a mathematical model, a reliability-based optimization process can be implemented to evaluate the optimum value of a vector-based parameter, herein referred as p, for which the retrofit intervention is financially feasible. A general objective function for maximization can be expressed as (i.e. Rackwitz R., 2006): $Z(p) = B(p) - C(p) - D(p)$ where B(p)=benefit derived from the retrofit intervention, C(p)=cost of design and construction and D(p)=expected damage/failure costs are assumed to be dependent from the vector parameter p.

Similarly a general objective function for minimization would be written in the form of the expected losses or, ultimately, of the global seismic risk to be mitigated (i.e. convolution of hazard, vulnerability and exposure).

## 2.3 *A Multi-Criteria approach*

When multiple criteria, mixing technical and social aspects, (costs, time, structural performances, architectural impact, occupancy disruption, etc.) need to be addressed, the identification of the most suitable mitigation strategy is not straightforward due to: 1) the fact that maybe no solution satisfying all criteria simultaneously can be achieved; 2) the difficulty in numerically quantifying social and societal criteria.

Multi-Criteria Decision Making (MCDM), currently applied in several fields, can be a valuable tool within seismic mitigation analysis. As a first step of any MCDM, a decision matrix (Table 1) is drawn clarifying the alternative retrofit strategies $RS_i$ and the assumed decision criteria $C_j$.

It is worth noting that the decision criteria might have different units, though being based on numerical parameters (i.e. dollars, days, probability of exceedence, number of injuries and victims) which require to be normalize to a common unit. However, social/societal aspects could be expressed via qualitative parameters (availability of skilled technician, social disruption, resilience of single organization or entire society). In such case, prior to implementing any MCDM, the qualitative parameters within the decision matrix have to be translated in term of crisp numbers. The fuzzy set theory might be adopted for the scope (Ross 1995).

**Table 1 : Decision Matrix**

| | | No intervention (As Built, AB) | Partial Retrofit (PR) | Total Retrofit (TR) | …… |
|---|---|---|---|---|---|
| | | $RS_1$ | $RS_2$ | $RS_3$ | $RS_u$ |
| Retrofit Cost (€) | $C_1$ | $RS_1C_1$ | $RS_2C_1$ | $RS_3C_1$ | … |
| Material Availability after earthquake (Q) | $C_2$ | $RS_1C_2$ | $RS_2C_2$ | … | … |
| Skilled technician Availability (Q) | $C_3$ | … | … | … | … |
| Downtime (days) | $C_4$ | … | … | … | … |
| P[Damage Limit State] (N) | $C_5$ | … | … | … | … |
| Life losses (N) | $C_6$ | … | … | … | … |
| ……. | $C_u$ | … | … | … | $RS_nC_n$ |

Note: (N)= numerical parameter, (N)= Qualitative parameter

Various mathematical techniques can then be implemented to find the optimum solution. A MCDM TOPSIS method (Technique for Order Preference by Similarity to Ideal Solution) proposed by (Hwang and Yoon, 1981) has, for example, been implemented by Caterino et al. (2006) for the assessment of the best retrofit solutions amongst different (three in that case) alternatives, for a single under-designed RC structure. According to the TOPSIS method the normalised values of the decision matrix are weighted in order to account for the relative importance of each criteria $C_i$ with respect to another. The TOPSIS method identifies the best alternative as the one with the shortest distance from an ideal solution and the largest distance from the negative-ideal solution, that are fictitiously obtained by taking for each criterion respectively the best and the worst performance values.

### 2.4 *Present Value and Discount Rate*

Most of the aforementioned approaches for evaluating mitigation analysis, might enquire that future benefits and costs are reduced to a present value so that comparisons between different projects or alternatives will be consistent. The present value of a given cash flow is, in simple words, the sum of money that if invested today at some relevant interest rate (or discount rate) will yield that cash flow. The larger the interest rate or discount rate, the smaller will be the present value of positive cash flows. An extensive technical literature discussing the appropriate choice of discount rate is available. In order to have a rough idea of appropriate values it could be said that the appropriate discount rate should reflect the cost of capital for a term similar to the life of the project for the government organization considering a project. This rate is approximately the rate on government bonds that mature at about the time the project is to be completed. Whichever type of discount rate is used, cash flows should be also adjusted for inflation. A discount rate reflecting inflation-adjusted currencies is called a real discount rate (=discount rate - inflation rate). It is worth noticing that, only the benefits and the costs that are listed in constant currencies need to be adjusted for the effects of inflation while the cost expressed in current currencies do not.

It is worth noting that the costs of repairing a given level of damage cannot be considered constant in the future, but shall vary proportionally to the cost of workmanship and materials which is reasonably expected to increase at a different rate than the inflation rate. When evaluating the Net Present Value of all future losses, the discounted value of future costs should thus be applied to the expected actual higher costs of the intervention. As anticipated, when assessing the impact of an event at a territorial scale, the costs associated to the post-event repair and reconstruction are likely expected to be further and significantly increased by the sudden lack of resources.

## 3 VULNERABILITY ASSESSMENT AND FRAGILITY CURVES BEFORE AND AFTER RETROFITTING

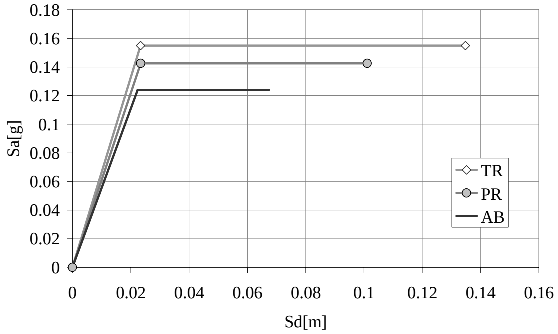
The representation of the buildings vulnerability before and after the retrofit intervention, has been carried out, in this paper, using a capacity spectrum-based method with simplified mechanical curves (in terms of fundamental period T, yielding acceleration $a_y$ and ductility capacity $\mu$) derived for European building typologies (Lagomarsino and Giovinazzi 2006) and calibrated on the basis of a macroseismic vulnerability method and observed damage data.

Simulated retrofit interventions can be easily represented within mechanical-based model by properly specifying the upgrading factors defined as the ratio between the condition after and before the retrofit intervention. For the bilinear capacity curves defined within the aforementioned capacity spectrum-based method, upgrading factors for the yielding acceleration $F_{ay}=a_y'/a_y$, the ultimate displacement $F_{du}=d_u'/d_u$ and the stiffness $F_k=k'/k$ could be easily applied for simulating selective upgrading and selective weakening interventions.

The concept of multi-level performance-based retrofit strategy, recently proposed in literature (Pampanin and Christopoulos, 2003) and implemented with reference to two alternative retrofit solutions (FRP or metallic haunch) for pre-1970 frame systems, can be directly represented in terms of modified capacity curves (Fig. 2a). According to the concept of multi-level performance-based retrofit strategy, a partial retrofit, aiming to achieve an intermediate performance objective, could be targeted if a full upgrade (total retrofit) is not achievable or impractical from a cost and invasiveness point of view. Table 2 shows the values of the upgrading factors and of the defining parameters of the capacity curves after a partial, PR and a total retrofit, TR interventions, with reference to a medium-rise, non-designed reinforce concrete frame RC1_M. Values of structural damage states median points (damage limit states thresholds) of the capacity curves for the as built condition, AB and after the PR and TR retrofit schemes are, moreover, provided in Table 2, in order to show the capability for the retrofitted structure of displacing farther than the original building before sustaining damage. The effects and efficiency of alternative retrofit strategies can be appreciated by comparing fragility curves describing the probability of exceed or equal pre-defined levels of damage $D_k$, as shown in Fig. 2b for $D_5$.

**Table 2. Upgrading factors, defining parameters and damage limit state thresholds for the RC1_M capacity curves, before and after retrofit intervention**

| | $F_{ay}$ | $F_k$ | $F_{du}$ | k | T | $a_y$ | $\mu_\Delta$ | $d_y$ | $d_u$ | $Sd_1$ | $Sd_2$ | $Sd_3$ | $Sd_4$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| As Built | - | - | - | 5.54 | 0.853 | 0.124 | 3 | 0.022 | 0.067 | 0.016 | 0.034 | 0.045 | 0.067 |
| Partial Retrofit | 1.15 | 1.1 | 2.5 | 6.09 | 0.813 | 0.143 | 4 | 0.023 | 0.101 | 0.016 | 0.035 | 0.059 | 0.101 |
| Total Retrofit | 1.25 | 1.2 | 3 | 6.64 | 0.778 | 0.155 | 6 | 0.023 | 0.135 | 0.016 | 0.039 | 0.073 | 0.135 |



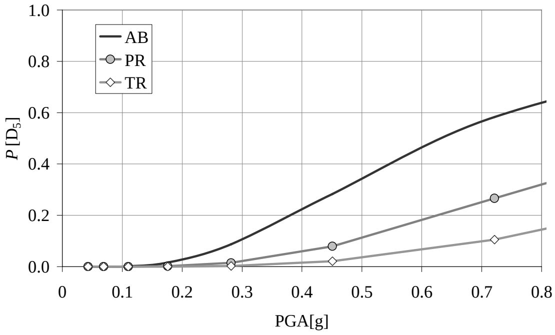




**Figure 2: Performance-based retrofit strategies (PR=partial Retrofit, TR=Total Retrofit) compared to as built condition: a) capacity curves, b) fragility curves for a given limit state ($D_5$)**

## 4 IMPLEMENTATION TO A STUDY CASE

The exemplification of the effects of retrofit strategies planned at a territorial scale are provided via damage scenarios referred to a case study identified with Western Liguria Region in Italy. The building vulnerability and the expected consequences of an earthquake in this area have been investigated as part of an Italian National research project for the definition of Earthquake scenario and strategies for the preservation of historic centres funded by the INGV-GNDT (2004).

The inventorying of the buildings stock including number and characteristics has been carried out processing census statistical data. The total number of current buildings in the selected region is 49372, with RC and URM typologies representing the 36% and 64% of the total, respectively, In spite of the higher number of URM buildings, the majority of population lives in RC buildings (60% out of the total 211349 inhabitants living in RC buildings, and 40% in URM buildings), mostly designed prior to 1981, date of adoption of seismic code provisions in that area (56% pre 1971, 33%, between 1971 and 1981, 12% after the 1981). Focusing on the characteristics of pre'71 buildings, it is worth noting that the majority consists of low rise buildings (59% 1÷2 floors, 33% 3÷5 floors, only 9% have more than 5 floors). Moreover, according to census data, a not negligible part of pre'71 buildings (18%) are of pilotis typology, i.e. infills present only in the upper storeys. The highest concentration of pre'71 buildings is in the costal area where the soil resulting from the geology-based microzoning belongs generally to class C ($T_C$=0,6). Soil amplification effects can be therefore expected for the pre '71 buildings whose period values range from T≈0.6÷≈0.8 (Table 2).

The expected consequences in terms of economic losses, damage to buildings and consequences to people have been evaluated, in this paper, for pre'71 buildings either for the as built condition, AB and after two different retrofit strategies: a partial retrofit, PR and a total retrofit, TR, defined as in Table 2.

### 4.1 *Costs of the Retrofit Intervention at Territorial Scale*

In the mitigation analysis implemented in this study case, only the cost directly associated to the retrofit intervention itself has been considered for simplicity.

The structural cost, C of a typical seismic retrofit intervention for existing R.C. buildings has been evaluated according to FEMA156 (1994) as a product of five different factors: 1) $C_1$ building group mean cost, 2) $C_2$ building area adjustment factor, 3) $C_3$ seismicity/performance objective adjustment factor, 4) $C_L$ location adjustment factor ($C_L$=1 assumed here), 5) $C_T$ time adjustment factor ($C_T$ =1.621 for an inflation rate =4% for the 2007). Table 3 shows the retrofitting structural cost C (€/m$^2$) for concrete moment frame and frame with infill walls to be retrofitted in an area of moderate seismicity. The structural cost are provided, as a function of the targeted performance level and of building area to be retrofitted (small, S medium, M, large , L, very large VL areas are distinguished). The retrofitting structural cost C (€/m$^2$) originally expressed in $/sq. ft., has been herein presented in term of €/m$^2$, where m$^2$ =10.76 sq.ft$^2$ and €=1.3US $.

**Table 3. Typical structural cost to seismically rehabilitate RC building for moderate seismicity after FEMA156 (1994) - Option2**

| Performance Levels | Life Safety | | | | Damage Control | | | | Immediate Occupancy | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Area | S | M | L | VL | S | M | L | VL | S | M | L | VL |
| €/m$^2$ | 215 | 209 | 199 | 165 | 257 | 250 | 238 | 198 | 423 | 411 | 392 | 326 |

In this contribution it has been assumed that a Total Retrofit solution, TR, would target a performance level in between "Immediate Occupancy" and "Damage Control" while a Partial Retrofit solution, PR would target a "Life Safety" one.

### 4.2 *Earthquake costs and benefits due to reduced losses*

For the sake of an easy and clear implementation of the study case analysis, the earthquake dependent costs have been roughly evaluated considering: building damage and collapse, injuries/fatalities and temporary shelter, as summarised in Tab. 4. It is well recognized that a comprehensive cost-benefit analysis should require to account for many others factors such as: 1) initial benefits (i.e. increased property value) and costs, 2) time dependent benefits and costs, e.g. related to maintenance, depreciation, insurance and assessed rental differentials, 3) further earthquake-dependent benefits and costs such as: loss of contents, allowance for the overall business interruption and social disruption. An example of detailed  benefit-cost study of actually designed retrofit intervention can be found in Hopkins et al. (2006), as part of a feasibility study (funded by a World Bank) to retrofit residential buildings in Istanbul.

In more details, the reconstruction cost for a residential RC building has been supposed to be 1400€/m$^2$, while a building value of 2500€/m$^2$ has been assumed for the assessment of the repairing costs. The ratio between cost of replacement and building value has been set as: 0.01 for $D_1$, 0.1 for $D_2$, 0.35 for $D_3$, 0.75 for $D_4$, 1 for $D_5$, respectively corresponding to the costs of 25€/m$^2$ for $D_1$, 250€/m$^2$ for $D_2$, 875€/m$^2$ for $D_3$, 1875€/m$^2$ for $D_4$ (in this case reconstruction is more convenient then repairing, thus a cost of 1400€/m$^2$ is assumed).

As far as the costs associated to injuries and loss of lives are concerned, the values adopted in the aforementioned Istanbul Retrofit Project (Hopkins et al. 2006) have been herein assumed (Table 4). These values are in good general agreement with those quantified by Rackwitz (2006) as a function of the Societal Life Saving Cost for European countries.

**Table 4. Typical earthquake costs**

| | | | |
|---|---|---|---|
| **Building Value** | 2500 €/m$^2$ | **Societal Life Saving Cost** | 195000 € |
| **New Construction** | 1400 €/m$^2$ | **Societal Injury Saving Cost** | 6250 €/person |
| **Repairing $D_4$ damage** | 1400 €/m$^2$ | **Cost of a temporary housing unit** | 6250 €/4 person |
| **Repairing $D_3$ damage** | 875 €/m$^2$ | | |
| **Repairing $D_2$ damage** | 250 €/m$^2$ | | |
| **Repairing $D_1$ damage** | 25 €/m$^2$ | | |

## 5 DETERMINISTIC COST-BENEFIT ANALYSIS

For the damage scenario analysis, the maximum historical event in the region has been considered, corresponding to the Western Liguria Feb 23, 1887 earthquake (M=6.3, $I_0$ = X, Long=8°,1430, Lat = 43°,7480), which caused over 509 victims, severe destruction in costal towns and villages. Different territorial scale mitigation interventions have been taken into consideration. Table 5 reports the number of buildings, people and surface involved in the different mitigation intervention. The expected costs in the occurrence of the deterministic scenario earthquake are also presented. Table 6 summarises the expected outcomes in terms of different benefit-cost parameters. It is worth noting that the first hypothesis to retrofit the total stock of the pre’71 buildings would be economically inconvenient either in the case of a partial retrofit intervention. Additional socio-political criteria should thus be considered to justify such a mitigation strategy. On the other hand, retrofit interventions restricted to the most vulnerable pre’71 r.c. building typologies (i.e. pilotis buildings) are shown to be the most effective from a cost-benefit point of view. Furthermore, the efficiency of a partial retrofit intervention in reducing the effects of the selected earthquake event is confirmed. Conversely, the additional reduction provided by the implementation of a total retrofit solution seems not be justified, from a cost-benefit point of view, when not even unfeasible, for a territorial scale implementation. More importantly, as show in Table 4, a partial retrofit solution, possibly localized within targeted localized area (selected spatial distribution of the intervention) can still guarantee a cost-effective intervention when initial constraints due to limited budget/resources should be accounted for.

**Table 5. Consequences to building and people and losses for as built condition (AS) and for different hypothesis of retrofit interventions: partial retrofit (PR) and total retrofit (TR)**

| | | <’71 all | | | <’71 pilotis only | | | localized <’71 pilotis only | | |
|---|---|---|---|---|---|---|---|---|---|---|
| N° building | | 9855 | | | 1792 | | | 45 | | |
| Surface ($m^2$) | | 4074774 | | | 685001 | | | 27086 | | |
| Inhabitants | | 80764 | | | 13048 | | | 3191 | | |
| Retrofit interventions | | AB | PR | TR | AB | PR | TR | AB | PR | TR |
| Buildings | Uninhabitable | 487 | 179 | 125 | 243 | 111 | 75 | 26 | 13 | 9 |
| | Collapsed | 36 | 6 | 2 | 25 | 5 | 2 | 6 | 1 | 1 |
| People | Homeless | 7665 | 2684 | 1790 | 3292 | 1580 | 1053 | 214 | 114 | 76 |
| | Casualties* | 231 | 38 | 17 | 155 | 33 | 15 | 16 | 4 | 2 |
| *Earthquake Cost (M€)* | | *844* | *411* | *358* | *552* | *325* | *252* | *39.8* | *5.56* | *3.09* |

*Casualties = 1/3lifes lost, 2/3 serious injury

**Table 6. Cost-benefit analyses of alternative retrofit solutions**

| | <’71 all | | | <’71 pilotis only | | | localized <’71 pilotis only | | |
|---|---|---|---|---|---|---|---|---|---|
| Retrofit interventions | AB | PR | TR | AB | PR | TR | AB | PR | TR |
| Retrofit Cost (M€) | | -852 | -1347 | | -143 | -227 | | -5.65 | -8.95 |
| Earthquake Cost (M€) | -844 | -411 | -358 | -552 | -325 | -252 | -39.8 | -5.56 | -3.09 |
| Benefit = Savings in damage (M€) | | 433 | 53 | | 227 | 300 | | 34.24 | 36.71 |
| Present value of Benefits (M€)* | | 416 | 51 | | 218 | 288 | | 33 | 35 |
| **Benefits minus Costs (NPV)** | | -436 | -1296 | | **75** | 61 | | **27** | 26 |
| **Benefit/Cost Ratio (B/C)** | | 0.49 | 0.04 | | 1.53 | 1.27 | | 5.83 | 3.94 |

(* after 1 year assuming a discount rate of 4%)

Table 7 shows the same results obtained for pilotis pre’71 buildings, represented in terms of Life-Cycle costs (which is, as mentioned, a subcategory of a BCA approach). It is worth noting that in spite of the different parameters chosen to present the outcomes of the intervention, a partial retrofit intervention is confirmed to be more convenient.

**Table 7. <’71 pilotis only intervention summarised in terms of Life-Cycle Costs for the**

| | <’71 pilotis all | | | Value of | |
|---|---|---|---|---|---|
| Retrofit interventions | AB | PR | TR | PR minus AB | TR minus AB |
| Retrofit Cost (M€) | | -5.65 | -8.95 | -5.65 | -8.95 |
| Earthquake Cost (M€) | -39.8 | -5.56 | -3.09 | 34.2 | 36.7 |
| **Total Life Cycle Cost** (M€) | -62 | -39 | -33 | **28.6** | 27.8 |

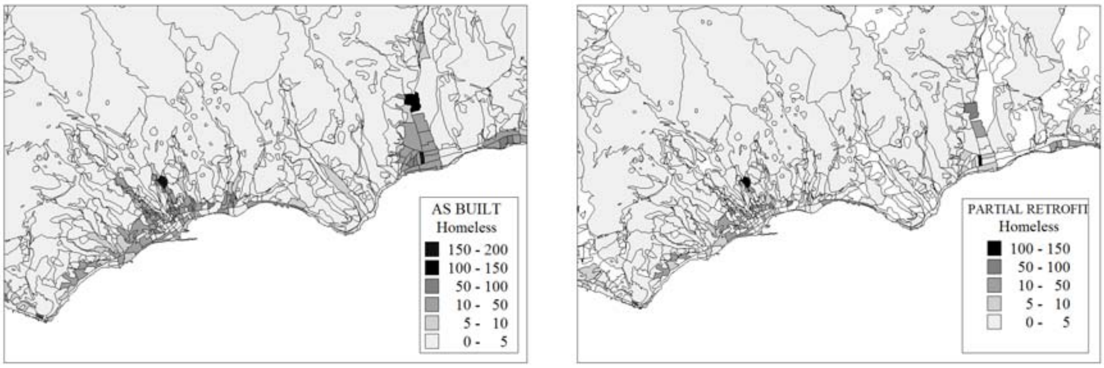



**Figure 3: Homeless people: a) as built conditions, b) after a partial retrofit intervention**

Another effective way of representing the results of a deterministic territorial scale seismic risk analysis is in terms of thematic maps within a GIS-environment (Fig. 3) . An addition advantage of the GIS-environment is that mitigation strategies can be defined, consisting of alternative levels of intervention (ranging from total retrofit to no- action), within specific unit of analysis, depending on the computed seismic risk. As an example, the possibility of limiting the retrofit intervention only to localised areas with an average damage level greater or equal than $D_k$=2 has been investigated (Table 4). Clearly, in such a case, the “benefit” of a targeted intervention are more evident.

### 5.1 *Probabilistic Cost-Benefit Analysis*

As mentioned, all the mitigation analyses presented in Par. 2 can be directly implemented within a complete probabilistic framework, with reference to a probabilistic hazard demand. In this study, the hazard maps included in the recently revised Italian Seismic Code (OPCM 3274, 2003) are adopted. Peak ground acceleration, PGA, values corresponding to the 16$^{th}$, 50$^{th}$ and 84$^{th}$ percentile are provided. Eight different values of -probability of exceedence in 50yrs (81%,63%, 50%, 39%, 22%, 10%, 5%, 2%) are considered, corresponding to various ground motion return periods (30, 50, 72, 100, 200, 475, 975, 2475 years). Table 6 and 7. shows the results of the localized (spatial-distribution and limited to one hundreds pre-1971 pilotis building) retrofit intervention at territorial scale in terms of expected losses (in M€) as well as numbers of injuries and victims, for different values of the earthquake probability of exceedence. In the right-end column, results are summarized by using the Expected Annual Losses parameter. A full SBCA would be obtained by combining the “annualized” benefits,.i.e. difference between the EAL prior and after retrofit, with the costs of retrofit.

**Table 6 – Expected Losses prior and after retrofit, for different earthquake probability of exceedence**

| LOSSES (M€) | $2\%/50_{yr}$ | $5\%/50_{yr}$ | $10\%/50_{yr}$ | $22\%/50_{yr}$ | $39\%/50_{yr}$ | $50\%/50_{yr}$ | $63\%/50_{yr}$ | $81\%/50_{yr}$ | | EAL(M€) |
|---|---|---|---|---|---|---|---|---|---|---|
| AB | 1200 | 730 | 390 | 16 | 4.8 | 2.2 | 7.1 | 1.1 | | 170 |
| PR | 680 | 380 | 210 | 8.8 | 2.7 | 1.2 | 0.37 | 0.052 | | 9.2 |
| TR | 450 | 260 | 150 | 6.4 | 2.0 | 0.85 | 0.025 | 0.0031 | | 6.5 |

**Table 7 - Expected homeless prior and after retrofit, for different earthquake probability of exceedence**

| HOMELESS (N.) | $2\%/50_{yr}$ | $5\%/50_{yr}$ | $10\%/50_{yr}$ | $22\%/50_{yr}$ | $39\%/50_{yr}$ | $50\%/50_{yr}$ | $63\%/50_{yr}$ | $81\%/50_{yr}$ | | EAH |
|---|---|---|---|---|---|---|---|---|---|---|
| AB | 2304 | 1240 | 494 | 88 | 6 | 1 | 0 | 0 | | 180 |
| PR | 984 | 318 | 72 | 6 | 0 | 0 | 0 | 0 | | 44 |
| TR | 367 | 75 | 11 | 0 | 0 | 0 | 0 | 0 | | 12 |

## 6 CONCLUSIONS

In this contribution, an overview of different mitigation analyses, either based on a single- or multi-criteria approach for the evaluation of the effectiveness of alternative retrofit strategy at territorial scale has been given. Alternative performance-based retrofit strategies based on a partial retrofit approach (i.e. achievement of lower performance level) and targeting a selected typology of buildings within a given region (localized intervention) would appear as more efficient, from a cost-benefit point of view, particularly when considering the limited amount of funds, materials and in general resources. Valuable confirmation have been provided by the results of a virtual retrofit implementation and mitigation analyses on a case study region.

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