Please cite this document as: Mistretta F., Stochino F., Sassu M., ”Structural and thermal retrofitting of masonry walls: An integrated cost-analysis approach for the Italian context”, Building and Environment, 155, 127-136, (2019). DOI: 10.1016/j.buildenv.2019.03.033

Structural and thermal retrofitting of masonry walls: an integrated cost-analysis approach for the Italian context

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Abstract

Constructions ageing is a relevant problem in developed country like Italy. In particular, in case of existing masonry buildings, retrofitting interventions aimed at improving structural and thermal performances represents an obvious need. At the same time, sustainability awareness of buildings life-cycle has grown in the last years. Consequently, the whole life-cycle of constructions should be analyzed and assessed during the design of retrofitting interventions. In order to take into account these aspects new design and planning methods are necessary. This paper presents an integrated approach to evaluate structural and thermal retrofitting strategies for masonry walls. Economic and ecological costs of each examined retrofitting solution are compared, taking into account thermal and seismic capacity demand of the construction site. Given the *economic cost*, a set of retrofitting solutions for masonry panels have been mapped with a couple of parameters (structural strength Vs thermal insulation). An analogous mapping, considering the *ecological cost* due to equivalent CO2 production, have been performed. A methodology to find the best solution among a set of retrofitting solutions is presented, depending on the location of the building and its seismic and thermal characteristics. Examples, based on six retrofitting techniques located in four different sites in Italy, are analyzed to explain the effectiveness and the feasibility of the proposed method. The comparison between ecological and economical cost allowed to highlight the characteristics of the different interventions. Thermal performance proved to be more important in cold weather conditions while structural retrofitting is preferable in high seismic risk areas.

1 Introduction

A large part of traditional European building constructions is made of masonry. Most of them were built in absence of seismic codes and thermal requirements. Indeed, the first European seismic code was published in 1997 (Eurocode 8: Design of structures for earthquake resistance - EN 1998), actually, before this year national seismic standards were already present in various

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countries but the situation was not homogeneous. The first European standard considering the thermal performance of building was UNI EN 832:1998. Furthermore, the first Energy Performance of Buildings Directive arrived in 2002, but most of European Nations already had national standards at the beginning of the 90s. Actually, masonry buildings in Europe built before 1990 often require retrofitting interventions aimed at improving structural and thermal performances, to fulfill current standards requirements. In addition, the sustainability awareness of buildings life cycle has grown in the last years and re-use of construction demolition waste is becoming a common solution to reduce the construction environmental impact [1-4]. It is then necessary to design and to retrofit, taking into account how much energy will be spent for the refurbishment and how much will change the thermal and structural performance of the construction.

It is useful to have a synthetic review of the current retrofitting strategies concerning both structural and thermal interventions.

The literature devoted to structural retrofitting is wide. A general approach to this theme is presented in [5]. It addresses the problem of associating a cost to each different retrofitting procedure and it develops a cost-benefit analysis to compare alternative choices in order to optimize the refurbishments.

Surface treatment of masonry represents a quite common technique: ferrocement [6], reinforced plaster [7] and shotcrete sprayed [8-9]. A current evolution is the application of Fiber Reinforced Polymers FRP nets on the masonry wall [10-16]. A recent trend is the use of Textile Reinforced Mortar (TRM) with inorganic mortar matrix strengthened by an open fabric made of fiber rovings, e.g. [17-22]. Another retrofitting method is grout and epoxy injection. This approach tends to restore the original integrity of the cracked or damaged masonry wall. Further examples can be found in [23-24].

External reinforcements represent useful retrofitting techniques: steel plates, tubes, grids are directly applied to the masonry to improve the lateral in and out of plane resistance of the wall. In [25] externally bonded grids are applied to existing masonry. Reticulatus technique [26] is characterized by a stainless grid able to adapt to the irregular texture of blocks. Other technique is the introduction of horizontal connectors (diaton) to anchor masonry walls from out-of-plane displacements [27-30]. The use of bionatural aggregates in masonry specimens could also be calibrated to optimize the structural and energetic performances [31].

The insertion of a RC frame inside masonry walls allows to improve the energy dissipation capacity and the ductility of the structure, as in [32-33]. This approach induces modification of the structure and is often inappropriate for historical buildings. Instead, post tensioning is the application of a compressive force to masonry wall counteracting the tensile stresses produced by external load. Unfortunately, it is often restricted to monumental construction due to its high cost [34-35].

Energy retrofitting of a building represents the whole set of interventions aimed at reducing its energy needs. In this work we will focus on the improvement of the thermal insulation of masonry buildings. A State-of-Art review for the energy retrofitting methods applied to existing buildings can be found in [36]. Special attention has been devoted to the improvement of thermal insulation and waterproofing properties of masonry walls [37-39]. Examples of masonry walls with high thermal insulation properties are in [40-41].

Building thermal performances are strictly linked to sustainability considerations. Indeed, the construction sector is responsible for a significant part of the primary energy consumption and for a large part of the greenhouse gas (GHG) emissions all over the world, see [42-44]. The effects of climate change on old building energy performance is discussed in [45] pointing out the reduction of the cooling energy usage due to climate warming. Climates effects on residential building durability are discussed in [46] with particular attention on the PassivHaus performance level in Canada weather.

Actually, each stage in building life, (construction, usage, demolition and recovery) contribute to the GHG emissions. In order to plan urban development and existing building retrofitting is essential to consider the environmental impacts both in terms of carbon footprint (CO2 ton.) and energy demands. The energy spent for the direct refurbishment or the energy necessary for the reconstruction should be compared with the building performance improvement, in order to find the best strategy for a proper management of existing buildings. Furthermore, the CO2/year emission, joined with the energy spent every year to reach serviceability comfort conditions, is a significant indicator of the efficiency of the building, in terms of protection of the environment. Attention is generally given to the façades to optimize the thermal resistance of the construction, see [47] for multi criteria analysis of different façade systems. In addition, the sustainability awareness of buildings life cycle is addressed to the evaluation of the energy spent for the direct refurbishment and versus the variation of the energy performance of the construction.

Recent political strategies have been adopted by several European countries in order to promote the sustainable refurbishment. Actually, those strategies can be better oriented to satisfy the structural and thermal demands of different local sites. Indeed, it is often required by political decision makers to consider the seismic and the energetic demands in a given area with a multicriteria analysis, able to treat the above-mentioned aspects in an integrated way. Currently there is not any international standard method for this kind of analysis.

The authors recently published a proposal [48] for a synthetic performance parameter considering both structural and thermal issues. Calvi et al., [49] discussed the idea of a common indicator for both structural and energy performances with a cost/benefit analysis for different retrofitting strategies. Okutan et al. [50] report on a presentational theory that places equal weight on energy and historic conservation perception of old buildings. These studies are useful but do not present an ultimate solution to this complex problem. In particular none of them considers the equivalent CO2 emission for each retrofitting intervention.

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Instead, in this paper an integrated approach to evaluate the structural and thermal retrofitting strategies, considering economic and ecological cost, is proposed. In addition, the seismic and thermal characteristics of the building site is taken into account. The retrofitting representative scenarios are discussed in Section 2. Then parameters measuring the retrofitting strategy of masonry building are presented in Section 3. A comparative economic and ecological cost analysis is discussed in Section 4, while Section 5 presents a criterion capable of considering the local characteristics of different sites. The main results are in Section 6 and finally, in Section 7, some conclusive remarks are drawn.

2 Retrofitting scenarios

The retrofitting techniques on masonry walls can improve in different way thermal and structural performances. A set of six emblematic retrofitting scenarios, presented in Figure 1, have been selected to explain the proposed method. Intervention (a) does not appreciably increase the strength, while it enhances the thermal resistance. It consists in the application of single insulating polystyrene panel, characterized by a thermal conductance λ=0.04 W/mK, on traditional plaster using adhesive glue. The same polystyrene panel with plaster and transverse connectors (diaton) has been adopted in intervention (b). In this case, both thermal resistance and structural strength have been improved. In case (c) a CFRP (Carbon Fiber Reinforced Polymers) reinforced plaster, characterized by a thermal conductance λ=0.08 W/mK, is applied to both side of the wall panel in addition to transverse connectors. The CFRP is characterized by a tensile strength f_{fRp} equal to 2.8 GPa and an elastic modulus E_{frp} of 350 GPa. Similarly, in case (d) a GFRP (Glass Fiber Reinforced Polymers) reinforced plaster is applied to both side of the wall panel in addition to transverse connectors. This intervention increases the structural performance but is also able to induce a superior thermal resistance. The GFRP is characterized by a tensile strength f_{fRp} equal to 1.0 GPa and an elastic modulus E_{frp} of 45 GPa. Finally, in case (e) and (f), a net of CFRP and GFRP respectively is applied on both sides of the wall panel. Thermal resistance is not appreciably increased due to the lack of any insulation layer, thus only the structural resistance is enhanced.

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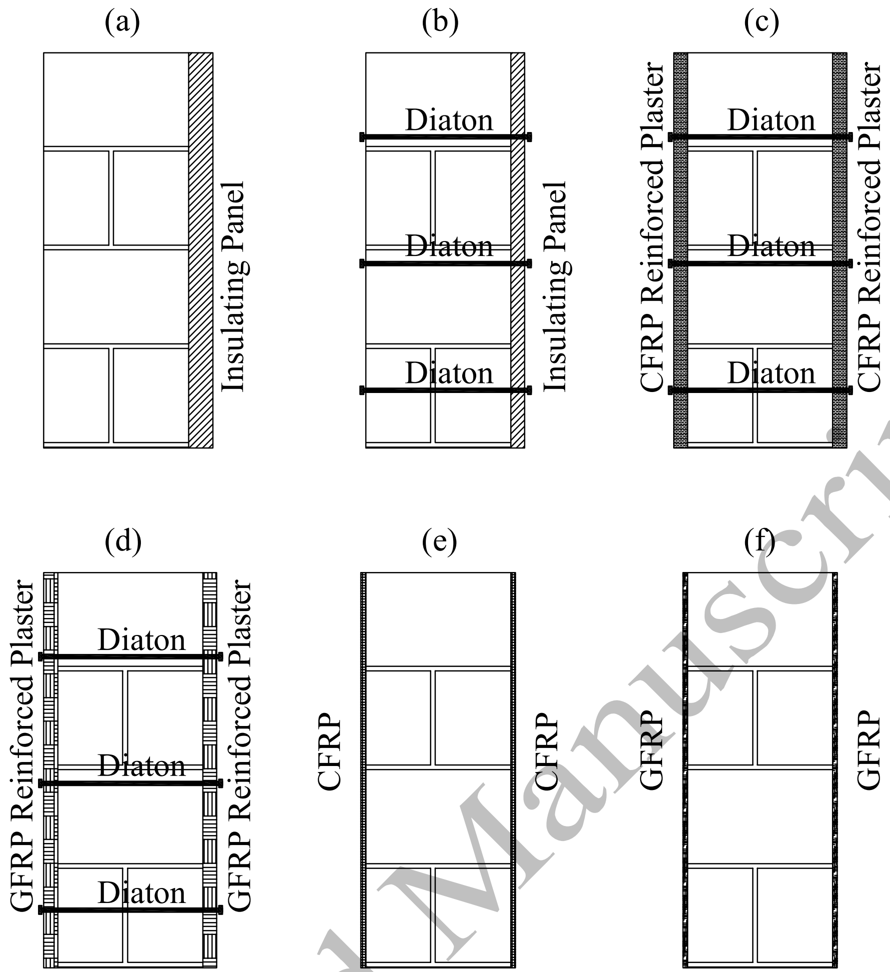

Figure 1: Retrofitting strategies.

3 Method to measure retrofitting strategy.

In this Section the retrofitting performance parameters are defined considering both structural and thermal performance.

For the sake of simplicity, the analysis of the thermal and structural performances is limited on a single unitary (1x1 m) masonry wall in order to quantify the effects of each retrofitting strategy.

The relative variation of a generic performance parameter ΔC is assessed by the ratio of the performance variation between its value before (C_0) and after the retrofitting (C_1) and the initial value C_0:

$$\Delta C = (C_1 - C_0)/C_0 \quad (1)$$

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Thus, for each wall panel is possible to calculate the relative increment of structural resistance referring to bending moment ΔM or shear force ΔV and the relative variation in the thermal resistance ΔR or the thermal inertia ΔT obtained after retrofitting.

In the forthcoming analysis, the variation of ΔM, ΔV and ΔR is considered for the mentioned 1x1 m wall panel. The masonry characteristics adopted for the numerical analysis are presented in Table 1. These are the characteristics of the emblematic case study of the school in Visso (Macerata – Italy) made of 70 cm thick stone blocks characterized by good weaving and lime mortar.

Table 1: Existing masonry characteristics, $f_{M,k}$ is the compressive strength, τ_0 is the shear strength, E is the longitudinal elastic modulus, G is the shear elastic modulus, W is the specific weight, λ is the thermal conductance.

$f_{M,k}$ [N/mm^2]	τ_0 [N/mm^2]	E [N/mm^2]	G [N/mm^2]	W [kN/m^3]	λ [W/mK]
3.2	0.06	1740	580	21	2.4

In case of diatons (retrofitting scenarios b-c-d Figure 1), the mechanical characteristics of masonry are conventionally improved of the 30% as in Italian code [51].

The resistant bending moment of a masonry wall retrofitted with FRP is evaluated using the approach presented in [52]. The stress condition in the masonry cross section can be represented by the translational and rotational equilibrium:

$$N = R_m + R_{frp} \tag{2}$$

$$M = \frac{t}{2} R_{frp} + \left(\frac{t}{2} - \frac{0.8}{2x}\right) R_m \tag{3}$$

Where R_m and R_{frp} are respectively the masonry and reinforcement internal forces. The adopted constitutive laws are reported in Fig. 2. Given the following definitions:

$$\rho = \frac{A_{frp}}{lt} \tag{4}$$

$$\omega = \frac{\varepsilon_{frp,u} E_{frp}}{f_{M,k}} \rho \tag{5}$$

$$\frac{\varepsilon_{frp,u}}{\varepsilon_{M,u}} = \frac{(1-\frac{x}{t})}{\frac{x}{t}} \tag{6}$$

where t and l are the width and height of the cross section, respectively; A_{frp} is the FRP cross-sectional area; E_{frp} is the Young's modulus of the fibers; $\varepsilon_{frp,u}$ and $\varepsilon_{M,u}$ are the ultimate tensile and compressive strains for the fibers and the masonry, respectively; $f_{M,k}$ is the compressive strength of the masonry; and x is the neutral axis depth. Enforcing equations (4) - (6) into (1) and (2) it is possible to obtain:

$$\frac{M_{Rd}}{lt^2 f_{M,k}} = \frac{\frac{1}{2}\omega\left(1-\frac{x}{t}\right)}{\frac{x}{t}} + \frac{0.4}{\gamma_m}\frac{x}{t}\left(1\text{-}0.8\frac{x}{t}\right) \quad (7)$$

$$\frac{x}{t} = \frac{\gamma_M}{1.6}\left[\frac{N_{Rd}}{ltf_{M,k}} - \omega + \sqrt{\left(\omega - \frac{N_{Rd}}{ltf_{M,k}}\right)^2 + \frac{3.2}{\gamma_M \omega}}\right] \quad (8)$$

where M_{Rd} and N_{Rd} are the design bending moment and axial force of the cross section, while γ_m is the masonry partial safety factor. Equations (7) and (8) allow to express the resistant bending moment as a function of ω and of the axial load.

In the present case a standard axial load of $\frac{N_{Rd}}{ltf_{M,k}} = 0.3$ has been adopted.

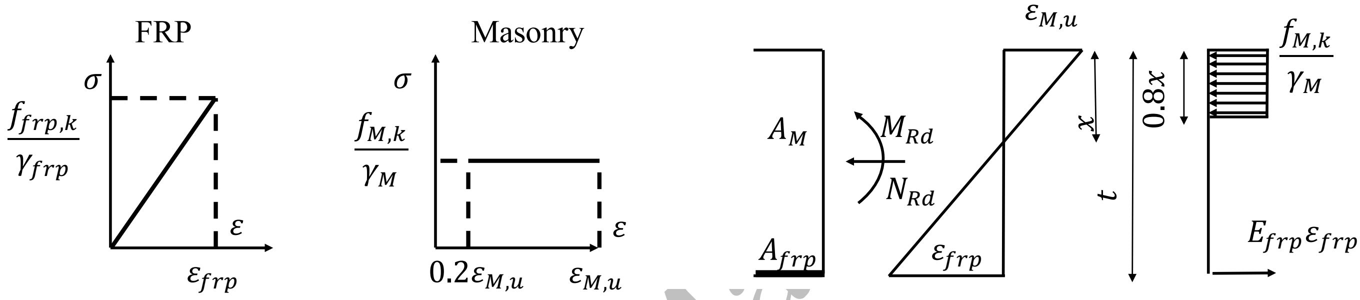

Figure 2: Materials constitutive law and cross section forces, taken by [52].

The shear force strength V of the wall panel is assessed following the methods presented in [53]. Considering the contribution of the masonry $V_{Rd,m}$ and of the possible FRP reinforcement $V_{Rd,F}$, the resistant shear value V_{Rd} is evaluated considering an equivalent truss approach. Thus:

$$V_{Rd} = \min\left(V_{Rd,m} + V_{Rd,f}, V_{Rd,MAX}\right) \quad (9)$$

$$V_{Rd,m} = d\ t\ f_{vd} \quad (10)$$

$$V_{Rd,f} = 0.6\ d\ 2\ t_f\ f_{fRp} \quad (11)$$

$$V_{Rd,MAX} = 0.15 f_{M,K} t d \quad (12)$$

Where d is the effective height depth, l is the panel length, f_{vd} is the masonry shear strength t_f and f_{fRp} are the FRP reinforcement thickness and tensile strength, respectively. The latter is defined as the minimum between the ultimate tensile strength of the FRP and the delamination stress.

Thermal insulation resistance has been evaluated considering the properties of each layer of the panel:

$$R = \sum s_i/\lambda_i \quad (13)$$

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where s_i and λ_i respectively are the thickness and the thermal conductance of the i-th layer of the panel. For the sake of simplicity, we neglect the aspect of transient thermal transmittance due to the mass of the walls.

4 Cost analysis

In this Section the regression curves representing economic and ecological costs are obtained starting from the retrofitting scenarios characteristics presented in Section 3.

The cost of the six interventions depends on the thickness of the retrofitting layers. In order to estimate a general economic cost relationship between Δ*M* and Δ*R*, six different investment cost scenarios varying between 100 €/m^2 and 350 €/m^2 have been considered. For each intervention, the thicknesses of the retrofitting layers have been tuned to obtain the required cost for construction (supply and manpower), see Table 2. These values have been based on the Italian public works market. In this way, each cost scenario is described by six points. They represent retrofitting conditions in which the economic cost is constant. They have been fitted with a hyperbolic regression curve, see Figure 3:

$$\Delta R(\alpha_1 - \Delta M) = \alpha_0 \quad (14)$$

where the numerical parameters (α_0, α_1) are determined by least squares approach using the `lsqnonlin` Matlab® function. The corresponding values are in Table 3.

Table 2: Adopted materials costs.

Material	Spec. Economic Cost	Spec. Ecological cost
Polystirene panel	1517 €/m^3	138 kgCO2/m^3
Diatons	80 €/m^2	0.25 kgCO2/m^2
CFRP reinf. plaster	17133 €/m^3	1096 kgCO2/m^3
GFRP reinf. plaster	10767 €/m^3	734 kgCO2/m^3
CFRP web	650000 €/m^3	77700 kgCO2/m^3
GFRP web	344000 €/m^3	520 kgCO2/m^3

Table 3: Economic cost regression coefficients for the ΔR-ΔM plane.

Cost Scenario	α_0	α_1
100 €/m^2	0.090	0.1427
150 €/m^2	0.120	0.1476
200 €/m^2	0.150	0.1488
250 €/m^2	0.180	0.1492
300 €/m^2	0.210	0.1495
350 €/m^2	0.250	0.1496

A similar approach has been adopted to obtain the ΔR - ΔV cost regression lines. The results are in Figure 4, while numerical parameters values are in Table 4.

Table 4: Economic cost regression coefficients for the ΔR-ΔV plane.

Cost Scenario	α_0	α_1
100 €/m^2	0.100	0.0100
150 €/m^2	0.150	0.0080
200 €/m^2	0.180	0.0100
250 €/m^2	0.210	0.0250
300 €/m^2	0.250	0.0203
350 €/m^2	0.300	0.0203

Looking at Figures 3 and 4 it can be highlighted that CFRP reinforced plaster retrofitting scenario (c) produced the best structural performance while scenario (a) corresponds, as expected, to the most effective thermal performance.

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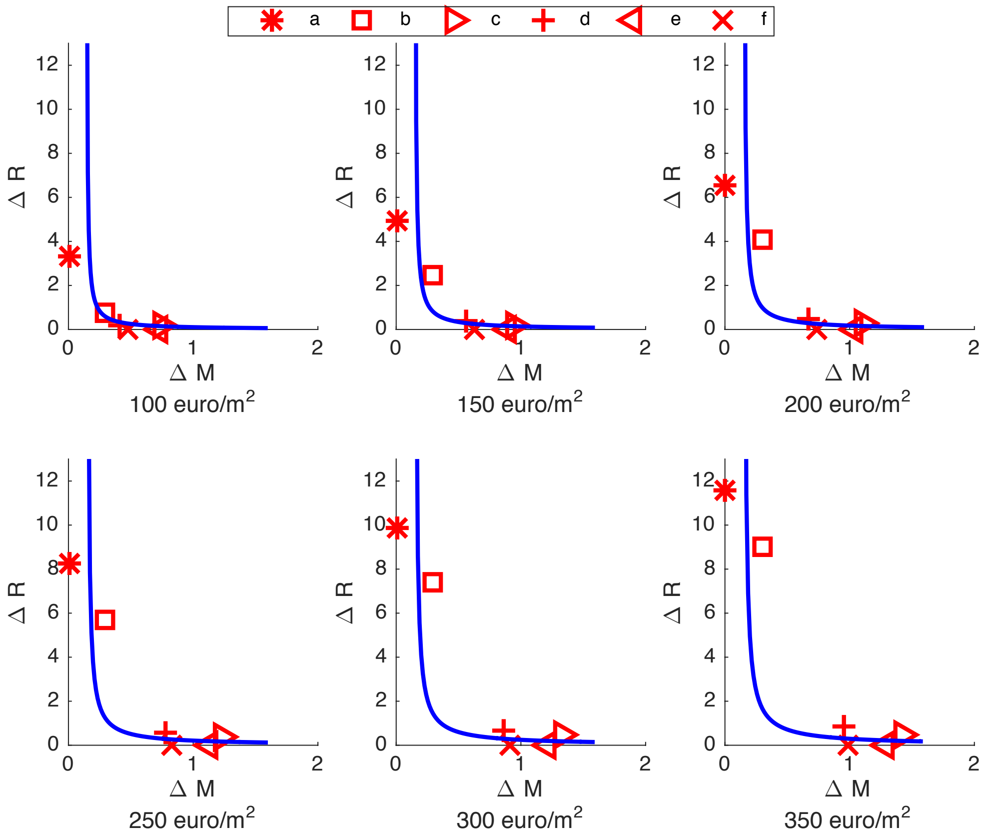

Figure 3: Cost regression lines ΔR, ΔM corresponding to six different budgets per square meter for the six retrofitting scenarios (a-f), see Figure 1.

Table 5: Ecological cost regression coefficients for the ΔR-ΔM plane.

Cost Scenario	α_0	α_1
10 kg CO2/m^2	0.100	0.1422
28 kg CO2/m^2	0.200	0.1494
46 kg CO2/m^2	0.300	0.1498
64 kg CO2/m^2	0.400	0.1500
82 kg CO2/m^2	0.500	0.1600
100 kg CO2/m^2	0.600	0.1700

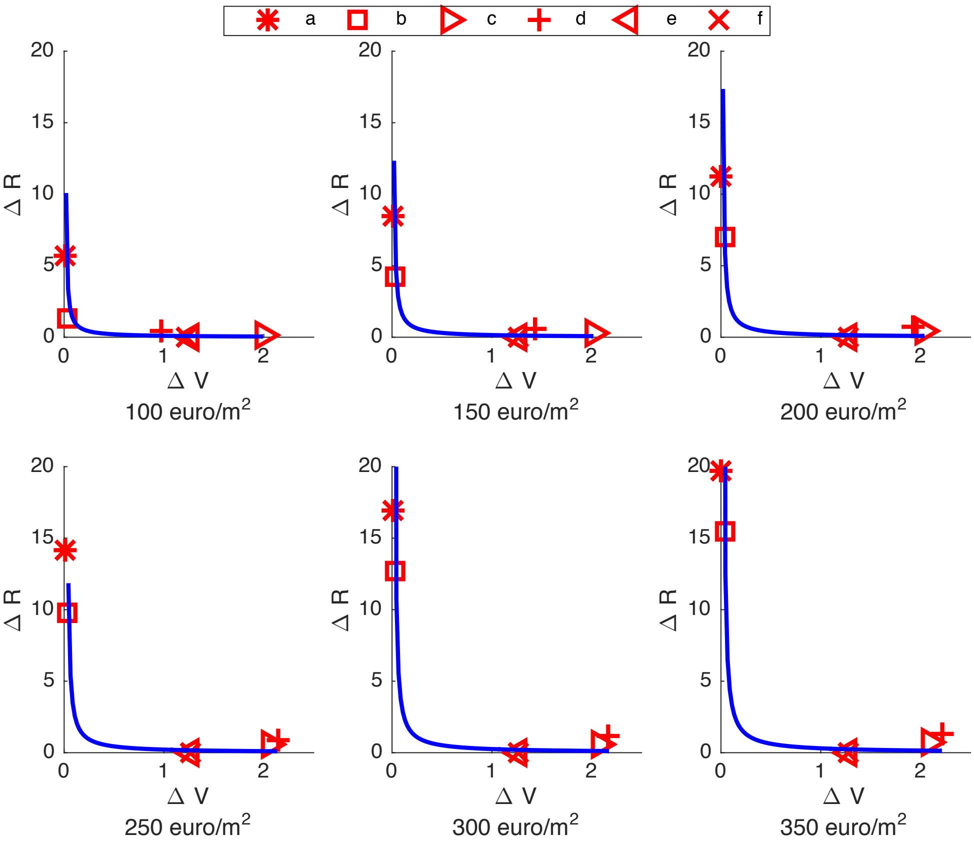

Figure 4: Cost regression lines ΔR - ΔV corresponding to six different budgets per square meter for the six retrofitting scenarios (a-f), see Figure 1.

Now, it is interesting to consider the problem from another perspective, using no longer an *economic cost* but an *ecological cost*. Given that carbon footprint is the total set of greenhouse gas emissions during the life cycle of a product, the ecological cost of each retrofitting intervention is described in terms of kg CO2 on a single 1x1 m masonry panel. It should be pointed out that this computation does not assess the life cycle carbon footprint of a building, focusing only on the masonry component. The detailed kg CO2 equivalent for each material, reported in Table 2, is taken from [54-56].

With this aim, a set of hyperbolic regression curve represented in equation (14) has been calculated for six scenarios characterized by a fixed mass of CO2 equivalent, in which the ecological cost is constant. The numerical parameters α_0, α_1 of the fitting curves are presented in Table 5 and 6, while Figure 5 presents the ΔR - ΔM results and Figure 6 the ΔR - ΔV one.

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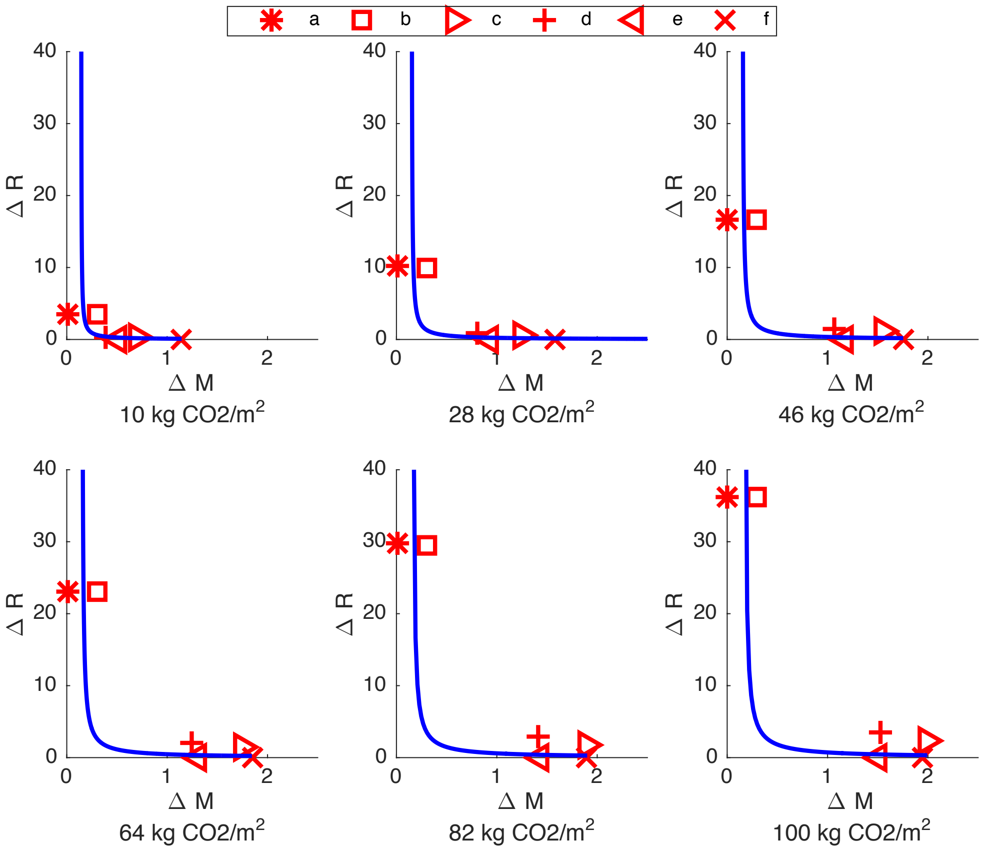

Figure 5: Hyperbolic regression functions ΔR - ΔM for six different scenarios of Carbon footprint in terms of CO2 equivalent for the six retrofitting scenarios (a-f), see Figure 1.

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Table 6: Ecological cost regression coefficients for the ΔR-ΔV plane.

Cost Scenario	α_0	α_1
10 kg CO2/m^2	0.100	0.0203
28 kg CO2/m^2	0.150	0.0205
46 kg CO2/m^2	0.210	0.0206
64 kg CO2/m^2	0.310	0.0207
82 kg CO2/m^2	0.400	0.0250
100 kg CO2/m^2	0.510	0.0300

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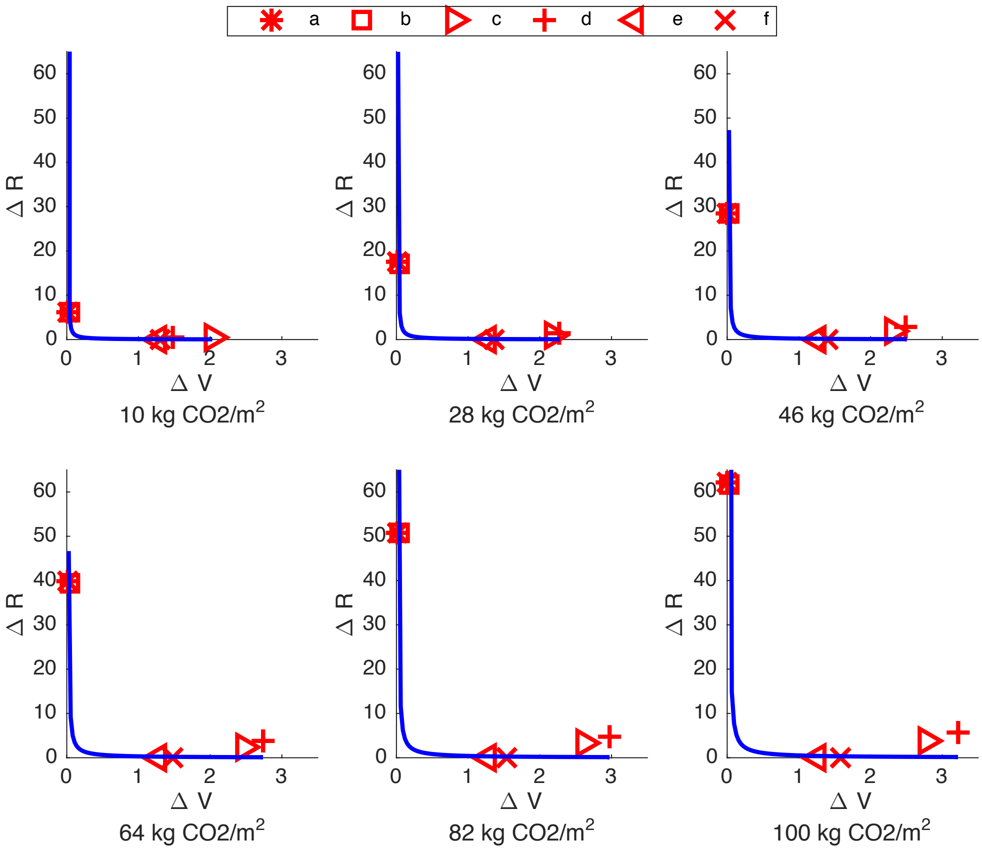

Figure 6: Hyperbolic regression functions ΔR - ΔV for six different scenarios of Carbon footprint in terms of CO2 equivalent for the six retrofitting scenarios (a-f), see Figure 1.

It is interesting to highlight that the equivalent CO2 scenarios (a) and (b) produced similar performances, while CFRP retrofitting seems to provide the most important structural performance in the ΔR - ΔM plane. Finally, the GFRP reinforced polymer obtains better structural results in the ΔR - ΔV plane. This last is due to the different CO2 cost of GFRP in comparison with CFRP, see Table 2.

Thus, Figures 3-6 represents the iso-cost (economic cost or ecological cost) performance curves that will be adopted to compare the retrofitting strategies in the next sections.

5 Local Parameters

In this Section the local sites characteristics are quantitatively defined for the Italian case study.

As said before, the retrofitting performance analysis should be referred to the specific site in which the building is located. Indeed, there are locations in which the seismic risk induces more relevant impact than the thermal conditions and others in which the climate conditions are more severe than the seismic risk. Assuming as example the Italian peninsula, the seismic event, commonly measured throughout the peak ground acceleration (PGA), is mapped in Figure 7. In the meanwhile, the thermal effect, commonly measured throughout the Degree

Day (DD), is depicted in Figure 8. Thus, both aspects can be detected by the following dimensionless parameters c_R and c_U:

$$c_R = \frac{PGA_i}{PGA_{MAX}} \quad , \tag{15}$$

$$c_U = \frac{DD_i}{DD_{MAX}} \quad . \tag{16}$$

where PGA_{MAX} denotes the maximum PGA of the Italian peninsula and PGA_i represents the peak ground acceleration for the considered i-th location of the building. In the same way, DD_{MAX} is the maximum Degree Day value for the same area and DD_i is the corresponding value for the given i-th location.

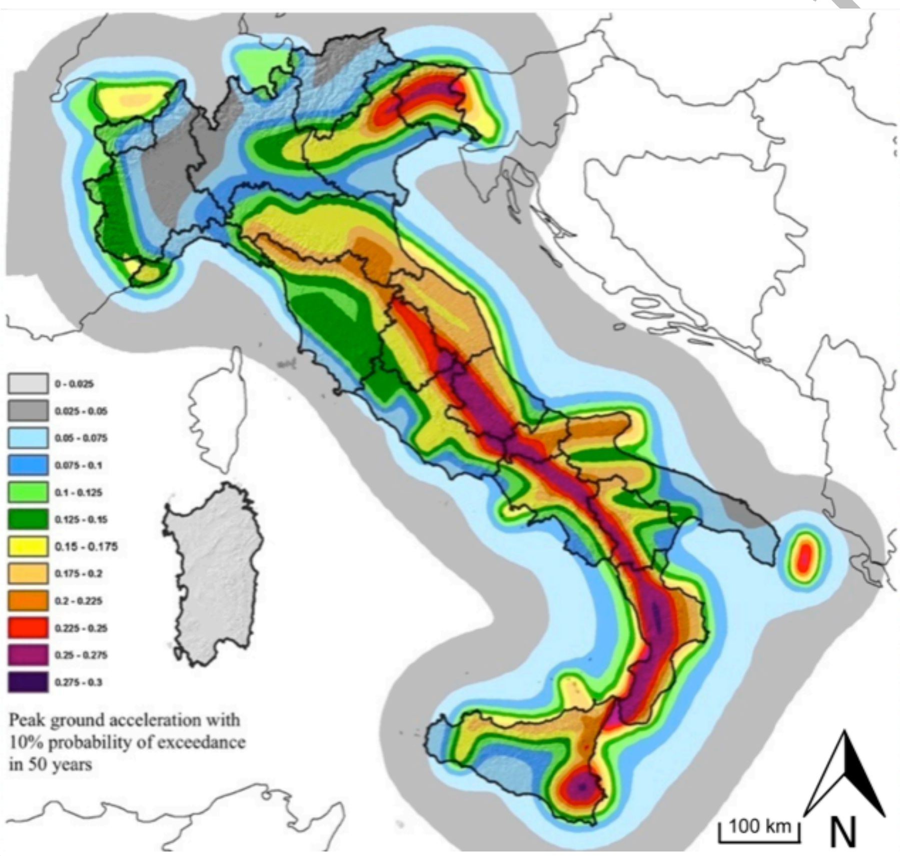

Figure 7: Italian map of seismic PGA (peak ground acceleration), taken from [57].

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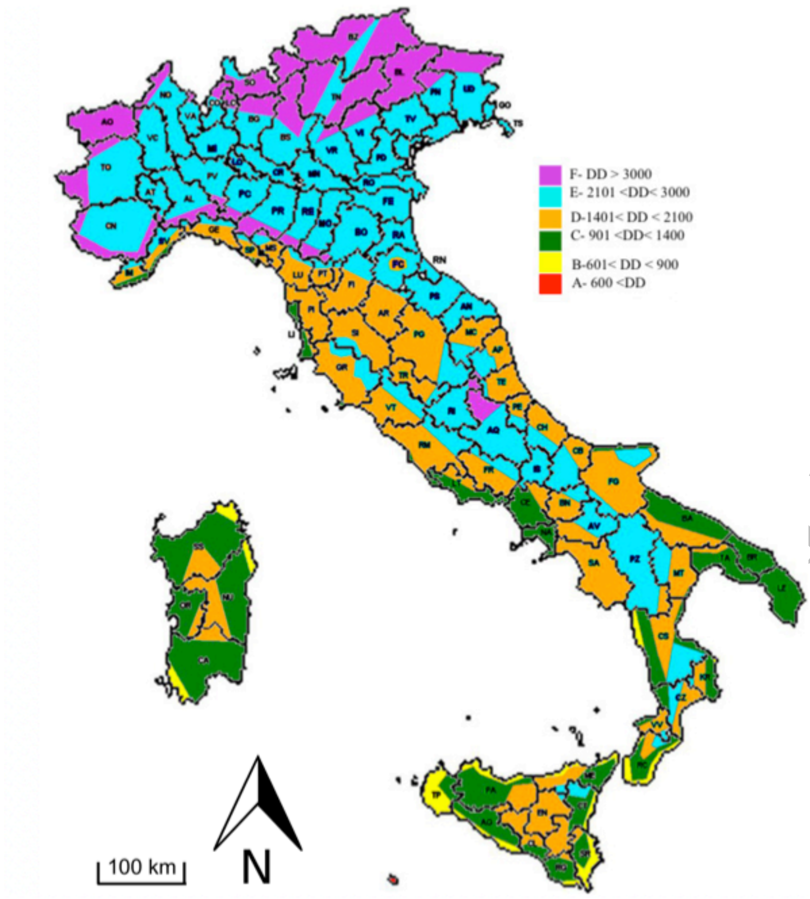

Figure 8: Italian map of heating DD (Degree Days), based on Italian technical code [58].

c_R and c_U parameters represent a "weight" of the structural and energy requirements in that area. The Italian peninsula is divided into 107 districts, assigning conventionally to each of them the values of P_i and DD_i, see Figure 7 and Figure 8, respectively. Equations (15) and (16), define c_R and c_U, allowing to rank each district for both weather conditions and seismic risk.

Four emblematic locations have been considered:

- Torino (low seismic load, high thermal requirements)
- L'Aquila (high seismic load, high thermal requirements)
- Catania (high seismic load, low thermal requirements)
- Cagliari (low seismic load, low thermal requirements).

The values of c_R and c_U are presented in Table 7:

Table 7: Site parameters for the considered cases.

Location	c_R	c_U
Torino	0.228	0.507
L'Aquila	0.868	0.487
Catania	0.782	0.161
Cagliari	0.196	0.192

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A possible criterion to design masonry panel retrofitting intervention is to fix the ratio between the thermal and structural performance improvements using the above-mentioned parameters. Equation (17) presents the proposed criterion for the ΔR - ΔM performance plane while equation (18) the one for the ΔR - ΔV plane.

$$\Delta R = \alpha \frac{c_R}{c_U} \Delta M \quad (17)$$

$$\Delta R = \alpha \frac{c_R}{c_U} \Delta V \quad (18)$$

α represents a tuning parameter that can be assigned by the political decision-makers. Indeed, it is possible to encourage thermal retrofitting interventions versus structural ones. Without political needs α can be assumed equal to one.

6 Results

For the above mentioned four characteristics locations in Italy (Torino, L'Aquila, Cagliari, Catania) the criterions represented in equations (17-18) and the economic or ecological cost regression line can be plot on the ΔR - ΔM plane (Figure 9 -11) or on the ΔR - ΔV plane (Figure 12 and 13). These Figures represent a synthetic way to evaluate retrofitting scenarios for the different locations linking the performance parameters ΔR, ΔM, ΔV to the economic or ecological costs. Each crossing between a retrofitting criterion (equations 17-18) curve and a cost regression one represents an optimal retrofitting solution.

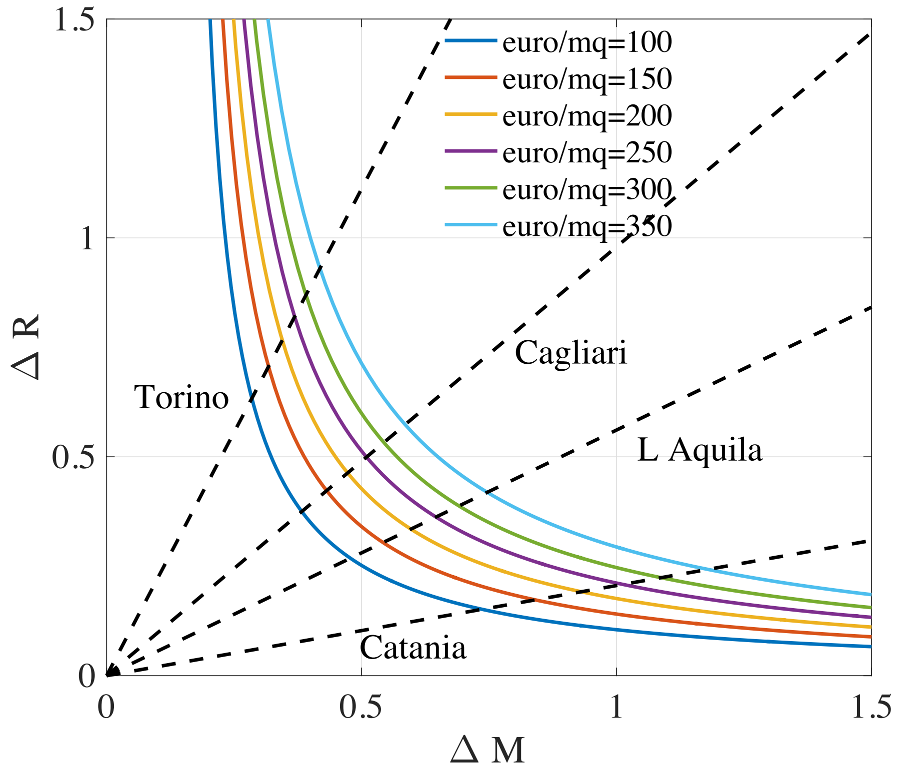
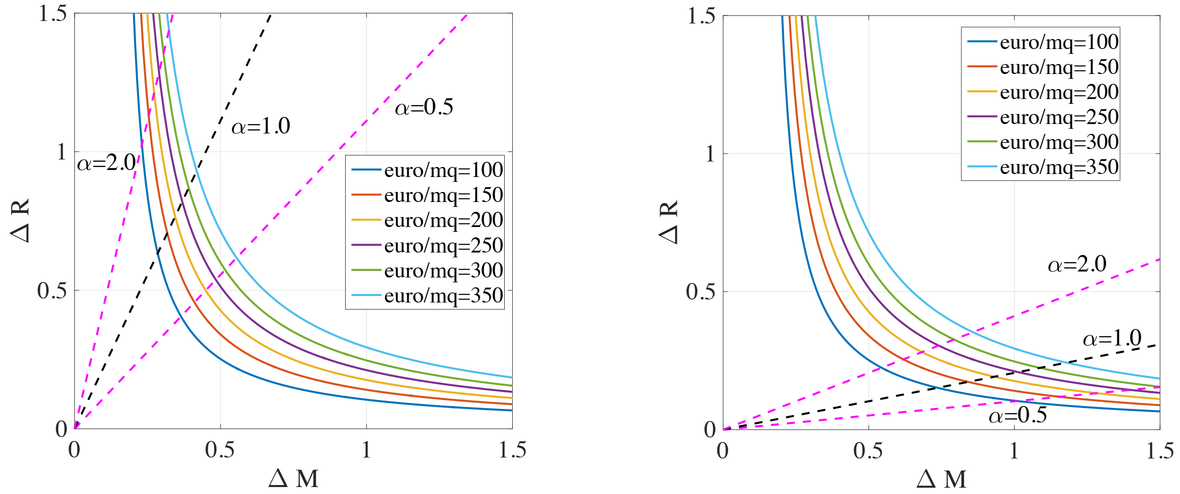


Figure 9: Retrofitting strategy considering economic costs for plane ΔR - ΔM.



(a) (b)

Figure 10: Torino (a) and Catania (b) retrofitting strategies for different values of the α parameter.

Figure 10 presents the specific case of Torino and Catania using different values of the α parameter (the so called “political parameter”). Indeed, varying α it is possible to modify the results of the retrofitting intervention in order to follow different political strategies. Figure 10 shows that the mentioned approach produces a wide set of retrofitting cases for Torino, while in the Catania case the specific conditions tend to encourage structural intervention in contrast to thermal ones. It means that in Torino the value of α can have a stronger influence on the optimal solution.

Figure 11 presents the possible retrofitting strategies that follow equation (17) considering the ecological cost (in terms of CO2 kg) in the ΔR - ΔM plane. As already discussed in case of Torino, thermal retrofitting is more relevant than structural one. On the other hand, the same quantity of CO2 kg can be used to improve the structural resistance of the masonry wall in Catania.

Finally, considering the ΔR - ΔV plane, Figure 12 presents the economic cost analysis of the retrofitting interventions while Figure 13 the ecological cost in terms of CO2 production. Comparing Figures 12-13 with the corresponding Figures 9 and 11 the shear strength increment ΔV can be obtained with lower cost than the equivalent ΔM improvement. This can be due to the adopted structural model presented in Section 3 and to the assumed specific costs presented in Table 2.

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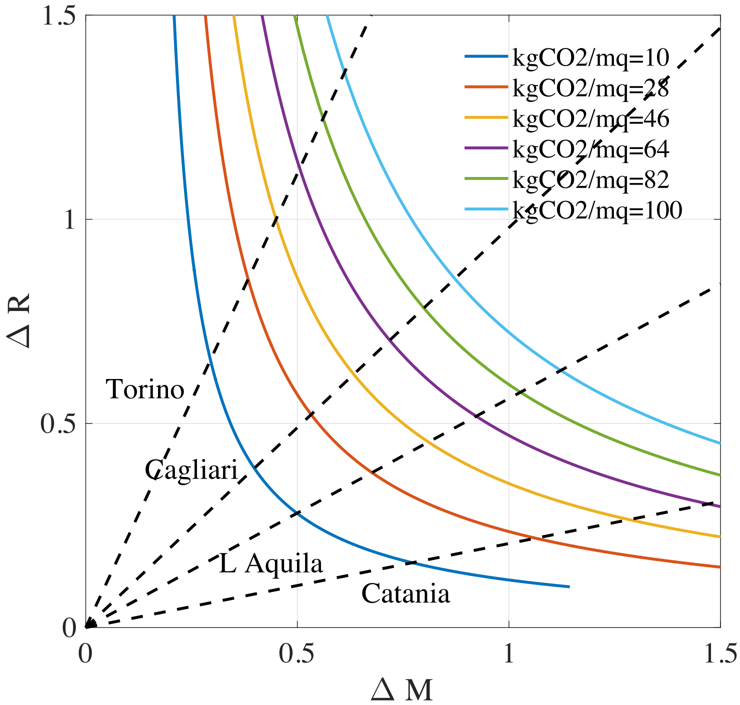

Figure 11: Retrofitting strategy considering ecological costs for plane ΔR - ΔM.

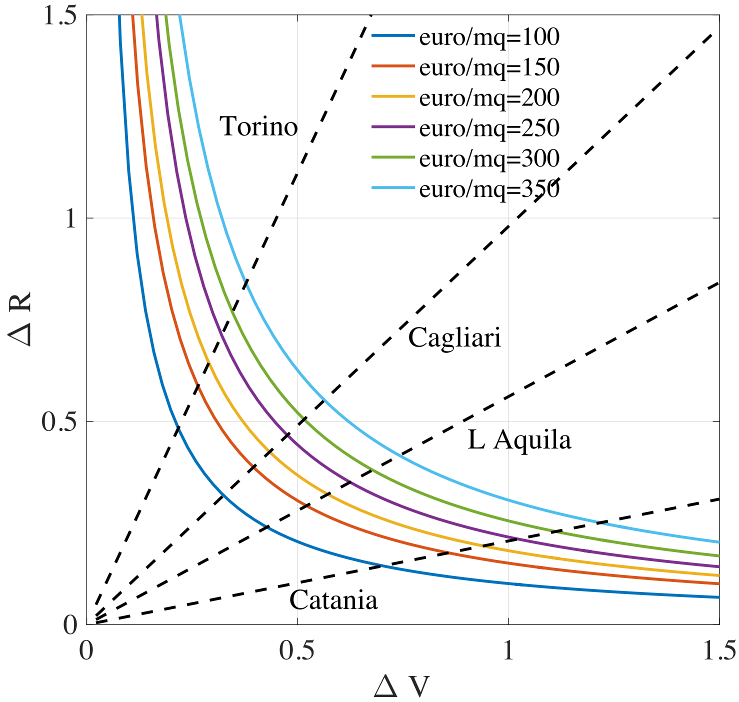

Figure 12: Retrofitting strategy considering economic costs for plane ΔR - ΔV.

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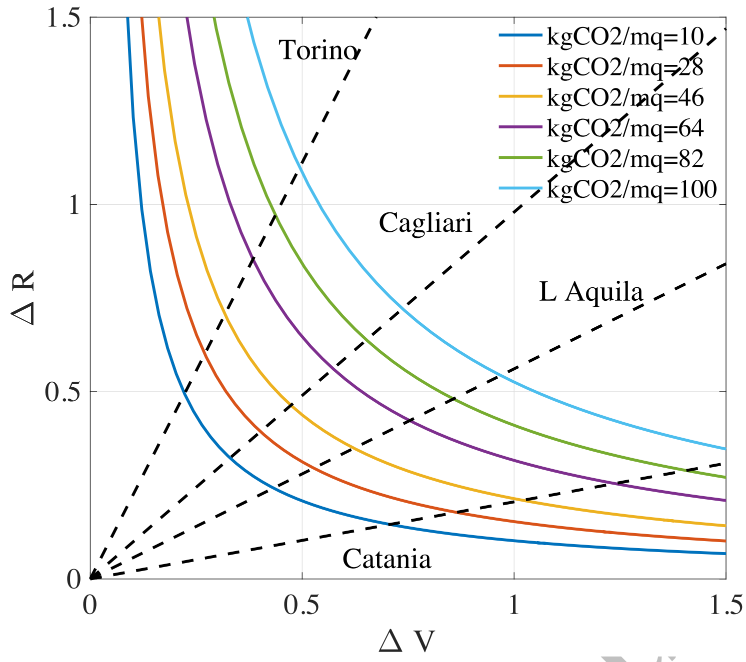

Figure 13: Retrofitting strategy considering ecological costs for plane ΔR - ΔV.

7 Conclusions

In this paper, the problem of retrofitting a single unitary masonry wall has been assessed considering both structural and thermal performances in a cost analysis framework.
First, six representative retrofitting interventions have been parameterized by the improvement of thermal resistance, bending moment and the shear structural strength.
The unitary economic (€/m^2) and the ecological (kg CO2/m^2) costs of the retrofitting have been analyzed to obtain regression functions that allow a direct comparison of different actions.
The peculiarity of the local sites has been accounted with specific parameters based on the seismic and the thermal demands. The approach has been shown on four different Italian cities representing different local conditions.

The comparison between ecological and economical cost allowed to highlight the characteristics of the different interventions. Thermal performance proved to be more important in cold weather conditions (Torino) while structural retrofitting is preferable in high seismic risk areas (Catania). In addition, the political parameter α, seems to have a bigger impact in low risk seismic area (Torino and Cagliari) than in higher seismic area (Catania and L’Aquila).

The main results presented by Figures 9-13 are a synthetic view of the possible alternative masonry building retrofitting strategies. In this way given a fixed cost (economic or ecological) it is possible to find the best solution taking into account the local site characteristics. Thus, in order to plan an urban redevelopment plan a set of graphs like those presented in Figures 9-13

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can give to the political decision makers an effective and synthetic view of this complex problem and its possible solutions.

An extension of this study to other countries is possible once the seismic PGA map and the degree days analysis is available for the considered areas. Currently, there are several territories with these information (whole Europe, North America, far east Asia etc.)

Further developments of this approach are expected considering other constructive components, in order to analyze an entire building, but also other types of construction. Indeed, an extension of existing concrete and steel frames can be useful. Clearly, in these cases the retrofitting interventions should be updated for the specific structural and thermal requirements.

Funding Statement

The financial support of ReLUIS-DPC2018—PR1 (Masonry) is acknowledged. Flavio Stochino also acknowledges the financial support of the Italian Ministry of University and Research, the Conference of Rectors of Italian Universities and Confindustria, the Italian Industrial Federation, under the PhD-ITalents programme grant n. 145145711, and the support of the Autonomous Region of Sardinia under grant P.O.R. SARDEGNA 2014–2020, CCI: 2014- IT05SFOP021, Project: Retrofitting, rehabilitation and requalification of the historical cultural architectural 506 heritage (R3-PAS).

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