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Short communication

A multi-criteria approach for selecting the seismic retrofit intervention for an existing structure accounting for expected losses and tax incentives in Italy

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ABSTRACT

A multi-criteria decision tool to evaluate alternative seismic retrofit solutions for under-designed reinforced concrete (RC) structures is proposed herein. Besides structural performance, other criteria are evidently involved in such a choice, which deals with social and economic issues. In Italy, a recent law established significant tax incentives for those owners who decide to invest money for improving the structural safety of their buildings, with particular regard to earthquake resistance. The benefit is based on the classification of seismic risk of the construction prior to and after the intervention. It allows owners to recover up to 85% of the total expenses for retrofit, depending on the degree of improvement in the seismic classification as a result of the intervention. The seismic class is related to the expected annual losses, and it considers the most probable damages and repairing costs of structural and non-structural elements that are related to earthquakes and may occur during the economic life of the structure.

This Italian legislative novelty is expected to make owners reconsider the convenience of performing seismic upgrade interventions. It will also influence the comparison of alternative interventions, as initial costs may play a secondary role in relation to what has been usual in the past.

A framework for decision making on seismic retrofit is proposed. Its application to an RC-frame building, assumed as case study, is presented. Four different retrofit strategies (confinement of columns by glass fibre reinforced polymers, steel bracing, concrete jacketing of columns, and base isolation) are compared according to a set of criteria, including fiscal benefits. The discussion of the results highlights the main impact that the deductibility of intervention costs has on the decisions by owners.

1. Introduction

When one wonders what the best technical solution to seismically upgrade an existing structure is, the correct answer can only be: it depends. It depends not only on the type of structure and its deficiencies, but also on other factors such as the economic capability of the owner and his/her availability of time (interruption in use). Indeed, the number of factors depends on the specific case (for instance, in the case of monumental works or buildings with special destinations).

The authors investigate herein the possibility of supporting those who have to upgrade an existing structure (i.e., who have to decide on how to make it) in selecting the more suitable retrofit strategy for the specific case.

The criteria and alternative techniques available [1,2] generally do not allow a decision maker (DM) to make a rational choice, which should simultaneously take into account all the different variables involved. Thus, assistance for a careful selection of a retrofit technique is crucial, especially when the structure plays an important role from a socioeconomic point of view. To this aim, multi-criteria decision making (MCDM) methods can support the decision maker.

In the past, the authors have dealt with this topic, generating a multi-criteria procedure to support this type of decision [3] by comparing different approaches [5].

In Italy, a recent law (the so called 'Stability Law 2017', [17]) established significant tax incentives for the owners involved in projects that improve the seismic structural safety of buildings. It allows the owners to gain up to 85% of the total expenses for retrofit, depending on the degree of improvement the intervention obtains. The so-called

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'seismic class' of risk is related to the expected annual losses (EAL) and takes into consideration the most probable damages and repairing costs of structural and non-structural elements that are related to earthquakes and may occur during the economic life of a structure [19]. Evaluating the seismic class of risk prior to and after the intervention enables to compute the exact amount of tax deduction to which the owner is entitled.

In the last decades, the occurrence of destructive earthquakes and the consequent high repairing costs have attracted considerable attention from researchers and communities on the probabilistic loss assessment issue. The main scope of the loss estimation analysis is that of evaluating the several loss parameters involved, which could be direct (repair and/or reconstruction costs) or indirect (injuries, casualties, and downtime). The rigorous evaluation consists in the resolution of the well-known Pacific Earthquake Engineering Research Center (PEER) equation [7], which provides the mean annual frequency of the losses, indicated as damage variables (Dv). It is also called the multi-level integral because it is based on the knowledge of the probabilistic distribution of damages or damage measure (Dm), of the seismic structural demand expressed through the engineering demand parameters (EDPs), and of the seismic action estimated by the intensity measure (IM).

Owing to the complexity of loss assessments, many simplified approaches have been proposed in the literature. Welch et al. [31–33] suggested a simplified loss estimation procedure for existing structures based on a direct displacement-based assessment (DDBA), allowing a prompt evaluation of the deformation demands in correspondence with different performance levels [28]. The methodology aims to evaluate the EAL through the definition of the mean damage factor (MDF) in correspondence with different limit states, which are zero loss, operational, damage control, and near collapse. The bounding limit states are assumed to determine the 0 and 1 MDF values, respectively. The MDF values corresponding to the two intermediate limit states are evaluated through the EDP-DV functions proposed by Ramirez and Miranda [23], once the EDPs have been estimated as an output of the DDBA procedure.

Calvi [4] presented a comparative study of different strengthening strategies of an existing building, through an analysis of a cost-benefit parameter consisting in the ratio of the EAL variation after the intervention to its installation cost. Although it is an original research, which suggests grading a buildings' seismic performance or resilience through the definition of loss parameters, many simplifications and arbitrary assumptions about the EDP-Dm and Dm-DV functions have been employed, making the study a rather qualitative and conceptual application. An interesting performance-based assessment study has been conducted by Contini et al. [6] and Negro and Mola [22], which analyse the results of a non-ductile, seismically under-designed building pseudo-dynamically tested in three configurations: as-built, retrofitted by means of FRP wrapping, and reinforced concrete (RC) jacketing. The authors implemented a simplified loss assessment framework based on the application of the total probability theorem, associating the peak ground acceleration to the maximum interstorey drifts observed in the tests, selecting several limit states, and assigning to each of them a repair cost on the basis of engineering practice. The choice of the most convenient retrofitting solution was suggested in these works on the basis of a cost-benefit study, comparing the total loss and investment cost. The specific case study yielded a not justifiable economic expense for none of the strengthening interventions, even considering that the losses induced by the casualties and contents damage were neglected. In order to provide a further comparative parameter, Dattilo et al. [10] determined the environmental impact costs of various retrofitting strategies for the same benchmark structure. In particular, through a life cycle assessment analysis, the authors evaluated the CO_2 emissions for each structural configuration, then converted them to monetary terms, and finally added the results to previous loss costs and ranked the different solutions.

The abovementioned legislative novelty introduced for the first time in Italy the concept of 'seismic class' of a building as a function of the EAL and proposed a simplified procedure for such estimation of losses. It is expected to drastically change the way of judging the convenience of performing seismic upgrade interventions and of comparing alternative interventions because, in relation to the practice in the past, the initial costs may play a secondary role. The decision making procedure to assist the selection of the retrofit technique has to take into account this innovation. Therefore, it has to be revised with respect to the past. This is the attempt made in this study, where the initial cost to install the intervention is still included among the set of criteria, but this time together with the amount of state-reimbursed expenditure and the reduction in expected losses, which are also considered for the choice.

An illustrative application to a RC frame building, assumed as a case study, is presented. Four different retrofit strategies, each of them oriented to achieve different structural goals, are evaluated and compared using the above procedure. They involve the confinement of columns by glass fibre reinforced polymer (GFRP), steel bracing, concrete jacketing of columns, and base isolation, respectively. The discussion of the results highlights the main impact that the deductibility of the intervention costs has on the decision by owners.

2. Guidelines for evaluating tax incentives for seismic retrofit interventions

The aforementioned guidelines have been written by the Italian Ministry of Infrastructure and Transport [19] and represent the technical tool for the implementation of the tax reimbursement rules defined in the Italian 'Stability Law 2017' [17]. This document proposes a conventional method to evaluate the seismic class of a given structure. It involves two parameters:

- The EAL, evaluated according to Welch et al. [32,31], i.e., the economic losses owing to the possible damage to structural and non-structural elements expressed in terms of percentage of the reconstruction cost.
- The ratio between capacity and demand of the building in terms of peak ground acceleration (PGA) for the life safety (LS) limit state; this value is referred to as IS-V in the guidelines.

To determine these parameters, the following steps have to be done.

I. *Seismic demand*

The different levels of seismic demand, in terms of PGA (PGA_D, where 'D' stands for 'demand') and return period $T_{R,D}$, have to be evaluated. Such information, related to the four limit states of collapse prevention (CP), LS, damage limitation (DL), and immediate occupancy (IO), depends on the type of building, class of use, geographic location, and type of subsoil, according to the Italian technical standards for construction [20]. Further details about modelling of the above four levels of seismic demand parameters can be found in Iervolino et al. [15,16].

II. *Seismic capacity*

A structural analysis of the building has to be performed to evaluate the PGA capacity value for each limit state (PGA_C). In the absence of more specific analyses, the return period related to capacity, $T_{R,C}$, can be directly derived from the following relation:

$$T_{R,C} = T_{R,D}\left(\frac{PGA_C}{PGA_D}\right)^{\eta} \tag{1}$$

where η can be assumed equal to 1/0.49 (for the expected demand value of PGA on rock, $a_g > 0.25\,g$), or 1/0.43 (for $0.25\,g \geq a_g > 0.15\,g$), or 1/0.356 (for $0.15\,g \geq a_g > 0.05\,g$), or 1/