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ECONOMIC – TEMPORAL – ENVIRONMENTAL POST-EARTHQUAKE SCENARIOS FOR RC-MRF EXISTING BUILDINGS

Monica MASTROBERTI[1], Marco VONA[2], Dionysios BOURNAS[3], Helena GERVASIO[4]

ABSTRACT

Recent seismic events have been highlighted the strong vulnerability of existing buildings, responsible of huge amount of economic losses, low community resilience and environmental impacts.
Seismic risk mitigation strategies oriented in reducing the effects of seismic vulnerability, as consequence of possible arriving earthquakes should be defined according to different point of view.
In this work, probabilistic losses-temporal-environmental seismic scenarios for the most widespread RC-MRF building types have been defined. They are important support tools for decision makers in definition of accurate and multi-disciplinary seismic risk mitigation strategies in reducing the post-earthquake losses, recovery time and the environmental effects due to the building reparation. Seismic scenarios based on convolution between Fragility Curves and Cost-Temporal-Environmental Repair Functions have been proposed. Both the Fragility Curves and the repair functions have been defined based on accurate analysis of structural performance at component level. In defining of Cost-Temporal-Environmental Repair Functions, Damage Consequence Models for structural and non-structural components have been defined. The latter quantify the consequence of damage at component level in terms of repair cost, repair time and repair environmental impact. The repair functions derive from an extensive use of DCMs with regard to the whole building damage distribution.
The Life Cycle Assessment procedure has been employed in definition of Environmental Repair Functions and in environmental characterization of Damage Consequence Models.

Keywords: Existing RC buildings; Fragility Curves, Repair – Time and Environmental Functions – LCA Analysis.

1. INTRODUCTION

The quantification of the expected consequences of the seismic vulnerability plays a key role in defining new and more effective seismic risk mitigation strategies (Vona et al. 2017). Recent seismic events have been highlighted, as the high vulnerability of existing Reinforced Concrete – Moment Resisting Frame buildings, designed with any seismic previsions is responsible of economic losses, direct and indirect, very slow reconstruction process and environmental effects harmful to humans and ecosystem. Seismic risk mitigation strategies and resulted retrofitting priorities based only on the structural seismic risk level of buildings are incorrect. It completely neglects several important issues such as the economic, financial, resilient and environmental consequences of buildings damage.

[1]PhD Student, University of Basilicata, Potenza, Italy, monica.mastroberti@unibas.it
[2]Professor, University of Basilicata, Potenza, Italy, marco.vona@unibas.it
[3]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
[4]Scientific Officer, European Commission, Joint Research Centre (JRC), Directorate for Space, Security and Migration, Safety and Security of Buildings Unit, Ispra (VA), Italy, Helena.dos-santos-GERVASIO@ec.europa.eu

In this study is proposed an engineered procedure in defining seismic scenarios according to economic - resilient and environmental point of view and at building types level. The built seismic scenarios provide information on the expected values of the direct economic losses, the recovery time and the CO_2 emissions as consequence of a wide range of seismic intensities. For complete seismic risk evaluation their integration with hazard curves has a key role. The multidisciplinary seismic scenarios have been built according to a global building based assessment procedure. In fact, they derive from the convolution between fragility curves and repair functions. In this study are proposed advanced cost ratio – time ratio and CO_2 ratio repair functions, based on the analysis of the performance of each building structural and no-structural element resulted from NLDAs. The components performance are related to necessary repair cost – repair time and CO_2 emission thought advanced and new Damage Consequence Models.

1.1 METHODOLOGY FOR ECONOMIC – RESILIENT – ENVIRONEMNTAL SEISMIC SCENARIO

According to the traditional building based assessment methodology (D'Ayala et al. 2013), the seismic scenario derives from the convolution of the fragility curves and expected values for parameters expressing the consequence of damage in different manner (such as repair cost, financial losses, repair time, environmental, social and political issues). The fragility curves accounting for the occurrence probabilities of the damage levels given a seismic intensity, and subsequently are weighted for the expected values of the damage consequence. Analytically, a seismic scenario is expressed by the equation 1.

$$\mathrm{E}[DC \mid \mathrm{I}] = \sum_{i=1}^{n} \mathrm{E}[DC \mid \mathrm{d}_{l,i|\mathrm{I}}]\,\mathrm{P}[\mathrm{d}_l = \mathrm{d}_{l,i} \mid \mathrm{I}] \tag{1}$$

Where $\mathrm{E}[DC \mid \mathrm{d}_{l,i|\mathrm{I}}]$ is the expected value of the consequence of the damage level $d_{l,i}$ achieved for a given intensity, I. It may be expressed in terms of expected value of the repair cost $E[C_{r,r}|dl_{i|I}]$, repair time $E[T_{r,r}|dl_{i|I}]$ and global warming $E[GWP_{r,r}|dl_{i|I}]$ due reparation. Whereas $\mathrm{P}[\mathrm{d}_l = \mathrm{d}_{l,i} \mid \mathrm{I}]$ is the occurrence probability of the damage level, given the seismic intensity. According to the different damage consequence parameters , different types of seismic scenarios may be built:

$$E[C_{r,r}|I] = \sum_{i=1}^{n} E[C_{r,r}|dl_{i|I}]\,P[DS = dl_i|I]$$

DIRECT LOSSES SEISMIC SCENARIO (repair cost)

$$E[T_{r,r}|I] = \sum_{i=1}^{n} E[T_{r,r}|dl_{i|I}]\,P[DS = dl_i|I]$$

RECOVERY SEISMIC SCENARIO (repair time)

$$E[GWP_{r,r}|I] = \sum_{i=1}^{n} E[GWP_{r,r}|dl_{i|I}]\,P[DS = dl_i|I]$$

ENVIRONMENTAL SEISMIC SCENARIO (Potential Global Warming)

The Figure 1 shows the Flowchart of the proposed procedure in defining the main items of a seismic scenario.

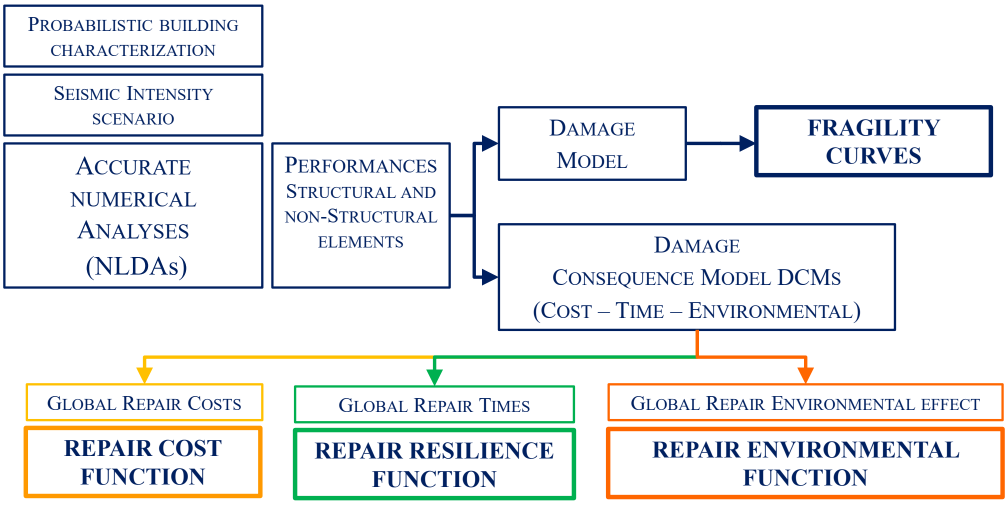

Figure 1. Flowchart of the proposed procedure in defining the main items of a Seismic scenario.

In this study, a procedure for Fragility Curves definition based on the analysis of the building local performance derived from probabilistic building characterization and Non-linear Dynamic analysis (NLDAs) is proposed. The NLDAs numerical results for a wide set of Reinforced Concrete – Moment Resisting Frame (RC-MRF) building types of previous studies of the authors have been employed (Masi and Vona, 2012, Vona 2014). The damage model is a fundamental step for reliable fragility curves definition. The Damage Model proposed is based on damage levels coherent with the qualitative description of the damage grades of the macro-seismic EMS-98 intensity scale (Grünthal, 1998); and at each of them is assigned a quantitative description in terms of limit states for ductility ratio of the more critical vertical structural elements (Table 1), for more details see Vona, 2014. They are coherent with seismic assessment procedure provided by seismic codes (such as NTC, 2008).

DL0 Grade 0 EMS98	DL1 Grade 1 EMS98	DL2 Grade 2 EMS98	DL3 Grade 3 EMS98	DL4 Grade 4 EMS98
IDR $\leq$ 0.1% and $DR_y \leq 0$	IDR > 0.1% and $DR_y \leq 0$	$0 \leq DR_p < 0.25$	$0.25 \leq DR_p < 0.75$	$DR_p \geq 0.75$

Table 1. Qualitative description of the considered Damage Model (IDR is the interstorey drift ratio, DR is the ductility ratio, $DR_Y=\theta/\theta_y$ and $DR_P= \theta - \theta_y / \theta_u - \theta_y$).

The analysis of achieved structural performance at component level is also fundamental in defining the repair cost, temporal and environmental functions. They account for the variability in building damage distributions into the same global damage level consequence of the mechanical-geometrical-structural uncertainties and of the earthquake-to-earthquake variability. The damage distribution variability is responsible of differences in repair costs, repair times and environmental effects. To define these functions, the buildings damage distributions have been investigated through Damage Consequence Models (DCMs). In study, Damage Consequence Model (DCM) for structural (beam-column) and non-structural components (infill panels), typical of RC-MRF building have been built. The DCMs relate the performance of the structural and non-structural elements to the consequence of achieved damage (Mastroberti et al. 2017). A Complete DCM consists in relationships, one for each component performance level that related the expected damage, the necessary repair activities, the consequent repair cost, time and environmental impact. In previous study of the authors (Mastroberti et al. 2017), based on experimental results and code suggests the relationships performance level – expected damage have been defined for structural (beam-column) and non-structural (infill panel) components. Subsequently, according with practical activities, professional and company information, sets of repair activities have been assigned. Based on Price List, the relationships are completed in terms of cost for the repair activities (accounting for the quantities information provided in expected damage characterization), and repair times (accounting for the percentage of incidence of worker, the actual price of a worker for hours, the working team, etc.). Further, to the aim of this work, the DCMs relationships may completed in terms of environmental impacts of repair activities. The Life cycle analysis (LCA) of repair activities should be performed (Gervasio et al. 2016, Vitiello et al. 2016, Napolano et al. 2014). In global terms, the Global Warming Potential (kg CO_2-Eq.) as environmental effect of repair activates may be considered. Particularly, the effects in Global Warming Potential due to raw material supply, transport and manufacturing and of transport of construction materials and construction equipment's to the site required for reparations have been considered (A1-A4). The extensive use of DCMs with regard to the whole building, accounting the probabilistic building characterization and the performance variability due to the earthquake-to earthquake ones, allow the definition of samples of Global Building Repair Cost - Time and Global Warming Potential, for each global damage level (Table 1) and different seismic intensity ranges. Consequently, the Repair Cost – Time and the Global Warming Potential functions are the theoretical density functions that best fit the empirical ones. Based on a practical point of view, for feasibility evaluation of the repair activities than the demolition and reconstruction one, the repair costs, times and global warming potential values are normalized respectively than the total building replacement cost, time and environmental effect (in kg CO_2-Eq). In this way, functions that provide values for the expected consequence of damage in terms of cost ratio, time ratio and Global Warming Potential ratio for damage level and seismic intensity range are defined.

2. CASE STUDY ON EXISTING RC-MRF BUILDINGS

In order to better explain the procedure for multi-aspect seismic scenario, the proposed methodology has been employed for the widely used Reinforced Concrete with Moment Resistant Frames (RC - MRF) Italian and European building types. The building types considered in the previous studies of the authors (Masi&Vona, 2012; Vona, 2014; Vona & Mastroberti 2017), based on their characteristics and acquired numerical performance have been considered. Detailed information about building types, their characteristics, numerical performance useful for this study are reported in (Masi&Vona, 2012; Vona, 2014; Vona & Mastroberti 2017). The main geometric characteristics (infill panel distribution and their effectiveness, number of story) of the types are shown in Figure 2.

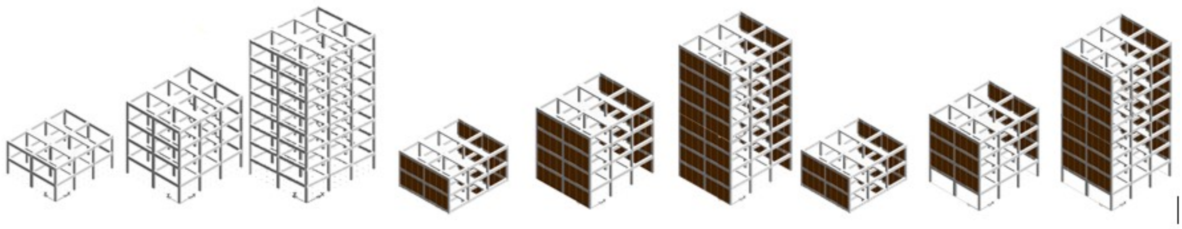

Figure 2. Geometric characteristics of the RC-MRF building types analysed - Storey number (2,4,8) and infill panels distribution and effectiveness (Bareframe BF, InfillFrame IF, PilotisFrame PF).

Based on the age of design and of construction, the Reinforced Concrete with Moment Resistant Frame (RC-MRF) types have been analysed as: RC-MRF low-engineered and designed with an Old Code (OC) and a Pre-modern seismic Code (PC) typical of Italy. According to the statistical distributions of the concrete strength of two construction periods, different concrete strength values have been considered. Each type has been accurately modelled and analysed through NLDAs and applying 50 recorded accelerogramms (Masi&Vona, 2012). To NLDAs 50 accelerograms have been selected considering the Housner Intensity range 0.09 - 2.34 m and the PGA one 0.05 - 0.50 g. According to the damage model of Table 1 and selecting the Housner as reference parameter for seismic intensity (Chiauzzi et al, 2012 and Masi et al. 2011), new fragility curves have been defined based on accurate numerical results.

To define function for the cost, time and Global Warming Potential ratio at typological level, the damage distributions numerical obtained have been analysed based on Damage Consequence Models

(DCMs). The Damage Consequence Models of two performance groups, beam-column and infill panels, are defined. In particular, the Damage Consequence Models built in previous study of authors (Mastroberti et al. 2017), which repair costs were quantified based on List Price of Abruzzo Region of 2014, have been further characterised in term of repair time and kg of CO_2-Eq. For repair time characterization the percentage of incidence of work as prescribed by the List Price of Abruzzo Region of 2014 are considered. The actual price of a worker for hours of 20 euro, and a working team, of 3 worker are considered. Finally, the LCA analysis has been performed for the repair activities for assessment of the environmental effects. The primary data for LCA have been retrieved from the database GaBi and from the Environmental Declaration Product (EDP) of materials employed. They give information on the amounts of different impacts (Global warning, Depletion of Abiotic Resources, Acidification, Eutrophication etc.) for specific unity of material (i.e. the impacts provided by 1 kg of concrete), and respectively in each stage of the life cycle of the material (Modules A1 to D) (EN 15804:2012 + A1:2013 and EN 15978:2011). In this study, the environmental effect has been estimated only in terms of Global Warming Potential [kg CO_2 eq.]. The Global Warming Potential produced by repair activities (prescribed by the DCMs) has been evaluated multiplied the effective amounts of materials for the Global Warming Potential produced by unitary amounts of material, and respectively for the A1-A3 stages. The effects of the transport of new materials to construction site and to landfill of the demolished material (i.e. the removal brick and plaster needed for new installation) has been evaluated based on Global Warming produced by the transport of 1000kg of material per 1 kilometer.

In Table 2 is reported an example of obtained DCMs for the structural and non-structural performance groups considered.

COMPONENT GROUP	EPP	DAMAGE LEVEL	PERFORMANCE LEVEL	MEAN REPAIR COST (per unit)	MEAN REPAIR TIME (per unit)	MEAN GWP [Kg CO_2 eq] (per unit)
DCM beam - column	Ductility (θ)	Weak Damage	$0,75\ \theta_y \leq \theta \leq 0,25\ \theta_u$	920 €	2 days	275 Kg CO2 eq.
		Moderate Damage	$0,25\ \theta_u < \theta \leq 0,50\ \theta_u$	1 400 €	3 days	298 Kg CO2 eq.
		Extensive Damage	$0,50\ \theta_u < \theta \leq 0,75\ \theta_u$	1 700 €	3 days	416 Kg CO2 eq.
		Near Collapse	$0,75\ \theta_u < \theta \leq \theta_u$	3 200 €	6 days	523 Kg CO2 eq.
DCM masonry infill panel	Drift ($IDR_{\%}$)	Weak Damage	$0,1 \leq IDR_{\%} \leq 0,3$	650 €	2 days	562 Kg CO2 eq.
		Moderate Damage	$0,3 < IDR_{\%} \leq 1$	1 050 €	2 days	943 Kg CO2 eq.
		Extensive Damage	$1 < IDR_{\%} \leq 1,75$	2 500 €	5 days	3450 Kg CO2 eq.
		Near Collapse	$IDR_{\%} > 1,75$	2 900 €	5 days	3450 Kg CO2 eq.

Table 2. DCMs for beam-column and masonry infill panel characterized in terms of cost-time and Global Warming effects of the reparation activities required for each performance level. For reason of brevity, the descriptions of expected damage and of the required repair activities are neglected. For more details, see (Mastroberti et al. 2017).

According to DCMs of Table 2, each numerical damage distribution has been characterized by a global repair cost, repair time and repair environmental impact. Subsequently, they have been respectively normalized than the standard Italian cost, time and Global Warming Potential for building rebuilding and demolition. Based on the obtained probability distributions of cost-time and kg Eq CO_2 ratio, log-normal functions have been defined. According to the results of the Kolmogorov-Smirnov estimator, applied to different density functions (Log-normal, Normal, Beta, Gamma, Weibull, Exponential) and empirical ones, the Log-normal distribution is defined as the best fit in empirical frequency discrete distributions (Yamin et al. 2017).Same results of the procedure are reported in Figure 3. The Figure 3 (a) shows the fragility curves for the 4 story BareFrame types (Old Code). Moreover, the functions describing the probability distribution (probabilities 0-1) of the cost ratio (b), time ratio (c) and global warming ratio (d) for all the damage levels occurring in a predefined seismic intensity ranges are reported. The considered Housner intensity ranges has been defined as coherent with the main differences in repair costs into the same global damage level and are related to the grades of the EMS98 scale~~s.~~

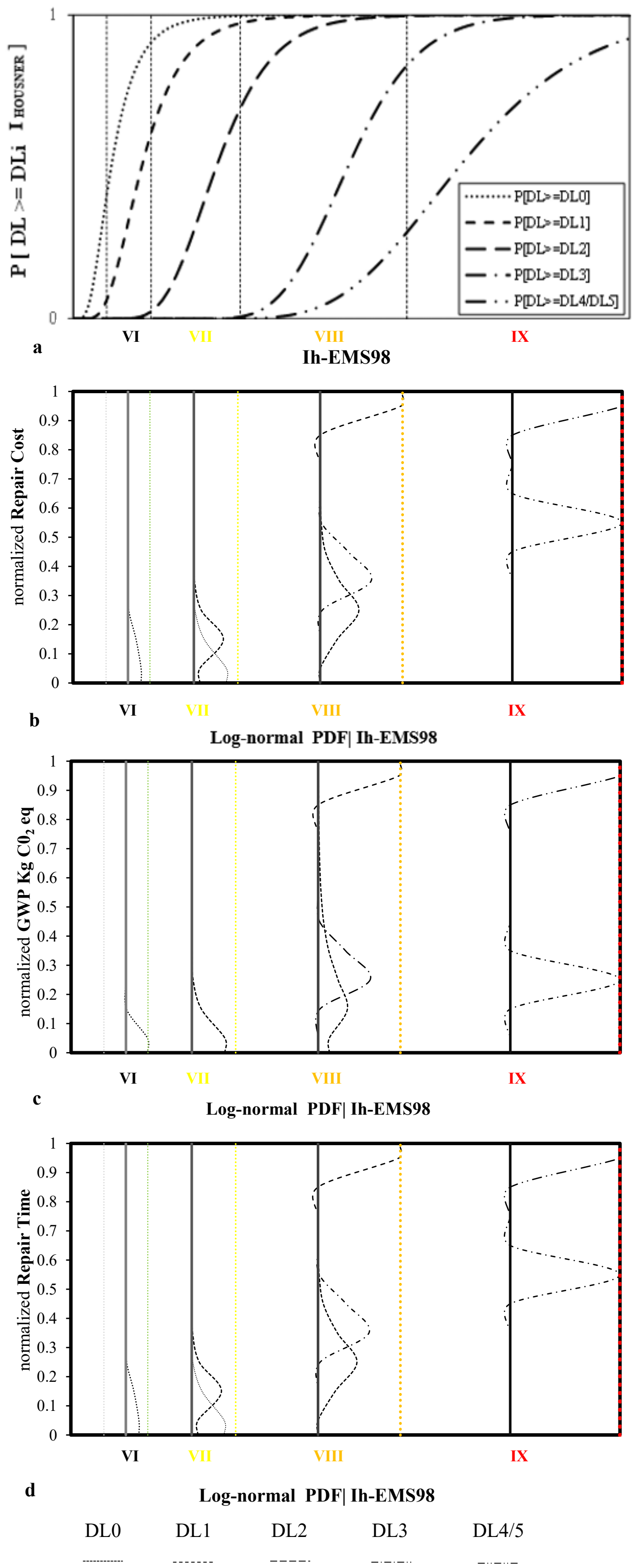

Figure 3. Fragility curves and cost ratio, time ratio and global warming ratio function (different for global damage levels and seismic intensity ranges) of 4 story BareFrame OldCode type.

Finally, according to equation 1, typological Economic-Resilient-Environmental seismic scenarios have been built based on convolution between Fragility Curves and Repair Cost Functions, Repair Time Function and Environmental Repair Impact Function, respectively. In Figure 4 are reported examples of obtained Economic-Resilient-Environmental seismic scenarios, for the story BareFrame OldCode type.

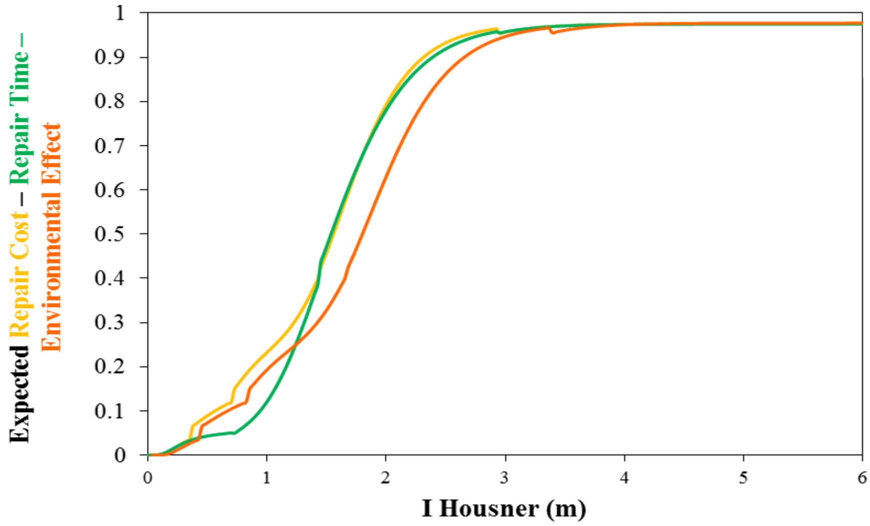

Figure 4. Economic-Resilient-Environmental seismic scenarios for 4 story BareFrame OldCode type.

Scenarios such as reported in Figure 4 are fundamental tools in seismic risk mitigation strategies definition, providing information on the expected economic-resilient-environmental consequence of possible arriving earthquakes.

3. CONCLUSIONS

In this study an engineered approach in seismic scenario definition, based on different types of consequence of the building damage has been proposed. It is based on fragility curves and repair functions. The novelty is in the repair functions definition. They are based on an accurate analysis of the performance at component level. These latter are related to the required repair cost – time and environmental effects through Damage Consequence Models. Complete Damage Consequence Models for the typical structural and non-structural components of RC-MRF types are proposed and applied. As result, innovative economic - resilient and environmental scenarios are proposed for several RC-MRF building types, and along a wide range of seismic intensities. They are useful tools in seismic risk mitigation strategies and in defining accurate and multi-disciplinary retrofitting strategies.

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