Structural and Thermal Retrofitting of Masonry Walls: The Case of a School in Vittoria (RG)

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Abstract. Sustainability awareness of buildings life-cycle represents one of the most important engineering challenge. This is more important in developed country like Italy in which buildings age and importance can be huge. Consequently, the whole life-cycle of constructions should be analyzed and assessed during the design of retrofitting interventions. This works reports on the application of an integrated approach to evaluate structural and thermal retrofitting strategies for masonry walls. Ecological (equivalent CO_2) and economic costs of each examined retrofitting solution are evaluated and compared. In this way the structural and thermal capacity of the masonry walls is represented by an iso-cost mapping. The environmental demand considering both thermal and seismic load of the construction site is represented by an equivalent function that is used to find the optimal retrofitting solution for each considered cost.

In this case study the masonry walls of a school located in Vittoria (RG - Italy) are considered. Six retrofitting techniques are described and the comparison between ecological and economical cost allowed to highlight the characteristics of the different interventions and the best retrofitting strategy.

Keywords: Masonry · Retrofitting · CO_2 equivalent · Structural engineering

1 Introduction

Masonry constructions represents a large part of traditional European buildings. Most of them were built in absence of seismic codes and thermal requirements. For this reason, the needs of integrated retrofitting interventions to fulfill current standards requirements is often patent.

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 approach to reduce the construction environmental impact [1–3]. It is then necessary to design the retrofitting, considering how much energy will be spent for the refurbishment and how much the thermal and structural performance of the construction will be changed.

The literature devoted to structural retrofitting is wide. A general approach to this theme is presented in [4]. In the latter paper the problem of associating a cost to each different retrofitting procedure is discussed with a cost-benefit analysis to compare alternative choices in order to optimize the refurbishments.

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Surface treatment of masonry panels represents a quite common retrofitting technique: reinforced plaster [5], ferrocement [6], and shotcrete sprayed [7, 8].

An interesting evolution of this set of techniques is the application of Fiber Reinforced Polymers FRP nets on the masonry wall [9–12]. A recent trend is the use of Fiber Reinforced Cementitious Matrix (FRCM), for example: basalt textile coupled to different inorganic matrices see [13].

Also grout and epoxy injection represent an interesting retrofitting method. With this approach it is possible to restore the original integrity of the cracked or damaged masonry wall, see [14, 15].

Finally, external reinforcements represent useful retrofitting techniques for masonry: steel plates, tubes, grids are directly applied to the masonry to improve the lateral in and out of plane resistance of the wall. The introduction of horizontal connectors (diaton) to avoid masonry walls out-of-plane displacements [16–18].

The whole set of interventions aimed at reducing its energy needs can defined as "energy retrofitting". In this paper the focus is 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 [19]. The improvement of thermal insulation and waterproofing properties of masonry walls is described in [20, 21]. Examples of masonry walls with high thermal insulation properties are in [22, 23].

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 [24, 25].

Sustainable refurbishment of existing buildings is promoted by the political strategies of several European countries. Actually, it is often required by political decision makers to consider the seismic and the energetic demands in a given area with a multicriteria analysis. The aim is to take into account both structural and energy needs of building in an integrated way. Unfortunately, there is not an international standard method for this kind of analysis.

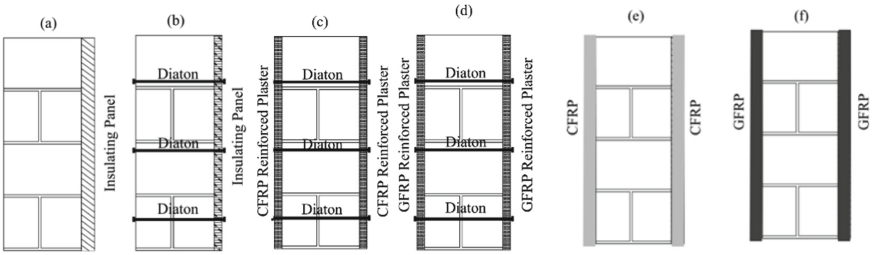


Fig. 1. Retrofitting strategies.

The authors recently published a proposal [26, 27] for a synthetic performance parameter considering both structural and thermal issues. Calvi et al. [28] presented the idea of a common indicator for both structural and energy performances with a cost/benefit analysis characterizing different retrofitting strategies.

Instead, this works reports on the application to a real case study of the integrated approach to evaluate structural and thermal retrofitting strategies for masonry walls introduced in [27]. Ecological (equivalent CO_2) and economic costs of each examined retrofitting solution are evaluated and compared. In this way, the structural and thermal capacity of the masonry walls is represented by an iso-cost mapping. The environmental demand, considering both thermal and seismic load of the construction site, is represented by an equivalent function to find the optimal retrofitting solution for each considered cost.

The paper is organized as follows: the retrofitting scenarios are discussed in Sect. 2. The iso-cost capacity curves are calculated in Sect. 3. Section 4 presents local demands and a design criterion. The main results are in Sect. 5 and finally, in Sect. 6, some conclusive remarks are drawn.

2 Retrofitting Strategies

In order to explain the proposed method a set of six emblematic retrofitting scenarios are presented in Fig. 1. Intervention (a) consists in applying single insulating polystyrene panel, characterized by a thermal conductance $\lambda = 0.04$ W/mK, on traditional plaster through adhesive glue. Clearly, it does not increase the strength, while it strongly improves the thermal performance. In case (b), both thermal resistance and structural strength have been improved using a polystyrene panel with lime plaster and transverse steel connectors (diaton). Intervention (c) is characterized by the application to both side of the wall panel of a CFRP (Carbon Fiber Reinforced Polymers) reinforced plaster, thermal conductance $\lambda = 0.08$ W/mK. Transverse connectors are present also in this case. 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, a GFRP (Glass Fiber Reinforced Polymers) reinforced plaster is applied to both side of the wall panel in addition to transverse connectors in case (d). The GFRP characteristics are: tensile strength f_{fRp} equal to 1.0 GPa and elastic modulus E_{frp} equal to 45 GPa. Finally, a net of CFRP and GFRP is respectively applied on both sides of the wall panel in case (e) and (f). In these last cases, thermal resistance is not appreciably increased due to the lack of any insulation layer, thus only the structural resistance is enhanced.

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, λ is the thermal conductance.

E [N/mm^2]	$f_{M,k}$ [N/mm^2]	τ_0 [N/mm^2]	λ [W/mK]
2000	4.9	0.07	1.4

3 Capacity Iso-Cost Curves

The relative variation of a generic performance parameter ΔC is defined 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:

$$\Delta C = (C_1 - C_0)/C_0 \tag{1}$$

Thus, for each wall panel is possible to calculate the relative increment of structural resistance referring to bending moment ΔM:

$$\Delta M = (M_1 - M_0)/M_0 \tag{2}$$

or shear force ΔV:

$$\Delta V = (V_1 - V_0)/V_0 \tag{3}$$

and the relative variation in the thermal resistance ΔR obtained after retrofitting:

$$\Delta R = (R_1 - R_0)/R_0 \tag{4}$$

In the following, the variation of ΔM, ΔV and ΔR is considered for a single 1×1 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 Vittoria (Ragusa – Italy) made of 70 cm thick stone blocks.

The resistant bending moment of FRP retrofitted masonry is calculated by the methods presented in [29]. The equilibrium conditions of the wall cross sections yield to the definition of the neutral axis and of bending moment capacity. The shear force strength V of the wall panel is assessed following the methods presented in [30]. Considering the contribution of the masonry and of the possible FRP reinforcement, the resistant shear value is obtained considering an equivalent truss approach: more details can be found in [27].

Thermal insulation resistance has been assessed by a layer-wise approach:

$$R = \sum s_i/\lambda_i \tag{5}$$

where λ_i and s_i are the thermal conductance and the thickness of the i-th layer of the panel, see [31].

Table 2. Adopted materials costs.

Material	Spec. ecological cost	Spec. economic cost
CFRP web	77700 $kgCO_2/m^3$	650000 €/m^3
GFRP web	520 $kgCO_2/m^3$	344000 €/m^3
Polystirene panel	138 $kgCO_2/m^3$	1517 €/m^3
Diatons	0.25 $kgCO_2/m^2$	80 €/m^2
CFRP reinf. plaster	1096 $kgCO_2/m^3$	17133 €/m^3
GFRP reinf. plaster	734 $kgCO_2/m^3$	10767 €/m^3

The thickness of the retrofitting layers strongly modifies the economic cost of the six interventions. In order to obtain a general economic cost relationship between ΔM and ΔR, six different cost varying between 100 €/m^2 and 350 €/m^2 have been taken into account. In the construction cost both supply and manpower have been considered, see Table 2. These values have been obtained from the Italian public works market. In this way, six points define each cost scenario. These points represent retrofitting conditions in which the economic cost is the same. Then, a hyperbolic regression curve has been found to fit these data, see Fig. 2:

$$\Delta R(\alpha_1 - \Delta M) = \alpha_0 \tag{6}$$

where the numerical parameters (α_0, α_1) are determined by least squares approach.

The cost regression lines have been found for the ΔR - ΔV plane, see Fig. 3. As expected, CFRP reinforced plaster retrofitting scenario (c) obtained the best structural performance while scenario (a) yields to the most effective thermal performance.

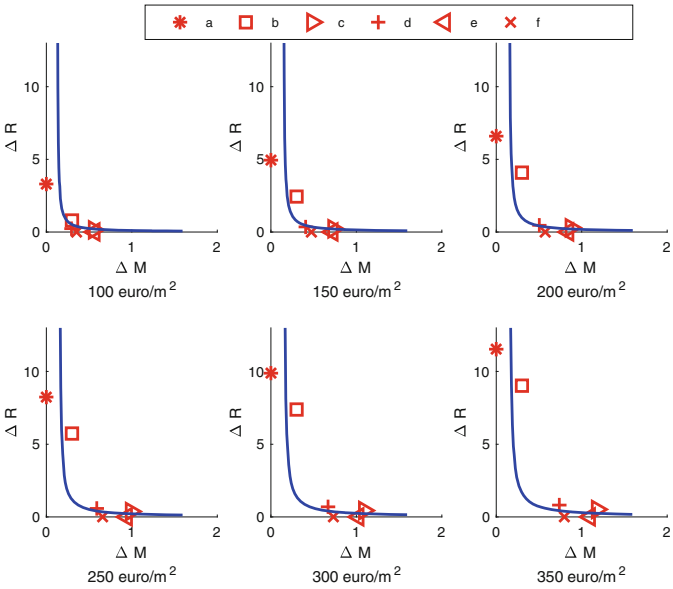


Fig. 2. Capacity regression functions ΔR - ΔM corresponding to six different budgets per square meter for the six retrofitting scenarios (a–f).

Now, it is interesting to see the problem no longer from an economic cost but from an ecological one. Given that carbon footprint can be defined as the total set of greenhouse gas emissions during the life cycle of a building, the ecological cost of each retrofitting intervention can be expressed as equivalent kg of CO_2 necessary for constructing the single 1 × 1 m masonry panel. Clearly, this computation does not assess the life cycle carbon footprint of a complete building, but it is focused only on the

masonry component and the construction stage. The detailed kg CO_2 equivalent is reported in Table 2 and has been taken from [32–34].

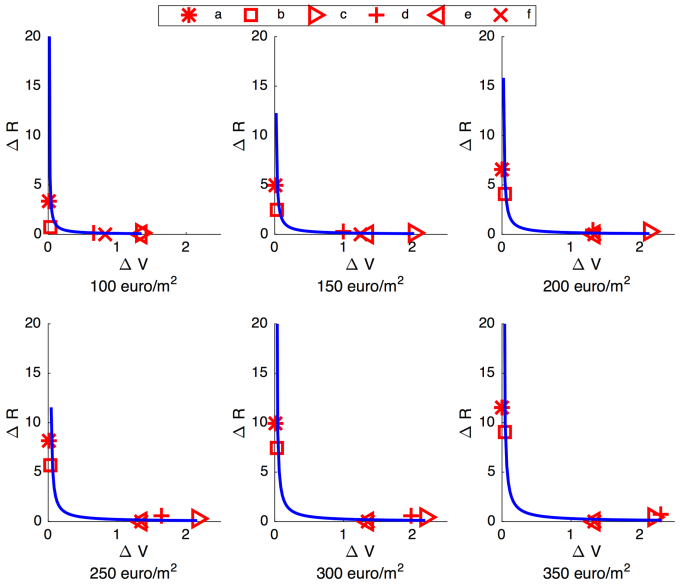


Fig. 3. Capacity regression functions ΔR - ΔV corresponding to six different budgets per square meter for the six retrofitting scenarios (a–f).

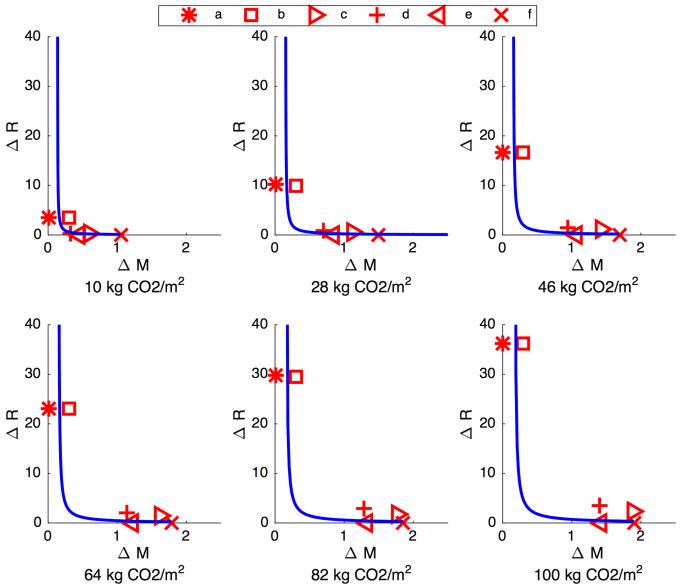


Fig. 4. Capacity regression functions ΔR - ΔM for six different scenarios of Carbon footprint in terms of CO_2 equivalent for the six retrofitting scenarios (a–f).

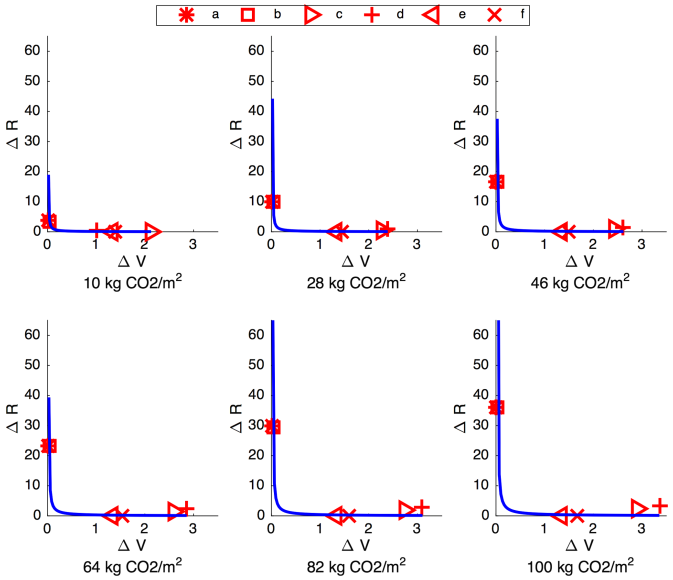


Fig. 5. Capacity regression functions ΔR - ΔV for six different scenarios of Carbon footprint in terms of CO_2 equivalent for the six retrofitting scenarios (a–f).

In this way, a set of hyperbolic regression curves, see Eq. (6) has been calculated for six scenarios characterized by a fixed mass of CO_2 equivalent. Figure 4 presents the ΔR - ΔM results and Fig. 5 the ΔR - ΔV one.

Figures 2, 3, 4 and 5 presents the iso-cost performance curves as an integrated capacity measure for the retrofitting interventions.

4 Local Demands

The retrofitting performance analysis should be based on the specific site of the building location. Indeed, there are zones in which the seismic risk is critical in comparison to the thermal conditions and vice versa. Considering the Italian example, the seismic demand is commonly expressed throughout the peak ground acceleration (PGA), see [35]. Furthermore, the thermal demand is measured throughout the Degree Day (DD) [36]

$$c_R = PGA_i/PGA_M \tag{7}$$

$$c_U = DD_i/DD_M \tag{8}$$

where PGA_M denotes the maximum PGA of Italy and PGA_i represents the peak ground acceleration for the considered i-th location of the building. Similarly, DD_M is the maximum Degree Day value for the same area and DD_i is the corresponding value for the considered i-th location.

c_R and c_U represent the "weights" of the structural and energy demands in that area. Italy is divided into 107 districts, assigning conventionally to each of them the values of PGA_i and DD_i.

In this work the assumed location is Vittoria (RG) in Sicily with c_R equal to 0.368 and c_u equal to 0.187.

A possible criterion to infer both thermal and structural demands for the design of masonry panel retrofitting intervention is represented by Eqs. (9, 10) considering respectively the ΔR - ΔM performance plane and the ΔR - ΔV plane.

$$\Delta R = \alpha \, c_R / c_U \Delta M \tag{9}$$

$$\Delta R = \alpha \, c_R / c_U \Delta V \tag{10}$$

Where α is a tuning parameter that can be assigned by the political decision-makers. Indeed, modifying α, it is possible to encourage thermal retrofitting interventions or structural ones.

5 Results

Based on the above-mentioned location (Vittoria, Ragusa) the criterions expressed in Eqs. (9, 10) and the economic (Figs. 6, 7) or ecological (Figs. 8, 9) cost regression line can be plot on the ΔR - ΔM plane or on the ΔR - ΔV plane. These Figures represent a synthetic way to evaluate the integrated retrofitting. Each crossing between a retrofitting criterion (Eqs. (9, 10)) and a cost regression curve represents an optimal retrofitting solution.

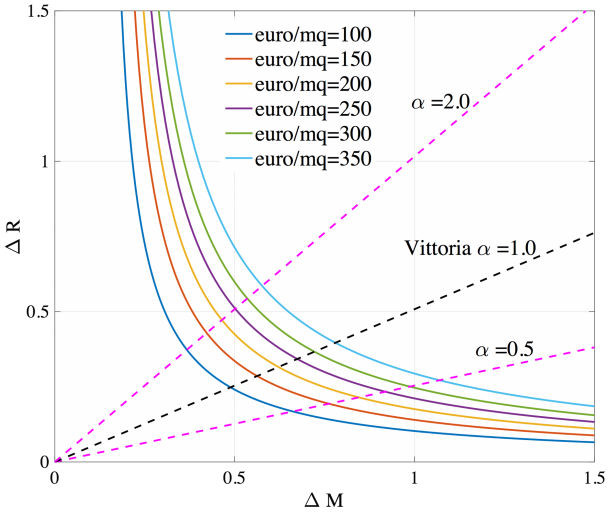


Fig. 6. Retrofitting strategy considering economic costs for plane ΔR - ΔM.

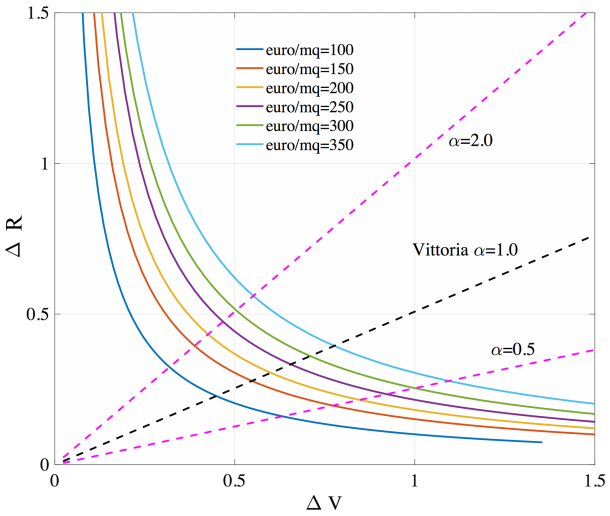


Fig. 7. Retrofitting strategy considering economic costs for plane ΔR - ΔV.

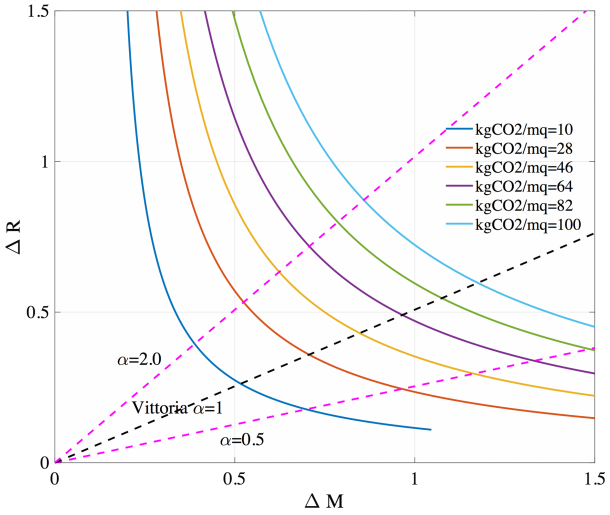


Fig. 8. Retrofitting strategy considering ecologic costs for plane ΔR - ΔM.

It is interesting to highlight that varying the α parameter (the so called "political parameter") it is possible to modify the results of the above described optimization of the retrofitting interventions, to fulfil different political strategies.

It is also important to underline that Figs. 6, 7, 8 and 9 can compare the ecological and economic cost of the same performance improvement. For example, in the given case an improvement of ΔR = ΔR = 0.5 corresponds to 300 €/m^2 and in an equivalent way to 26 kgCO_2/m^2. This information can be of primary importance to plan a sustainable retrofitting of urban areas and infrastructures.

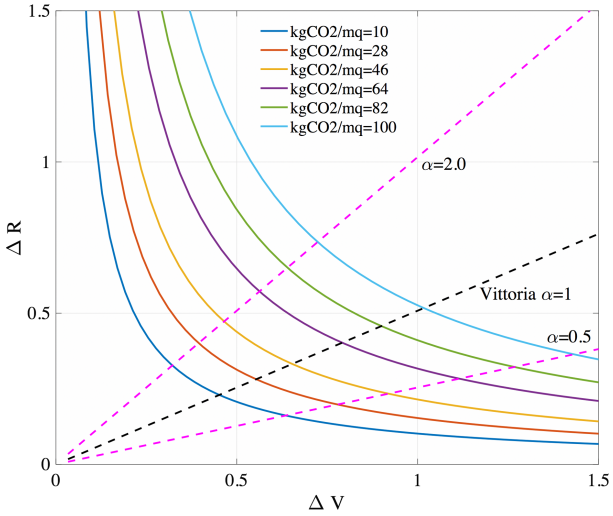


Fig. 9. Retrofitting strategy considering ecologic costs for plane ΔR - ΔV.

6 Conclusions

In this paper the application of an integrated approach to evaluate structural and thermal retrofitting strategies for masonry walls has been presented. Ecological (equivalent CO_2) and economic costs of each examined retrofitting solution have been evaluated and compared. Six representative retrofitting interventions have been parameterized by the improvement of thermal resistance, bending moment and the shear structural strength. The economic and ecological costs of the retrofitting have been evaluated to map the capacity of the retrofitting interventions in the structural and thermal framework. The local site demand has been accounted with specific parameters based on the seismic and the thermal characteristics of the zone.

The main results presented by Figs. 6, 7, 8 and 9 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.

Thus, in order to establish an urban redevelopment plan, this approach can give to the political decision makers an effective and synthetic view to manage both economic and environmental aspects. Indeed, the retrofitting strategy can be extended to the territorial scale similarly to what has been done for the thermal case in China [37].

Further developments of this approach are expected considering other constructive components. Indeed, an extension of this approach to existing concrete and steel frames (see [38, 39]) can be useful and effective.

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