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Reduce or transfer?
A framework for combined optimal seismic retrofit and insurance

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ABSTRACT

Structural retrofit (risk reduction) and insurance (risk transfer) can be used to increase an asset's earthquake resilience. This paper describes a framework to select the optimal combination of seismic retrofit and insurance for buildings. A user can choose a suitable retrofit strategy and the technique(s) for its implementation. This is designed "incrementally" to define interventions with increasing "amounts of retrofit": for example, the addition of an external wall with different stiffness/strength or the column jacketing at specific storeys. The cost of each intervention is calculated, along with the downtime-related costs due to the retrofit work. For each intervention, vulnerability curves are calculated based on pushover analysis combined with the Capacity Spectrum Method. Insurance solutions with different pay out algorithms and annual premiums are considered. For each retrofit/insurance combination, the net present value of the insured and uninsured economic losses within a given time horizon is estimated. The optimal retrofit/insurance combination is the one maximising the Tail Value at Risk of the retrofit/insurance lifecycle cost. This metric depends on the risk-aversion of the householder, which is an input for the algorithm. The framework is demonstrated for an Italian existing RC frame building retrofitted with concrete jacketing, also considering the Italian retrofit incentive ("Sismabonus").

Introduction

In earthquake-prone areas, existing structures (especially those designed considering gravity loads only) are often incapable of sustaining severe earthquake-induced structural/non-structural demands. After significant earthquake events, this may likely result in many casualties and vast economic losses (both direct and indirect). Generally, seismic risk mitigation can be achieved, for instance, by either implementing structural retrofit strategies that reduce the physical seismic vulnerability/expected damage of buildings (hard solutions) and/or by transferring the risk to the (re)insurance market (soft solutions).

There are ongoing debates about requiring/encouraging homeowners to undertake risk-mitigation or risk-transfer actions. In New Zealand, based on the outcome of a seismic rating [1], homeowners may be required to implement seismic retrofit within a given timeframe [2]. Moreover, earthquake insurance is effectively mandatory since it is connected to any given property's fire insurance [3]. California's seismic ordinances (seismicordinances.com) require the evaluation and mandatory (partial) retrofit of vulnerable building types (e.g. unreinforced masonry buildings, soft-storey-prone wood and concrete buildings). Within the Turkey Catastrophe Insurance Pool [3], the government and 24 insurance companies regulate compulsory earthquake insurance in Turkey. In Italy, seismic retrofit has been recently highly incentivised with the "Sismabonus" program [4]: a homeowner receives 110%

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of the retrofit cost (up to 96,000€ per apartment unit) in the form of tax rebates over the subsequent five financial years.

Regardless of any risk-mitigation policy/strategy, a rational framework is needed to identify the appropriate retrofit and/or insurance solutions. Many literature studies provide means to select the optimal retrofit solution among a set of alternatives, and they can be based on cost-benefit analysis [5–7], simplified probabilistic approaches [8,9], multi-criteria methods [10–12]. Although many studies involve risk-based lifecycle assessment [13–17], those normally assume a risk-neutral approach of the decision maker, and this is unsuitable if insurance is involved. On the other hand, fewer studies involve seismic risk transfer (e.g. [18]). Significantly fewer consider combined retrofit and insurance (e.g. [19]), although those do not explicitly consider the "level" of retrofit and amount of insurance coverage as variables.

This paper summarizes a recently proposed framework [20] for the optimal combined retrofit and insurance of buildings, including the risk aversion of the decision maker within a lifecycle approach. The framework is herein described and applied to a typical Italian reinforced concrete (RC) frame building. Seven retrofit solutions based on concrete jacketing are considered together with 30 insurance alternatives. Conclusions are finally drawn.

Methodology

The framework is summarised in Figure 1 while the relevant details are provided in [20]. The starting point (step 0) is an existing building in its as-built condition. The steps of the procedure can be summarised as follows:

1. Analyse the seismic response of the as-built structure. Since the framework aims at the preliminary/conceptual (retrofit) design phase, the seismic response analysis is based on a numerical pushover (or the simple lateral mechanism analysis, SLaMA [1,21–26]) combined with the capacity spectrum method (CSM [27]). Using several natural records, the CSM is used to derive the engineering demand parameter (EDP; e.g. inter-storey drift) vs earthquake-induced ground-motion intensity measure (IM; e.g. spectral acceleration at the building's fundamental period of vibration) space. This is defined as the cloud-CSM [28];
2. Select a suitable retrofit strategy and the associated technique(s) for its implementation. The retrofit strategy is implemented incrementally to define interventions with increasing retrofit levels: for example, the addition of external walls with different stiffness/strength characteristics or different levels of column jacketing. Arguably, this process does not increase the level of effort with respect to a traditional retrofit design, which always involves a trial-and-error component; an intelligent selection of retrofit "trials" can be used to define the incremental retrofit interventions. The level of retrofit of each alternative is quantified through the Capacity-Demand Ratio of the building calculated for the Life Safety (LS) damage state (CDR_{LS}). Such safety index is the ratio of the displacement capacity of the building (related to LS) compared to the code-based demand for a similar new one, calculated using the CSM for the LS code-based spectrum. Therefore, solutions with $CDR_{LS} \geq 1$ comply with the code provision for the LS damage state. Each retrofit alternative is evaluated as per step 1;
3. For the retrofitted and as-built cases, derive building-level fragility curves (probability that the specified structure will reach or exceed predefined damage states (DSs) as a function of a ground motion IM);
4. Retrieve the seismic hazard curve for a given site (in terms of mean annual frequency of exceedance, MAFE, of different IM levels). This can be calculated via an ad-hoc hazard analysis, or it can resort to available models;
5. Define insurance alternatives with pay-out functions (Eq. 1) characterised by different combinations of deductible and coverage. The deductible D, generally specified as a ratio of the total insured value, is the maximum loss value corresponding to a zero pay-out. The coverage C is the loss value beyond which the insurance pay-out is constant, defined as a percentage of the total insured value. Associate a yearly premium p_I to each alternative;

$$PO = \begin{cases} 0 & L < D \\ L - D & D \leq L \leq C \\ C - D & L > C \end{cases} \tag{1}$$

6. Calculate the probabilistic distribution of the net present value of the insured (IL) and uninsured (UL) economic losses for each combination of retrofit and insurance. By considering a financial discount rate r, the distribution of the net present value of the aggregate uninsured losses over the building service life (occurred at times τ_i) is calculated. The step-by-step mathematical formulation for this step is provided in [20] while the code implementation is freely available at https://github.com/robgen/distNPVaggregateLosses;
7. Calculate the Life Cycle Cost (LCC, Eq. 2) performing a discounted cash flow analysis considering the remaining cash flows in the building service life, such as the retrofit cost C_R, any available retrofit incentive I_R, and the cost of renting another property during the retrofit implementation (move-out cost C_M) and the insurance premium;

$$LCC = C_R - I_R + \frac{C_M}{1+r} + \sum_{t=1}^{T_H} \frac{p_I}{(1+r)^t} + \sum_{i=1}^{N_{ev}} UL_i \frac{1}{(1+r)^{\tau_i}} \qquad (2)$$

8. Define the optimal risk-mitigation solution by minimising the tail value at risk of the LCC. $TVaR_\alpha(LCC)$ is the expected value of LCC, given that LCC is greater than the value at risk VaR_α (whose probability of being exceeded is α). This last parameter, an input of the framework, allows considering the decision maker's level of risk-aversion in a simple-yet-effective way.

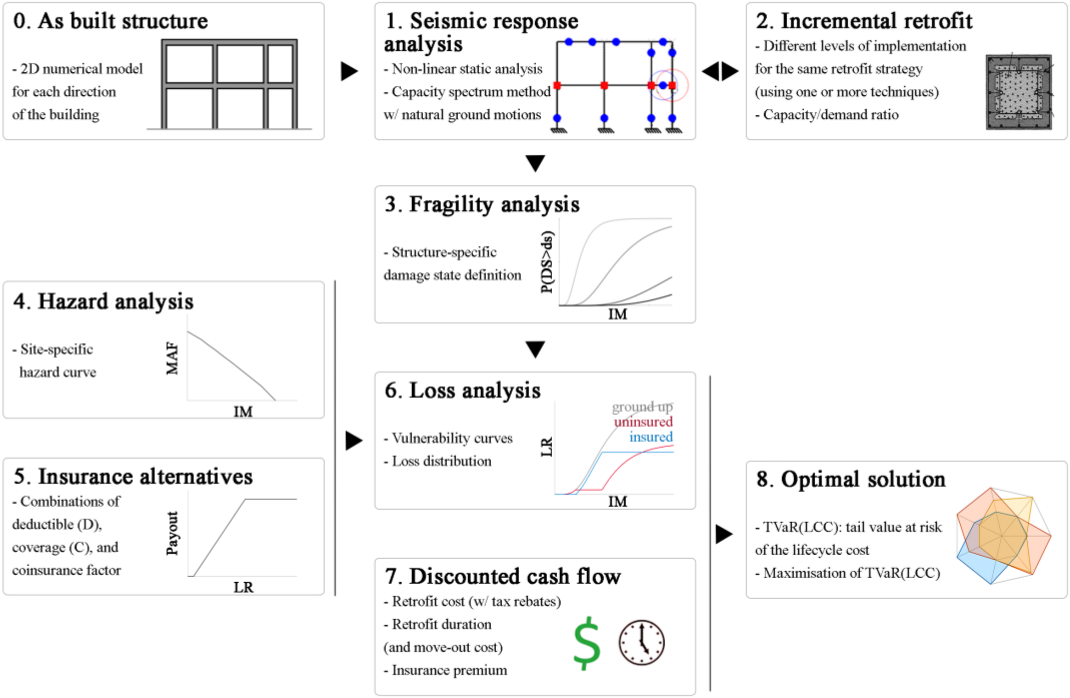

Figure 1. Combined optimal retrofit and insurance framework (modified after [20]).

Illustrative application

This section gives a short overview of a practical application of the framework to an RC building (described in extensive details in [20]). The case-study site is L'Aquila, a high-seismicity city in central Italy, for which it is possible to retrieve the code-based hazard curve [29] and the response spectrum [30] consistent with the life-safety DS (useful to define CDR_{LS}). Such models are directly adopted, thus no *ad hoc* hazard analysis is carried out.

The case study structure is a 1970s three-storey RC building with rectangular plan geometry and composed of three parallel frames. Structural details of beams, columns and beam-column joints are consistent with a gravity-only design and no capacity-design provision. It shows a plastic mechanism mainly involving the first storey columns and beam-column joints. This approximately corresponds to 0.2g peak spectral acceleration capacity (Figure 2a), considering an effective mass equal to 90% of the total building mass.

The main retrofit approach is to improve the plastic mechanism of the structure. This is applied incrementally using concrete column jacketing as the selected retrofit technique. This results in seven retrofit solutions with

CDR_{LS} ranging between 0.59 and 2.73: the i1, i2, i3 solutions involve jacketing only for the interior columns (respectively up to the first, second and third storey), while for the solutions ie1, ie2, ie3 jacketing is applied also to the exterior columns. The solution ie3+ is an improved version of ie3 involving jackets with higher capacity.

The implementation cost of each retrofit solution is calculated considering the demolition of the structural/non-structural components to access the jacketed columns, the installation of the intervention itself, and the demolished parts' reconstruction. The "Sismabonus" retrofit incentive is equal to the reconstruction cost, up to 96,000€. The move-out cost is also calculated by assuming a monthly rent price equal to 620€ (average price for a 100 m2-apartment in L'Aquila). Seven insurance alternatives are considered in this simplified example: they correspond to a deductible equal to zero and coverage seven levels of coverage ($C = 0, 0.05, 0.1, 0.2, 0.3, 0.4, 0.5$ of the reconstruction cost). The insurance premium is assumed equal to $p_I = 1.25EAL_I$, where EAL_I is the insured portion of the building expected annual loss and the factor 1.25 allows accounting for the transaction costs of the insurer and the risk premium (loss uncertainty).

Fragility functions are derived adopting four DSs defined according to HAZUS (hazard united states, [31]) and the damage-to-loss model proposed by Martins et al. [32]. The building nominal service life is assumed equal to 50 years, while the assumed discount rate for the discounted cash flow analysis is 2.0%.

Figure 2b shows the mapping of $TVaR_\alpha(LCC)$ for a risk-averse decision maker (with $\alpha = 75\%$). Under the adopted assumptions, the optimal resilience-enhancing solution involves the i2 retrofit with insurance with zero deductible and $C = 0.5$. Due to Sismabonus, the "effective" cost of the intervention (the difference between the retrofit cost and the incentive) is zero for interventions costing up to 96,000€. Therefore, the optimal retrofit is the one maximizing the retrofit intervention. On the other hand, the optimal insurance coverage depends on the level of risk aversion. Therefore, a detailed calibration of α based on utility theory is fundamental.

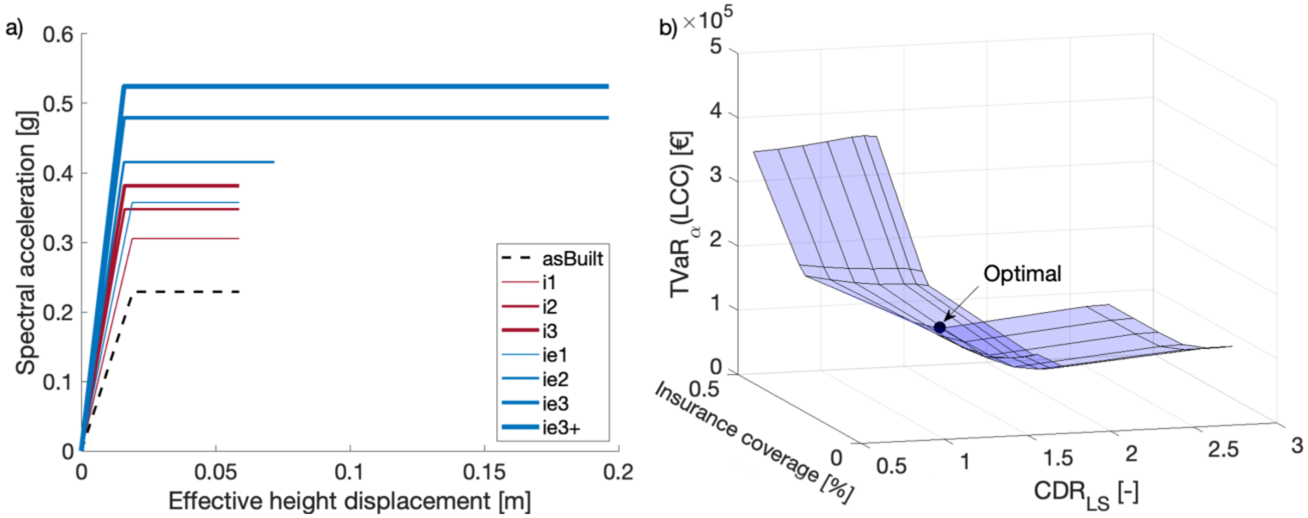

Figure 2. a) SLaMA-based force-displacement (pushover) curves for the incremental retrofit solutions; b) $TVaR_\alpha(LCC)$ mapping for a risk-averse ($\alpha = 75\%$) decision maker, considering zero deductible. Modified after [20].

Conclusions

This paper described a framework to select the optimal combination of seismic risk reduction (through retrofit) and risk transfer (via insurance) for buildings. The optimal solution involves the specific structural performance increase (retrofit) and the amount of insurance coverage that, combined, minimize the tail value at risk of the risk-based lifecycle cost. Such metric allows to explicitly account for the risk aversion of the decision maker. The results showed that the framework is successful in providing a rational way to identify the optimal combined retrofit and insurance combination. The framework involves adopting an intelligent selection of the trial structural designs normally produced within a retrofit project, and it involves simplified methods to analyze them (i.e. pushover analyses). Therefore, framework does not increase -at least in principle- the level of computational effort generally involved in a retrofit projects within the engineering practice.

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