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COMBINED SEISMIC PLUS ENERGY RETROFITTING FOR THE EXISTING RC BUILDINGS: ECONOMIC FEASIBILITY

Monica MASTROBERTI[1], Dionysios BOURNAS[2], Marco VONA[3], Benedetto MANGANELLI[4], Valentina PALERMO[5]

ABSTRACT

The vast majority of the existing European building stock has been built without modern provisions for earthquake resistance and energy efficiency, resulting in seismic vulnerable and low energy performance buildings. Although many studies to address both these needs exist, energy and seismic retrofitting are nowadays treated separately. In this study, a combined seismic and energy retrofitting approach is adopted. Retrofitting strategies for existing RC buildings, combining seismic and energy features are investigated and compared. For what concerns seismic retrofitting, two different seismic retrofitting techniques for RC-moment resisting frames, namely addition of RC Walls and TRM Jacketing). The economic benefit deriving from their implementation has been evaluated using a probabilistic vulnerability building based approach (based on fragility curves and mean repair costs). Moreover, a simplified method for fragility curves in retrofitted state has been proposed. For what concerns energy retrofitting, an attempt was made to evaluate the energy performance and cost improvements of buildings receiving various thermal insulation materials (i.e. *EPS*, *XPS*, *PUR*) to their building envelopes, following a simplified procedure in line with the requirements of the Italian regulation. To evaluate the economic feasibility of an integrated seismic plus energy retrofitting approach, this paper proposed an expected annual loss (EAL) parameter combining both the economic benefits related to reduction of the seismic risk and energy losses. It was found that a number of retrofitting techniques were effective and economically feasible, with the combination of advanced textile composites (i.e. TRM) and thermal insulations materials (i.e. EPS) being the most effective scheme, than the combination based on more localized seismic interventions. Overall, this study demonstrates that the concurrent energy and seismic retrofitting using advanced materials is a quite promising alternative approach for upgrading the existing RC buildings in seismic EU regions.

Keywords: Existing RC buildings; Integrated Retrofitting Approach, Feasibility Analysis.

1. INTRODUCTION

The European existing building stock is deficient both in terms of seismic resilience and energy efficiency. Both the existing buildings energy and seismic performance are responsible of high economic losses resulting from high operational energy consumption and from wide post-earthquake reparation interventions (Belleri and Marini, 2016). Seismic and the energy retrofitting interventions could lead to an economic return at public and local level. The seismic one results in savings from expenditures for future reconstruction for public administration and the owners. On the other hand, the energy efficiency interventions provide the opportunity to have a financial return as a result of lower expenditures for warming or cooling private or public buildings, providing at the same time social and environmental benefits. The evaluation of the economic feasibility of an integrated seismic and energy intervention is a fundamental parameter in the decisional phase both at public and private level.

[1]PhD Student, University of Basilicata, Potenza, Italy, monica.mastroberti@unibas.it
[2]Scientific Officer, European Commission, Joint Research Centre (JRC), Directorate for Space, Security and Migration, Safety and Security of Buildings Unit, Ispra (VA), Italy, Dionysios.BOURNAS@ec.europa.eu
[3]Professor, University of Basilicata, Potenza, Italy, marco.vona@unibas.it
[4]Professor, University of Basilicata, Potenza, Italy, benedetto.manganelli@unibas.it
[5]Scientific Officer, European Commission, Joint Research Centre (JRC Directorate for Energy, Transport and Climate, Energy Efficiency and Renewables Unit, Ispra (VA), Italy, Valentina.PALERMO1@ec.europa.eu

The studies on the combined seismic and energy retrofitting are very limited. Triantafillou et al. 2017 proposed a system combining polymer-coated glass-fibre textile with expanding polystyrene (EPS) for the structural and energy retrofitting of masonry walls. Bournas 2018 proposed similar systems for the concurrent seismic and energy retrofitting for the case of RC building envelopes. In this study, a new approach in quantifying the economic feasibility of an integrated seismic and energy retrofitting intervention is proposed. It is based on a preliminary assessment of the seismic and energy performance of buildings, both in their initial and retrofitted states. The approach is based on a new and simplified procedure for the assessment of the seismic economic performance of "retrofitted" buildings. Based on this novel approach, the economic effectiveness of different integrated (energy plus seismic) solutions have been studied on selected existing building typologies.

Seismic interventions able to provide unitary seismic vulnerability index for life safety performance level and energy ones that reduce the energy consumption of respectively 60%, have been considered. Finally, the economic feasibility has been also studied according to the geographical location of the type, as characterized by specific seismic and climatic parameters.

2. METHODOLOGY FOR ECONOMIC FEASIBILITY OF INTEGRATED SEISMIC AND ENERGY RETROFITTING

From an economic point of view, evaluating the potential financial benefits for such an integrated approach, the net present value (NPV) of the energy and seismic benefit provided throughout the building residual service life plays a fundamental role (Calvi. 2013). The expression of the NPV of an integrated retrofitting is expressed by Eq. 1:

$$NPV = \sum_{t=1}^{Vr,E} \frac{(\Delta \mathrm{EAL}_E)}{(1+r)^t} + \sum_{t=1}^{Vr,S} \frac{(\Delta \mathrm{EAL}_S)}{(1+r)^t} \tag{1}$$

In definition of the NPV to a given year (t), the reduction in the expected annual losses (ΔEAL_S seismic and ΔEAL_E energy) is normalized than $(1+r)^t$, where r is the interest rate. The latter measures allow to take into account the amount to pay if the capital was borrowed from others or the rate of return of the investment (Calvi, 2013). Integrated retrofitting techniques with progressively higher NPV values are the most convenient retrofit strategies to be adopted. Another effective financial indicator for the comparison is the internal Rate of Returns (IRR) (Main MA, 2002 and Manganelli B., 2013). The latter is the discount rate r that makes the NPV of all cash flows associated to a given project equal to zero. The higher IRR values make more convenient the project. Finally, the time at which the return of initial investment will be achieved could be considered as further economic feasibility parameter. The payback time is the number of years after which the cost of the integrated solution can be deemed to be fully amortized by the benefit due to total EAL reduction. In this way, an integrated retrofitting solution is economic effective if the pay-back time is lower than the residual life of the building after retrofitting, or of a reasonable investment return time (that in this study is seated equal to 25 years).

In this study, the research of the most financial effective integrated solutions have evaluated according to an index based on the comparison between the payback time and the acceptable investment return time (25 years). The economic feasibility established through an index could be useful for decisional phase, and in prioritization retrofitting ranking list definition. The expression for the proposed economic feasibility index (for integrated retrofit interventions) is given by Eq. 2:

$$EFI = 1 - \frac{Pay\ Back\ Time_{S+E}}{Residual\ life_{after\ S+E}} \tag{2}$$

It measures the feasibility comparing the number of years after which the cost of the intervention can be deemed to be fully amortized by the benefit of the investment and a maximum time acceptable. According to Eq. 2, if the payback time of the intervention is lower than the reasonable investment return time, then the investment can be considered economic feasible (its return time is acceptable). In this case, the economic feasibility index is in the range 0-1. EFI values close to one are typical of investments that return immediately, whereas values close to 0 demonstrate low or no-economic feasible investment. For the economic feasibility analysis, the assessment of the economic consequences from the performance of the as-built and retrofitted buildings are of crucial importance. Methodologies able to transform the seismic and energy performance in cost should be implemented. The economic losses consequence of the seismic vulnerability and of the implementation of the seismic retrofitting interventions may be evaluated according to different approaches (i.e. D'Ayala D. et al. 2013).

In this study, a vulnerability building based approach is proposed. It is based on convolution between fragility curves and mean repair costs. The main output are the vulnerability curve and the value of the expected annual loss, that provide respectively information of the expected losses given a seismic intensity, and of the value of potential amount to pay every year to repair the building damage accounting for the all possible earthquake at the site of interest and in the time of reference.

The economic consequence of the energy performance has been evaluated according to a deterministic procedure based on the Europe code (UNI-TS 11300 (a) and (b)) standard and the actual Italian cost of energy vectors. Moreover, in the energy performance evaluation, only the heating has been considered as the major energy use in buildings.

2.1 Seismic and Energy performance evaluation

In this study, a novel multi-step approach was proposed, enabling to evaluate the seismic and energy performance of building typologies (both in the as-built retrofitted states) and allowing in transforming those performances into cost. The flowchart in Fig. 1 summarizes the approach.

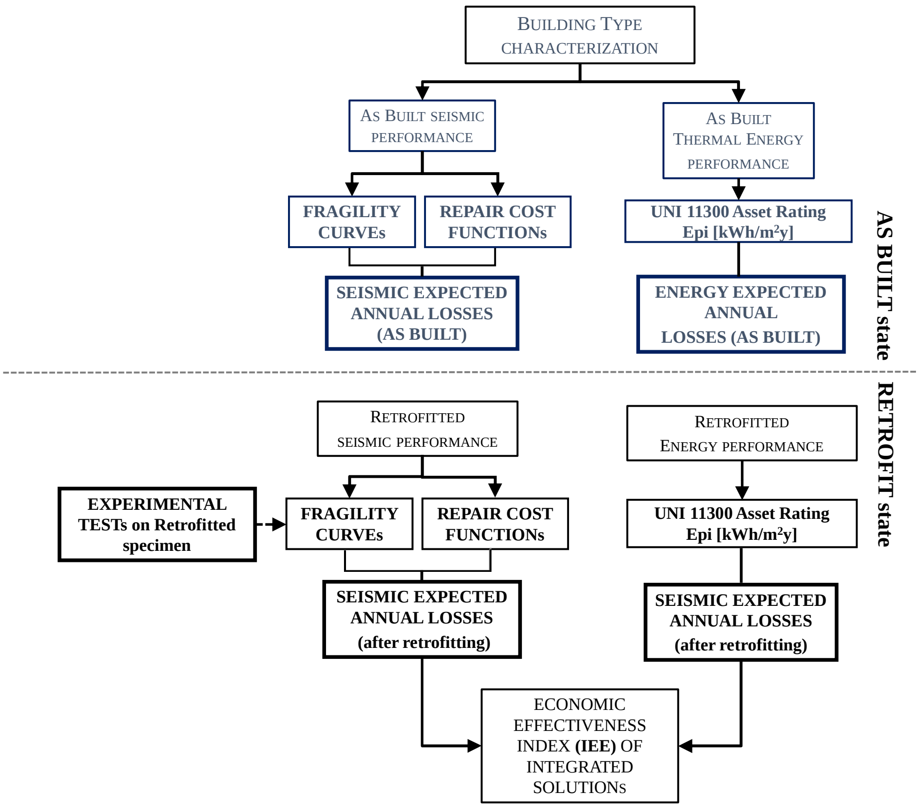

Figure 1. Flowchart of the proposed approach.

The fundamental output of the above methodology is the values of the Expected Annual Loss for seismic and energy performance, both in as-built and retrofitted states.

2.1.1 Seismic performance and losses evaluation

The seismic Expected Annual Loss (*EAL_S*) is the potential amount to pay every year to repair the building damage due to the earthquakes that may hit an area during the residual life of the building. It is a useful parameter in measuring the economic losses deriving from the seismic building vulnerability, and accounting for the site hazard. According to the building – based vulnerability assessment approach, the seismic Expected Annual Loss is obtained by relating the vulnerability curve and the hazard one. Different methodologies exist for vulnerability curves evaluation; namely more or less simplified, deterministic or probabilistic, based on a component approach or building one. In this study, a vulnerability building based approach is used, that transform the fragility curves into vulnerability one through the following total probability relation (Eq. 3):

$$\mathrm{E}[\mathrm{C}_{r,r} \mid \mathrm{I}] = \sum_{i=1}^{n} \mathrm{E}[\mathrm{C}_{r,r} \mid \mathrm{d}_{l,i|\mathrm{I}}]\mathrm{P}[\mathrm{d}_l = \mathrm{d}_{l,i} \mid \mathrm{I}] \quad (3)$$

Where $\mathrm{P}[\mathrm{d}_l = \mathrm{d}_{l,i} \mid \mathrm{I}]$ are the fragility curves that allow the probabilistic quantification of seismic vulnerability on a wide seismic intensity scenario, in terms of occurrence probabilities of damage levels to vary the seismic intensity. On the other hand, $\mathrm{E}[\mathrm{C}_{r,r} \mid \mathrm{d}_{l,i|\mathrm{I}}]$ are the repair cost functions that quantify the economic consequence (repair cost) to repair the damage levels at a specific seismic intensity range. Different approaches exist for fragility curves and repair cost functions definition: analytical, empirical, based on expert judgment and so on (Yamin et al, 2017). The procedure employed in this study is based on analytical fragility curves and repair cost functions. More details are reported in Mastroberti el at. 2017.

Then, alternative tools for defining fragility curves and repair cost functions are needed, particularly for preliminary considerations. In this work, a simplified procedure is proposed in defining fragility curves and repair cost functions for retrofitted buildings. The basic concept of the simplified procedure is that the retrofitting provides an increment in seismic intensity of achievement of same damage states that instead in as-built condition are achieved earlier; such as the fragility curves of a building in retrofitted state move forward toward high seismic intensity level, as shown in Fig. 2.

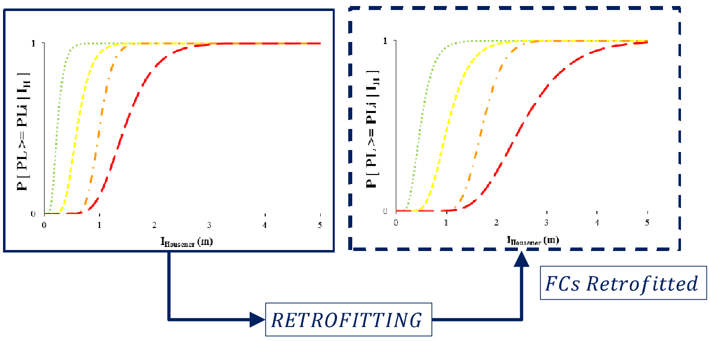

Figure 2: Comparison between the fragility curves in as-built and retrofitted state.

An experimental based methodology to calibrate the mean value of the fragility curves in retrofitted state, starting from the as-built ones is proposed in this study. The mean value of the fragility curves in retrofitted state is established equal to the original one multiplied with a modification factor $MF_{\mu|DLi}$ ($\mu_{retrofitted|DLi} = \mu_{as\text{-}built|DLi}$ x $MF_{\mu|DLi}$). The modification factors may be calibrated using the results of past experimental activities on prototypes, similar to the building under examination, both in as-built and retrofitted state, which are used as benchmark. The first and fundamental step of this simplified procedure consists in the selection of experimental tests on nearly full-scale prototypes both in as – built configuration and in retrofitting one, whose mechanical, geometrical and structural characteristics, damage mechanism are similar than those of real existing building or type under exam. According to the progressive damage observed during the tests and the recorded results, both on the un-retrofitted and retrofitted specimen, different damage states are identify and characterize in terms of seismic response parameter, and corresponding value of the seismic intensity parameter (PGA, spectral acceleration, displacement etc.) that mark their achievement. The mean modification factor (for a damage level) is the ratio of the values of the seismic intensity that leads to the achievement of the same damage state, respectively, in as-built and retrofitted condition. In this way, the mean modification factor measures the advantages of the retrofitting in terms of seismic intensity of achievement of a damage level. Finally, the observed damage on the retrofitted specimen could be taken as benchmark in mean estimation of the repair cost required by each damage level after the retrofitting.

2.1.2 Energy performance and losses evaluation

The energy Expected Annual Losses (EAL_E) is the amount to pay every year due to thermal energy demand for indoor space heating. In this paper, only the heating has been considered since it is the main energy use in buildings. The methodology employed for energy performance assessment is developed by Fichera et al. (2016) and consists on a simplification of the procedure of the "Italian guidelines for building energy certification" (DM, 2009) and standard UNI-TS 11300 (a and b) which represents the Italian version of EN ISO 13790 (CEN, 2008). These provide a simplified procedure for existing buildings that allow calculating the energy needs for space heating ($Q_{H,ND}$) with a thermal energy balance and then the indicator of Energy performance (Epi) according to Eqs 4 and 5:

$$Q_{H,ND} = (Q_{H,TR} + Q_{H,VE}) - \eta_{nd}(Q_{SOL} + Q_{END}) \tag{4}$$

$$Epi = \frac{Q_{H,ND}}{S \cdot \eta g} \tag{5}$$

where $Q_{H,TR}$ is the heat loss due to transmission, $Q_{H,VE}$ is the heat loss due to ventilation, Q_{SOL} is the solar heat gain and Q_{END} represents internal heat gains. More details about their evaluation, hypothesis and simplifications for calculus are reported Fichera et al. (2016). Finally, the EPI is the Energy Performance Index, expressed in kWh/m^2y and gives a prompt interpretation of the results and an immediate comparison between the buildings. The parameters at stake in the procedure to gain the thermal energy demand mainly regard climatic data of the location area and building geometrical and thermos-physical properties (Floor space of the building, Surface to Volume Ratio, Orientation, Roof transmittance, Windows transmittance, Thermal bridges and so on.). The final value of the expected annual losses due to energy building performance is calculated by multiplying the building annual energy consumption for the unit energy cost of thermal energy. In retrofitted state the thermos-physical properties are different than the original one, according to the external coating insulating systems, material employed and thickness of insulation panels.

3. CASE STUDIES ON EXISTING RC-MRF BUILDINGS

The earlier presented procedure to assess the seismic and the energy performance and the resulting economic losses have been applied in four existing RC building types with moment resisting frames, most widespread in Italy and in other European countries: low - middle rise bare (2_BF – 4_BF) and infilled frame (2_IF – 4_IF) RC building type designed only for gravity load (PC) /designed with low antiseismic criteria (OC). For further details about the mechanical, geometrical and structural characteristics of the types see previous work of authors (Masi and Vona, 2012, and Vona, 2014).

3.1 Seismic performance of existing RC-MRF typologies

Firstly, the seismic and energy expected annual loss were evaluated in the as- built state. For fragility curves the numerical results derived from Non-Linear Dynamic Analyses of accurate non-linear types models proved under a wide set of recorded earthquakes have been employed. More details about the models and the analyses method can be found in Vona, 2014. The seismic EAL_S values have been evaluated considering the expected values of the repair costs providing by the repair cost functions for the types analysed built in another study of the authors (Mastroberti et al. 2017). The EAL_S values have been evaluated for the four Italian seismic regions and are synthesized in Figure 3.

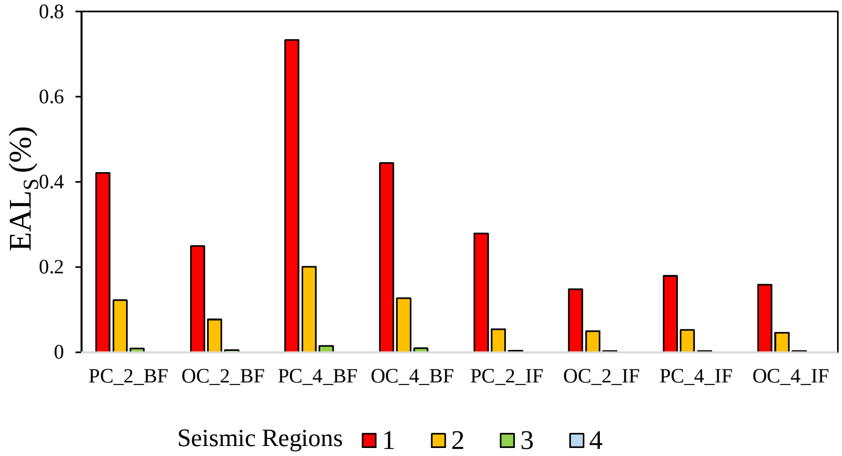

Figure 3: Seismic Expected Annual Losses *(EAL_S)* values for the considered RC-MRF typologies in as-built condition and for the four Italian seismic regions (1-2-3-4)

Each building type has been further analysed in the retrofitted state. The bare frame type has been has been retrofitted through the addition of RC walls, while a novel strengthening material the so-called TRM -textile reinforced mortar (i.e. Bournas et al. 2009) to confine the masonry infills (Koutas et al. 2015). The first conventional retrofitting technique substantially increases the global stiffness and strength of the RC framed building (Furtado et al. 2015). The second is an innovative technique based on advanced textiles impregnated in inorganic matrix, aiming to convert the masonry infills into a more reliable source of resistance over the whole spectrum of structural response. Its effectiveness was demonstrated for RC masonry infilled frames by Koutas et al. 2015. The choice in building types retrofitting technique is linked also to compatibility with the type and the prototype proved in the tests selected.

The seismic performance of the retrofitted buildings have been evaluated based on fragility curves obtained modifying the un-retrofitted ones (analytically defined) by means modification factors for the mean parameter. Proper modification factors for the selected technique are obtained exploiting the results of the experimental tests on RC-MRF specimens both in as–built configuration and in the retrofitting one. The qualitative and quantitative results of the experimental test described in Chrysostomou et al. 2013 (for infilled RC walls), Koutas et al. 2015 (for masonry infills TRM Jacketing) have been considered as reference.

Figure 4: (a) RC-MRF 4 story prototype retrofitting with two infilled RC-wall in transversal direction proved in Elsa lab (Chrysostomou et al. 2013); (b) RC-MRF 3 storey frame of a 2:3 prototype retrofitted with masonry infills TRM Jacketing proved in Patras University Lab (Koutas et al. 2015).

The experimental results of a four-story prototype retrofitted using RC wall infilling and tested at the ELSA laboratory have been exploited (Figure 4a). More details about the specimen, tests and results are reported in (Chrysostomou et al. 2013, Kyriackides et al. 2015). For each of the identified damage states the PGA values was defined. To define modification factors coherent with the built fragility curves for the as-built state, the acceleration values for as-built and retrofitted state were previously transformed in Housner intensity values, based on previous defined relationships I Housner – EMS98 / EMS98 - PGA (Chiauzzi et al, 2013). The resulted mean parameters (for retrofitted state) highlight as two infilled RC-Wall in the building longitudinal direction extended along the total height allow an improvement of 60% in median intensity values of achievement for all damage states. The obtained fragility curves are reported in Figure 5.

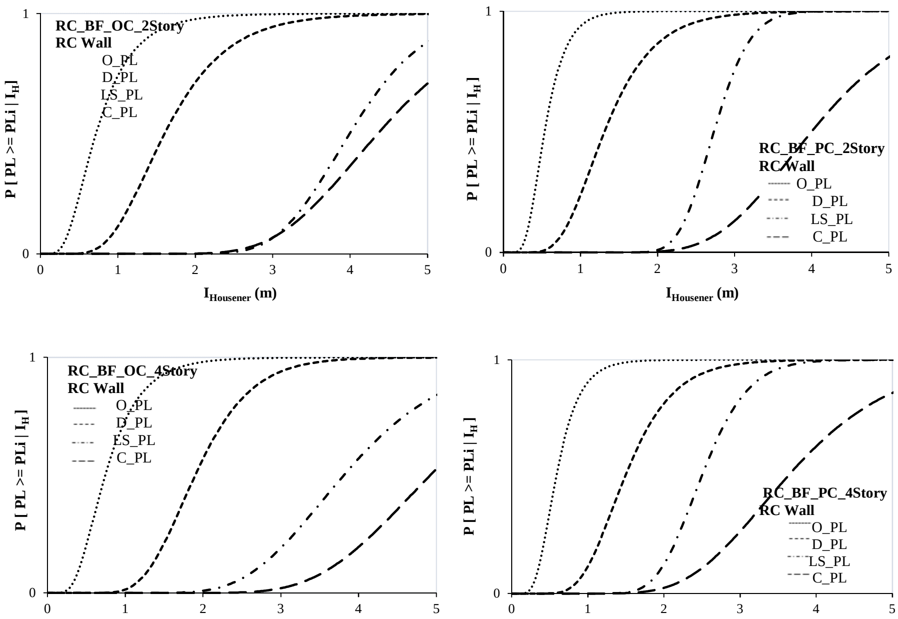

Figure 5: Fragility curves for bare frame RC-MRF typologies after the retrofitting with RC-wall, defined according to the simplified procedure.

To estimate the performance of the masonry infilled RC frames after receiving seismic retrofitting by TRM, the three-story (2:3 scaled) RC frame tested by Koutas et al. (2015) both in as-built and retrofitted configuration has been considered as benchmark structure (Figure 4b). Based on the

evaluated PGA values of achievement of damage states, both in as-built and retrofitted condition, modification factors for infill TRM Jacketing technique have been defined. Since the experimental test was stopped before reaching the structural collapse, the modification factor for collapse damage state is not quantified. Thus, the original collapse fragility curve has been modified based on modification factor of the previous damage state. The modification factors obtained highlight as the TRM jacketing of infills and columns provides an increase of about 40% of median values of seismic intensity of achievement of damage states. The obtained fragility curves are reported in Fig. 6.
Finally, in Fig. 7 are reported the new values of EAL_S after the retrofitting. Although the EAL_S values according to TRM jacketing are higher than those obtained with the RC-wall, they are very low (< of 10% of rebuilt cost).

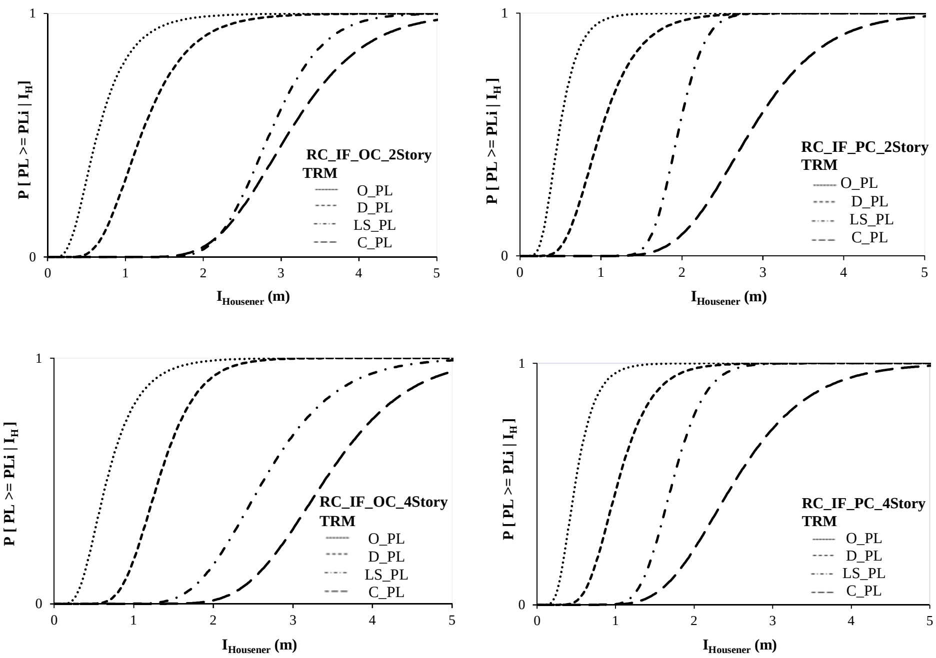

Figure 6: Fragility curves for Infilled frame RC-MRF typologies after the retrofitting with TRM jacketing of infills, defined according to the simplified procedure.

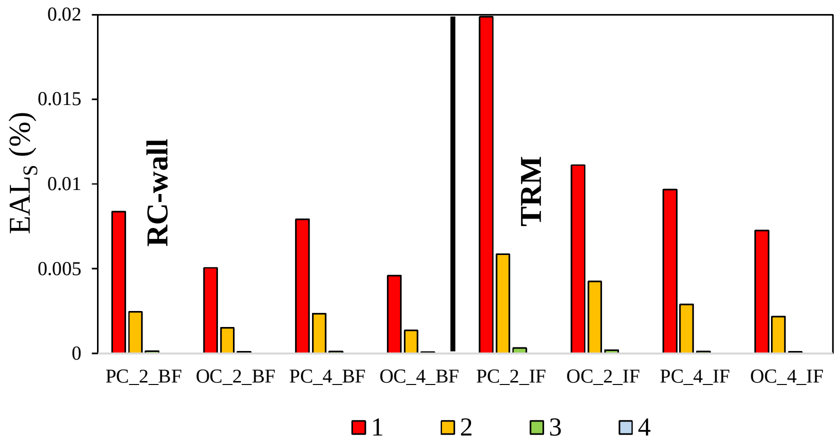

Figure 7: EAL_S values for the considered RC-MRF typologies in retrofitted condition and for the four Italian seismic regions (1-2-3-4).

3.2 Energy performance of existing RC-MRF typologies

The energy assessment of the building types described above has been performed according to the procedure reported in section 2.1.2. In particular, according to the two construction periods identified as PRE code (<1971) and OLD code (≥1971), the characterization of the building envelope has been performed. In this regard, the database of Corrado et al. 2014 has been referred to for choosing the technological system of the building elements and, therefore, for assigning the U-values of transmittance according to climatic zones and building and architecture tradition.
The building energy demand has been measured by means of the degree days of the different Italian climatic zones. The latter have been evaluated as the average value of the degree days of each city that fall into both each climatic category. The assessment of the energy performance has been developed for the two typologies of buildings (two-story and four-story), for the two construction periods (Pre 1971 and Post 1971) and for the six Italian climatic zones (from A to F), resulting in 24 case study buildings. Finally, the energy EAL_E has been evaluated according to the actual energy vector cost. Results of the procedure show that the energy performance index increases with the number of degree days, which implies a higher energy demand in colder areas. Furthermore, it must be highlighted that the geometry characteristics of the buildings have a significant effect in the thermal energy demand: four-story buildings have a smaller Epi than two-story buildings for the same year of construction and location. Results in terms of EAL_E show that buildings built more recently have lower losses, which is all the more true if they belong to warmer climatic zones.
Since the energy consumption of buildings is strongly dependent on the characteristics of the envelope, three materials for the insulation panels applied on the wall-envelope have been considered: Expanded Polystyrene (EPS), Polyurethane (PUR) and the Aerogel panels. The insulation panel's thickness has been evaluated to achieve a 60% reduction of the overall thermal energy consumption of buildings, according to their thermal properties and considering the contribution of thermal break aluminum frame and double-glazed with low emissivity. From the cost-benefit point of view, the concurrent seismic plus energy retrofitting may be considered as an economic investment. As such, it is considered economically viable if the payback time of the integrated solution is lower than a maximum acceptable return time of an investment (for example 25 years).
The first step to assess the economic feasibility of an integrated solution is the payback time evaluation. It is provided imposing the equality between the total benefit of the integrated solution and its total cost. The benefit is the sum of the total prevented seismic losses due to future probable earthquakes during the residual building life after the seismic retrofitting and of the total prevented energy consumption in heating the building along the service life of the energy solution.
The seismic and energy expected annual loss evaluated both in as-built and retrofitted condition for the building types considered have allowed the evaluation of the total benefit of the follow integrated solutions:

- RC WALLs + EPS panels/thermal window (140 €/mq), RC WALLs + PUR panels/thermal window (130 €/mq), RC WALLs + Aerogel panels/thermal window (185 €/mq).
- TRM + EPS panels/thermal window (120 €/mq), TRM + PUR panels/thermal window (110 €/mq), TRM + Aerogel panels/thermal window (165€/mq).

The cost of the RC walls intervention has been evaluated considering that two infill panels along the transversal direction and for all the story are demolished and substituted with RC walls. However, the cost of the second retrofitting technique has been evaluated considering that TRM jacketing is applied to all corner infills (but not the middle ones), of the first and second floor for the low-rise type, and of the first three floors for the middle rise type. In both cases, the insulation panel has been applied on the total building walls envelope. For estimating the cost all the preliminary, supplementary and

secondary activities required for realizing the interventions, have been considered, including safety operations such as application of dust curtains, installation of scaffoldings and/or work platforms, installation of shoring adjacent to the columns to support gravity loads, etc. Moreover, demolition activities removing the furnishings, floor finishes; replacement and restoration activities including the replacement of furnishings, restoration of plaster have also been considered. The operations costs have been evaluated according to Italian standard prices.
The cost analysis demonstrated that when the TRM retrofitting is integrated with insulation materials (energy plus seismic retrofitting), the total retrofitting cost is lower than the sum of the costs if the energy and seismic retrofitting were applied independently. The TRM installation process allows the simultaneous application of the insulation panels, both in terms of scaffoldings and surface preparation.
Finally, the payback times of the considered integrated solutions have been evaluated, for all the seismic and climatic scenarios (given by the combinations of the four Italian seismic regions and the six climatic zones). Practically, they have been evaluated by the intersection between the total NPV curve and the line of the total cost intervention (for example Fig. 8).

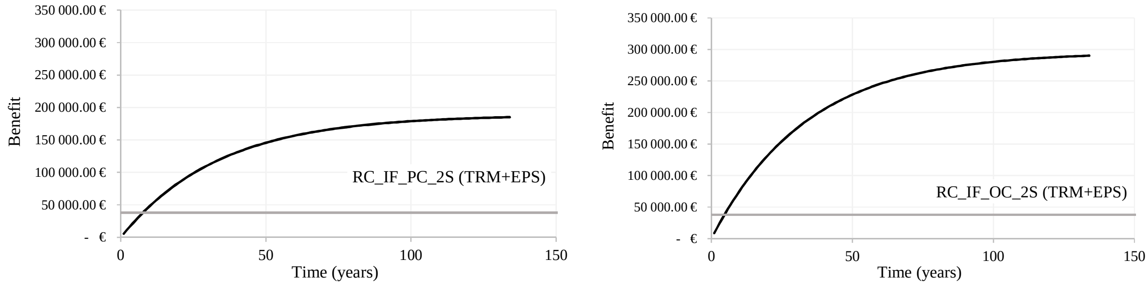

Figure 8: Intersection between the NPV-Time curves and the intervention cost for two Infilled frame typologies (Pre code – Old Code) retrofitted by mean the TRM + EPS integrated system (for the seismic region 1 and the climatic zone F).

Based on the payback times and the consequent obtained economic feasibility indexes for each type, integrated solution and concerning the 24 Italian seismic-climatic scenarios spatial distributions for the economic feasibility index have been defined (Fig. 9).

For defining maps, the seismic hazard and the climatic demand of each Italian municipality have been evaluated. According to municipality seismic and energy scenario, the economic feasibility indexes for the integrated solutions have been assigned. The maps on the first row of Fig. 9 report the spatial distribution of the economic feasibility indexes for middle-rise Bare Frame PreCode building type retrofitted with masonry Infill RC_wall and integrated with three different types of external insulation panel: EPS – Polyurethane and Aerogel. While the maps on the second row of Fig.9 are related to the middle-rise InfillFrame Precode building type retrofitted with masonry Infill TRM_jacket integrated with the same types of external insulation panel. The maps highlight as well the economic feasibility of the integrated solutions based on infilled RC walls decreases passing from EPS, PUR and Aerogel. As expected, higher economic feasibility index characterizes the more seismic and colder regions. TRM jacketing appears more feasible from the economic point of view that RC walls when combined with energy retrofitting, as the retrofitting works are combined. . Finally, the economic feasibility indexes are high also if the TRM is implemented in low seismic regions and if it is integrated with new and expensive insulation material (such as Aerogel panels).

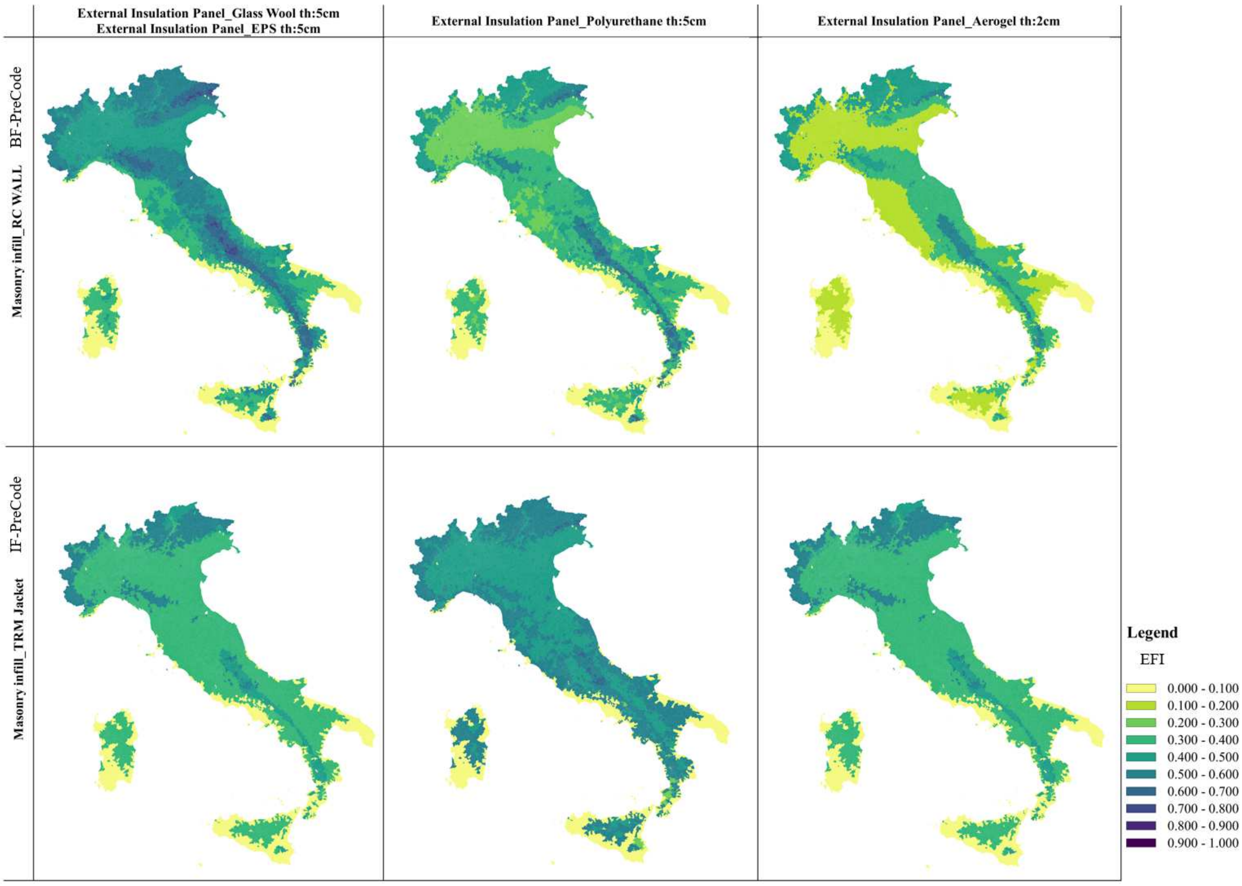

Figure 9: Italian maps for economic feasibility index for the integrated retrofitting solutions studied applied to middle-rise BF PreCode type (first row) and to middle-rise IF PreCode type (second row).

4. CONCLUSIONS

In this study, a new methodology to study the economic feasibility of the combined seismic and energy retrofitting interventions was proposed. The seismic performance is assessed using analytical fragility curves and mean ratio costs. Based on experimental tests of buildings before and after receiving seismic retrofitting, the initial FCs were modified to account for the observed and improved experimental behaviour. In future developments, this simplified procedure will be validated based on the result of numerical analyses simulating the same retrofitted methods and materials.
The cost analysis demonstrated that when the TRM retrofitting is integrated with insulation materials (energy plus seismic retrofitting); the total retrofitting cost is lower than the sum of the costs if the energy and seismic retrofitting were applied independently. The TRM installation process allows the simultaneous application of the insulation panels, both in terms of scaffoldings and surface preparation.

REFERENCES

Balleri A, Marini A (2016). Does seismic risk affect the environmental impact of existing buildings?. *Energy and Building*, 110 (2016) 149–158.

Bournas, D.A., Triantafillou, T.C., Zygouris, K., and Stavropoulos, F., (2009), "Textile-Reinforced Mortar (TRM) Versus FRP Jacketing in Seismic Retrofitting of RC Columns with Continuous or Lap-Spliced Deformed Bars", *Journal of Composites for Construction,* 13(5), 360-371.

Bournas D.A., (2018). Concurrent Seismic and Energy Retrofitting of RC and Masonry Building Envelopes Using Textile-Based Composites Combined with Insulation Materials: A New Concept. Elsevier Composites Part B, under review.

Calvi G M, (2016). Energy Efficiency and Seismic Resilience: A Common Approach, *Multi-hazard Approaches to Civil Infrastructure Engineering*, DOI 10.1007/978-3-319-29713-2_9.

Calvi G M (2013). Choices and Criteria for Seismic Strengthening, *Journal of Earthquake Engineering*, DOI 10.1080/13632469.2013.781556.

Chiauzzi, L., Masi, A., Mucciarelli, M., Vona, M., Pacor, F., Cultrera, G., Gallovič, F., & Emolo, A. (2012). Building damage scenarios based on exploitation of Housner intensity derived from finite faults ground motion simulations. *Bulletin of EarthquakeEngineering*, 10(2), 517-545.

Chrysostomou C Z, Poljansek M, Kyriakides N, Taucer F, Molina F J (2013), Pseudo-Dynamic tests on a full-scale four-storey reinforced concrete frame seismically retrofitted with reinforced concrete infilling, *Structural Engineering International,* DOI: 10.2749/101686613X1343914915631.

Corrado V, Ballarini I, and Corgnati S P, (2014), Building Typology Brochure –Italy – Fascicolo sulle tipologie edilizia italiane. Tabula Project ISBN: 978-88-8202-065-1.

D'Ayala D, Meslem A, Vamvatsikos D, Porter K, Rossetto T, Crowley H, Silva V (2013), Guidelines for analytical Vulnerability Assessment, GEM foundation.

Fichera A, Inturri G, La Greca P, Palermo V (2016), A model for mapping the energy consumption of buildings, transport and outdoor lighting of neighbourhoods, Cities 55 (2016) 49-60.

Furtado A, Rodrigues H, Varum H and Costa A, (2015). Evaluation of different strengthening techniques' efficiency for a soft storey buildings, *European Journal of Environmental and Civil Engineering,* DOI 10.1080/19648189.2015.1119064.

Koutas L, Bousias S N, Triantafillou C T (2015), Seismic Strengthening of Masonry- Infilles RC frames with TRM: experimental study, *Journal of Composites for construction ASCE 04014048-1*.

Kyriakides N, Kotronis P and Georgiou E, (2015), Numerical simulation of the experimental results of a RC frame retrofitted with RC Infill walls, *Earthquakes and Structures* DOI 10.12989/eas.2015.9.4.000.

Main MA (2002). Project Economics and Decision Analysis, Volume I: Deterministic Model. PennWell Books, 2002.

Manganelli B. (2013). La valutazione degli investimenti immobiliari (In Italian). Angelini ed.:Milano 2013.

Masi, A., &Vona, M. (2012). Vulnerability assessment of gravity-load designed RC buildings, evaluation of seismic capacity through nonlinear dynamic analyses. *Engineering Structures*, 45, 257–269.

Mastroberti M, Vona M, and Manganelli B. (2017), Novel models and tools to evaluate the economic feasibility of retrofitting intervention. COMPDYN 2017 6th ECCOMAS Thematic Conference on Computational Methods in Structural Dynamics and Earthquake Engineering Rhodes Island, Greece, 15–17 June.

Negro P and Mola E, (2017), A performance based approach for the seismic assessment and rehabilitation of existing RC buildings, *Bull Earthquake Eng* DOI 10.1007/s10518-015-9845-8.

Triantafillou, T. C., Karlos, K., Kefalou, K., and Argyropoulou, E. (2017). "An innovative structural and energy retrofitting system for URM walls using textile reinforced mortars combined with thermal insulation: Mechanical and fire behaviour". Construction and Building Materials 133, pp. 1-13. ISSN: 0950-0618.

Vona M. (2014). Fragility Curves of Existing RC Buildings Based on Specific Structural Performance Levels, *Open Journal of Civil Engineering*, 4. 120-134.

UNI –Italian Committee for Standardization (2008) (a). Standard UNI TS 11300 Part 1: Evaluation of Energy performance of buildings: Evaluation of energy need for space heating and cooling.

UNI –Italian Committee for Standardization (2008) (b). Standard UNI TS 11300 Part 2: Evaluation of Energy need and of system efficiencies for space heating and domestic hot water production.

Yamin E L, Hurtado A, Rincon R, Dorado J F, Reyes C J (2017), Probabilistic seismic vulnerability assessment of building in terms of economic losses, *Engineering Structures* 138 (2017) 308-323.