Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2017) 3213-3224

ECCOMAS
Proceedia

COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June 2017

NOVEL MODELS AND TOOLS TO EVALUATE THE ECONOMIC FEASIBILITY OF RETROFITTING INTERVENTION

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Keywords: Seismic Performance, Fragility Curve, Repair Cost, Depreciation, Retrofitting Strategies

Abstract. *In order to mitigate the seismic risk, politician decision-makers, insurance companies, banks, professional engineers, private owners, (despite operating at different territorial scale and with different aims) need of accurate tools able to highlight the negative economic effects of an earthquake in terms of reduction of building economic value and earning power effective time. In this way, accurate seismic direct economic losses scenarios have a key role. In this paper, a new procedure for probabilistic, analytical seismic direct economic losses scenarios has been discussed and applied. Economic fragility curves for different existing building types (RC-MRF) have been defined. The economic feasibility of different form of retrofit interventions strongly depends by the entity of negative seismic damage economic effects, in terms of reduction of building economic value and earning power effective time. In this paper, a first attempt in estimation of building residual economic life after an earthquake has been performed. An innovative tool based on the integration of seismic direct losses models in building life-cycle cost value models has been presented and applied. This tool plays a fundamental role in promotion of a private seismic risk mitigation strategies, highlighted as accurate retrofitting intervention in peacetime could be able to minimize the negative seismic financial effects that is a primary objectives of owners-investors.*

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Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5639.18165

1 INTRODUCTION

The high vulnerability of existing buildings is a crucial issue in modern earthquake engineering. This issue plays a fundamental role in seismic risk mitigation strategies and it should be strongly considered in all planning activities. The available studies are generally based on buildings stock and the possible seismic occurrence of earthquakes [1], [2], [3]. The main problem is the strong disproportion between the available public economic resources and the buildings that require retrofitting interventions.

For this reason, the accurate definition and the implementation of effective seismic risk mitigation strategies require a multidisciplinary approach based on new and effective tools. These tools should be based on accurate studies of seismic hazard, vulnerability, and economic consequence of earthquake. Unfortunately, these tools and studies are often remained an academic topics and their application is still largely unrealized [4].

Recently indirect actions able to grow the awareness of seismic risk, seismic vulnerability, and the importance of maintenance operations in the population have been implemented [5]. Actually, tools able to indirectly recall the owners to seismic issues could be identified developed and promoted. A private seismic risk mitigation process, differently to public one, could be moved also by economic-financial convenience criteria.

In this work, new approach to quantify the reduction of economic life due to seismic damage has been described. This approach is based on integration of seismic direct losses scenarios in building life-cycle economic value models. New and effective seismic direct losses scenarios for existing RC-MRF buildings is illustrated. The proposed approach has been also applied and validated.

2 METHODOLOGICAL APPROACH

Seismic direct losses scenarios play a key role in seismic risk mitigation. It provides information about the expected economic losses refer to all possible arriving earthquakes [3]. Generally, a seismic economic losses model could be referred to different kind of losses (direct and indirect). The direct losses are the repair costs necessary to restore the buildings pre-earthquake state [1].

In Figure 1, a flow chart illustrative of the built process for losses scenarios is reported. It is based on the convolution between fragility curves and repair cost functions. In next part of the section, several considerations and statements about the definition both of fragility curves and repair cost functions are reported.

The fragility curves are need in order to provide accurate information about the structural performance in a probabilistic way. The probability of exceeding for specific damage levels is evaluated. In several works, the advantages and disadvantages of different FCs built approaches and analyses methods have been discussed [6], [7], [8].

The accuracy of FCs mainly depends on Damage Model (DM) [9]. A Damage Model consisting in different damage levels, which should be characterized by a qualitative description of expected damage, a structural limit state, and a global engineered response parameter threshold. In order to define accurate seismic risk mitigation strategies the damage levels should be able to identify the building seismic safety level during and after the event. Consequently, limit states referred to structural performance of primary structural elements should be employed.

Based on FCs, a seismic direct losses scenario can be defined. It is a probabilistic tool able to provide information on direct economic losses when a given seismic intensity occurs.

Mathematically, a seismic direct losses scenario is computed through a probabilistic convolution operation between fragility curves and repair cost functions, as:

$$E\left[C_{r,r}\middle|I\right]=\sum_{i=1}^{n}E\left[C_{r,r}\middle|dl_{i|I}\right]P\left[DL=dl_i\middle|I\right] \tag{1}$$

Where $E_i\left[C_{r,r}\middle|dl_{i|I}\right]$ is the expected value of the repair cost function for a specific damage level $dl_{i|I}$ and intensity range I . $P\left[DL=dl_i\middle|I\right]$ is the occurrence probability of damage level $dl_{i|I}$ for a specific seismic intensity value I, definable starting from the FCs.

In this work, the main efforts have been made in order to define the repair cost function in the more accurate way.

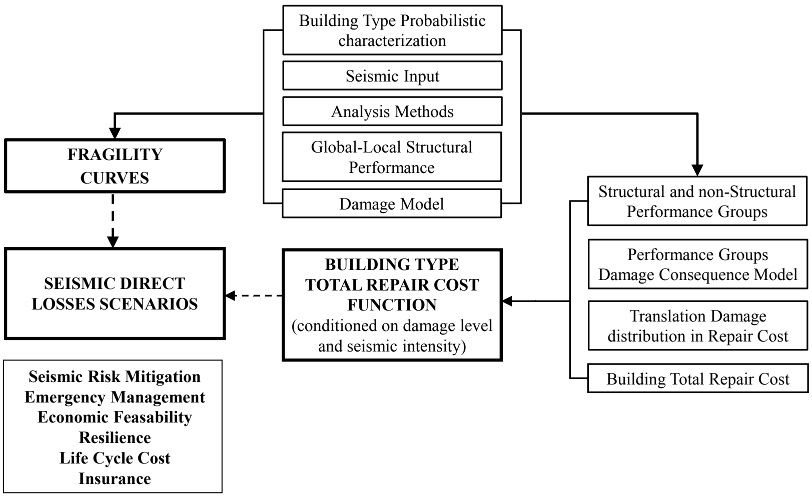

Figure 1. Procedure for analytical Seismic Direct Economic Losses Scenarios.

The strong variability in performance of each building type have been considered by FCs. Then, for same type the difference in damage distributions provides different consequent global repair costs. Repair Cost Functions have been defined for each building type, as different for each damage level and macro-seismic intensity range. For Repair Cost Functions a continue probability density function has been considered in order to be the best fit of discrete empirical frequency distribution of Ratio Cost.

The Ratio Cost ($C_{r,r}$) is the ratio between the total repair cost that are need to restore the pre-earthquake condition and the building replacement cost (including the demolition cost), [6]; it is ranging between 0 and 1.

Damage Consequence Models (DCM) for different performance groups have a key role in definition of building global ratio cost. DCMs are tools able to correlate the seismic damage of each structural and non-structural element to their repairing costs. As performance group, different components of building (such as column-beam, column-slab, shear wall, masonry wall etc.) could be considered. In this way, it is to be highlighted that accuracy of relation seismic damage of each structural and non-structural element to its repairing costs strongly depends on approach used to define FCs (in particular, modeling and analysis methods), as briefly reported in figure 2. Only accurate approach, based on macro-elements models, reliable behavior models, and structural analysis methods allow knowing the real damage state of each structural and non-structural elements.

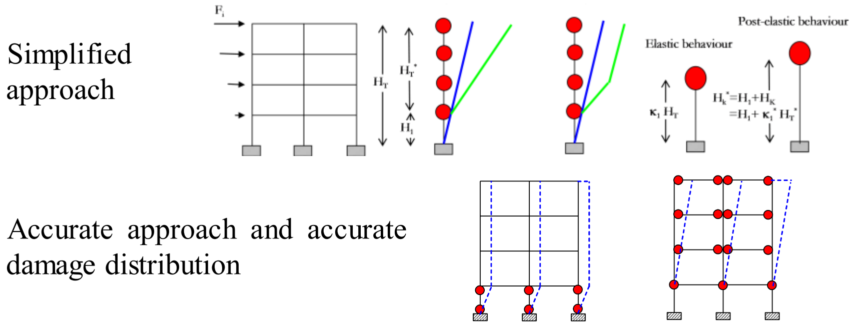

Figure 2. Accuracy of FCs and damage distribution analysis.

Damage states should be defined for each performance groups. Moreover, a relationship between damage states and damage levels of engineering demand parameters should be defined. In addition, detailed repair actions and associated repair costs should be identified for each performance group and damage states. Repair cost must be evaluated including all collateral, preliminary and supplementary works. Finally, for each investigated types total repair cost has been obtained combining the repair costs associating at each structural and structural components through specific DCM.

In order to evaluate the benefit of retrofitting, the building owner should be considered a consumer or production goods depending on the economic agents that require them to conform to the behavior all pattern of the consumer or investor [10]. This issue could be used also to prioritization strategies [11].

For many owners-investors the maintaining of building property economic value and the increasing of building economic life is the best goal. In this way, the interventions (such as extraordinary maintenance, repair, retrofitting, consolidation) must be able to meet also this objective, otherwise the intervention less frequently are realized. Therefore, the assessment the economic feasibility and the economic effects of an intervention are important questions.

In this way, building life cycle economic value model able to describe the temporal trend of building economic value during its lifetime, and provide indications on building economic life has a key role.

The property cost value may be split into two part: building and land cost value. Both vary in time following absolutely different dynamics [12]. The land value due to the land rent, normally, in time does not undergo any depreciation, indeed more readily, it grows. The first building part of deprecation is due to the age that determines a progressive achievement of service life. A second part of depreciation, always connected to physical degradation, is the income decay depreciation. Other forms of depreciations are linked to building obsolescence, that provide a decline in value not directly related to physical deterioration, but resulted from an outdated appearance and increased demands by occupants for a more efficient and controlled facilities. In [12] has been reported a simplified methodology for evaluation of temporal trend of cost value taking into account the deductions linked to the different forms of deprecation. In accordance with this procedure, the building is subdivided in functional elements (or homogeneous parts); for each of them the percentage of cost respect to total reconstruction cost and the depreciation functions must be evaluated.

The economic life concerns with earning power; without topics linked to cultural heritage, a building is often demolished before its physical life expiry to permit a more profitable use of the site, or because it is found cheaper to clear and rebuild rather than to adapt the building to the change requirement. Analytically, the end of building economic life corresponds with the point in which the depreciated building value is equal to zero. The above concepts are considered in this work in order to define the proposal.

3 APPLICATION AND RESULTS

In this section, a first application of the proposed approach is reported. Firstly, analytical FCs for several RC-MRF existing building types (Figure 3) have been defined from previous NLDAs numerical results [6] and following the improved approach of [8].

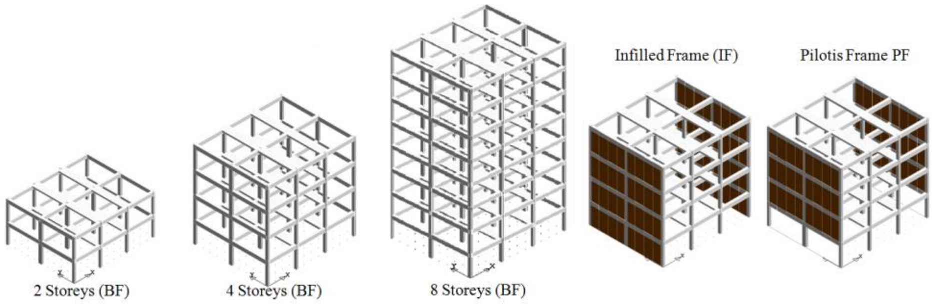

Figure 3. Considered building types: number of storey and infill distributions.

More detailed information about structural, geometrical, and mechanical characteristics of each considered building types and details about NLDAs are reported in [6], [8] and [9]. Fragility curves have been defined considering the Housner intensity.

Consequence Damage Models have been defined using the price list of Abruzzo Region of 2015. Wide set of results of experimental tests and real post-earthquake observations have been used to validate the model.

Damage consequence models for three performance groups have been built: beam-column joint, slab-column joint, masonry infill panel. The ductility ratio has been considered the most relevant parameter for beam-column joint and slab-column joint performance group. However, the interstorey drift ratio for masonry infill panel.

Four damage states have been considered for each performance groups. Each damage state has been characterized by a specific threshold value for the selected engineering response parameter, and a set of repair activities necessary to restore the components to its pre-earthquake state. In these latter were been included all necessary collateral works, such as installation of scaffoldings, installation of shoring to support gravity loads, demolition of partition and furnishing that obstruct the access to RC members that must be repaired, consequent replacement and restoration, technical costs etc. The damage consequent models have been also defined for masonry infill panels.

In Figure 4, for three types considered as example (BF-IF-PF 4 storey Old Code), the FCs and the associated repair cost functions are reported in terms of damage level and macro-seismic intensity grade. In this application, the EMS-98 intensity [14] has been considered as reference intensity. In this way, based on relationship between European macro-seismic scale EMS-98 and Housner intensity (I_H) proposed in [3] the equivalence between I_H and EMS-98 has been defined.

A repair cost function coherent with near collapse condition suggested by the Italian and European seismic codes based on ultimate rotation ($3/4\ \theta_u < \theta < \theta_u$) has been defined. Moreover, an un-repairable collapse condition has been considered and a unitary ratio cost has been assigned. The Figure 4 synthetically characterizes the building types (BF-IF-PF 4 storey Old Code) structural fragility and their monetary consequence.

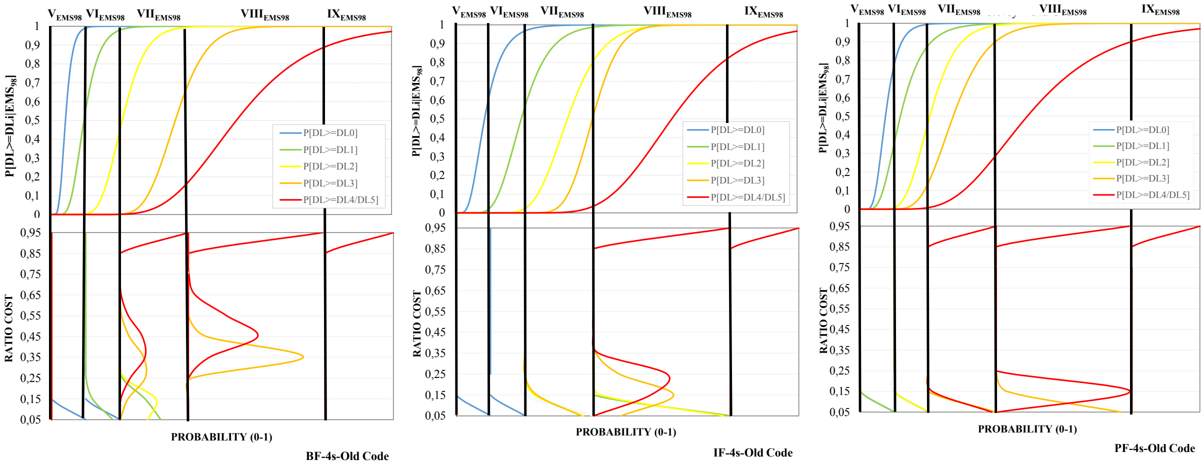

Figure 4. Fragility curves and Repair Cost Functions for RC-MRF Bareframe (BF) – Infillframe (IF) – Pilotisframe (PF) 4 storey - Old Code.

The repair cost functions reported in Figure 4 highlight difference both in mean and in variance value of repair cost for the same damage level (or seismic risk level) and seismic intensity range.

In particular, the BareFrame type is always characterized by mean values of ratio cost greater than those characterize Infilled and Pilotis type. A similar consideration is valid for variance values. These results are coherent with their different deformation capacity. This latter implies a different number of severe damaged non-structural elements and of structural elements at the same or low yield level.

A global relationship interstorey drift ratio – ratio cost has been defined for existing RC-MRF building types taking into account the structural performance variability in a large range of seismic intensity (Figure 5).

The global relation has been defined characterized all considered building types in terms of economic consequence of structural performance (employing the consequence damage models and a simple assembly procedure) and maximum interstorey drift ratio.

The Figure 5 shows a strong correlation between the interstorey drift ratio and ratio cost until infill panel collapse interstorey drift ratio (0.75-1%). The Figure 5 shows a step in interstorey drift ratio – ratio cost relation in correspondence of 0.75-1% interstorey ratio; this latter is due to the contribute of structural damage to ratio cost, that starts to be relevant. In particularly, for the same interstorey drift ratio, BF types ratio cost is greater than IF and PF ones.

Then, overlapping the infill panel collapse interstorey drift ratio, the relation depends by deformation capacity, which influences the entity and distribution of structural damage.

The deformation capacity also influence the occurrence of collapse; PF types have been characterized by unitary ratio cost soon after the collapse of few infill panels, in general at upper of pilotis storey.

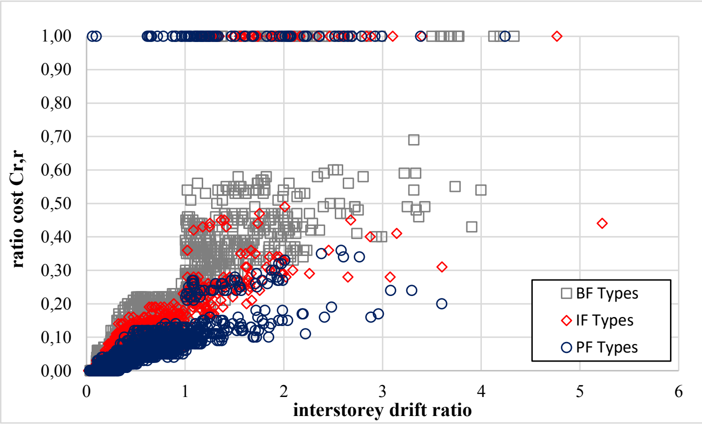

Figure 5. Analytical relationship interstorey drift ratio-ratio cost for existing RC-MRF building types.

The reliability of built consequence damage models and repair cost functions have been validated on the basis of L'Aquila earthquake reconstruction program and its resulting repair costs.

After L'Aquila earthquake (9 April 2009) several Ordinances of the Council Prime Minister [15], [16], have been issued in order to regulate the reconstruction process. In particular, they have established that the financial support of the Italian government to the reconstruction was given and it is managed by private owners. The financial available resource was based on the building usability rate, as defined by in situ inspections [13] and [17]. Assigned the usability rate for each damaged building, professional engineers were engaged by owners; repair and strengthening interventions have been defined and the corresponding costs have been computed. These projects have been the technical support in order to define the funding applications by the owners. These funding applications have allowed to collect a database containing information on 5775 residential buildings of several municipalities and located outside of the historical centre of the L'Aquila.

In order to validate the DCMs and consequent repair cost function the following correspondence between usability rating - damage level has been considered:

- Damage Level 1-2 \ usability rating B and C;
- Damage Level 3\ usability rating E-B (E treaty as B);
- Damage Level 4 \ usability rating E;

In Table 1, the obtained mean and standard deviation repair cost values for BF-IF-PF types 4 storey Old Code have been reported, and compared with those provide by statistics cost of L'Aquila reconstruction process [13] and [17].

	BF - 4 storey - Old Code				**IF - 4 storey - Old Code**			**PF - 4 storey - Old Code**			**L'Aquila reconstruction process (9/4/2009)**	
	VI $_{EMS}$	**VII** $_{EMS}$	**VIII** $_{EMS}$	**IX** $_{EMS}$	**VI** $_{EMS}$	**VII** $_{EMS}$	**VIII** $_{EMS}$	**VI** $_{EMS}$	**VII** $_{EMS}$	**VIII** $_{EMS}$		
DL1 RC mean (€/sqm)	146	176	--	--	65	97	117	57	89	--	**B and C** RC mean (€/sqm)	174
DL1 RC dev.st (€/sqm)	30	29	--	--	34	43	15	26	21	--		
DL2 RC mean (€/sqm)	158	184	--	--	--	141	142	103	123	149	**B and C** RC dev.st (€/sqm)	118
DL2 RC dev.st (€/sqm)	29	28	--	--	--	18	19	21	22	12		
DL3 RC mean (€/sqm)	--	221	250	--	--	162	195	134	157	198	**E-B** RC mean (€/sqm)	270
DL3 RC dev.st (€/sqm)	--	39	50	--	--	33	43	34	29	35	**E-B** RC dev.st (€/sqm)	141
DL4 RC mean (€/sqm)	--	255	321	358	--	--	289	--	222	270	**E** RC mean (€/sqm)	426
DL4 RC dev.st (€/sqm)	--	55	46	63	--	--	52	--	346	38	**E** RC dev.st (€/sqm)	178

Table 1. Comparison between analytical defined (for BF-IF-PF 4 storey Old Code types) and empirical (L'Aquila 9/4/2009 reconstruction process) repair cost (RC) for square meter (mean and standard deviation values).

The comparison highlights a good accordance between the mean value of repair costs (€/sq.m) analytically obtained and those provided by L'Aquila reconstruction process, in particular for Bareframe type. The main differences, especially in standard deviation values, are due to the lack in empirical data of distinction in terms of storey number, age construction, structural types, architectural features and maintenance state. For this reason, the comparison have been also conducted in a global point of view; the repair cost of all analysed building types have been considered without any distinction in terms of typological parameters.

The global comparison has been highlighted as the procedure and tools (DCMs) used in translation of an analytical damage distribution in a global ratio cost provide results similar to empirical ones. Therefore, the defined tools (Damage Consequence models) are able to provide a realistic estimation of expected repair cost based on a simple assignment and assembly methodology. However, the difference could be linked to characteristics of buildings compared, specific buildings conditions influencing the repair costs, such as accessibility, position iteration with others building, maintenance state, which in analytical process have been neglected, and the difference in damage models employed.

Based on a simple convolution between FCs and Repair Costs functions, expected direct economic losses models have been defined for each building types considered. Finally, economic fragility curves have been defined. In Figure 6 the obtained direct economic losses models for BF-IF-PF 4 storey Old Code types have been reported. The Seismic Direct Losses Models provide useful information on the total expected monetary losses resulting of building types structural fragility and taking into account the deformation capacity that influences the repair costs.

The defined Seismic Direct Losses Models have been highlighted as the expected ratio cost seems to be influenced by infill panel effectives and distribution. Bareframe and Pilotisframe types are responsible of similar monetary losses. On one hand the greatest fragility of Pilotis Frame is balanced by a less deformability that required less repair costs; on the other hand the less fragility of BareFrame (than Pilotis) is recovered by a greater deformability and so necessary repair costs. Infillframe type is responsible of lower monetary losses, due to the beneficial role of infill panels that positively influence both the strength and deformation capacity. Finally, the others typological parameters (such storey number, design code, material strength etc.) seem less influence the expected direct economic losses.

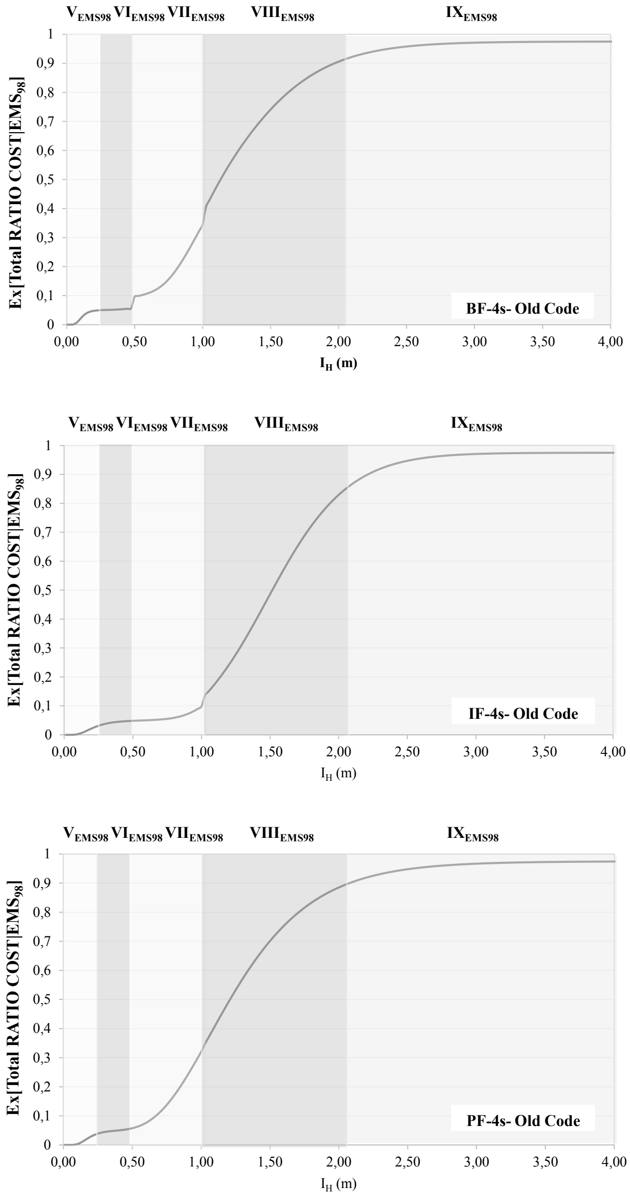

Figure 6. Seismic Direct Losses Models for RC-MRF Bareframe (BF) – Infillframe (IF) – Pilotisframe (PF) Old Code 4 storey.

Finally, in Figure 7, the temporal trends of the depreciated cost value (starting from the construction time), normalized then the total reconstruction cost, also called "life-cycle cost value model" for a residential existing RC building is reported. It is built using the information reported in technical manual of Italian building type costs. The two temporal trend have been defined assuming respectively the absence of extraordinary maintenance operations (black line) and occasional maintenance operations regarding few functional elements (grey line). The life-cycle cost value models highlight a building economic life equal to 55 years in absence of maintenances, whereas of 70 years with corrective maintenance operations. Building economic life is the time interval during which the depreciation runs from 0 to 100%.

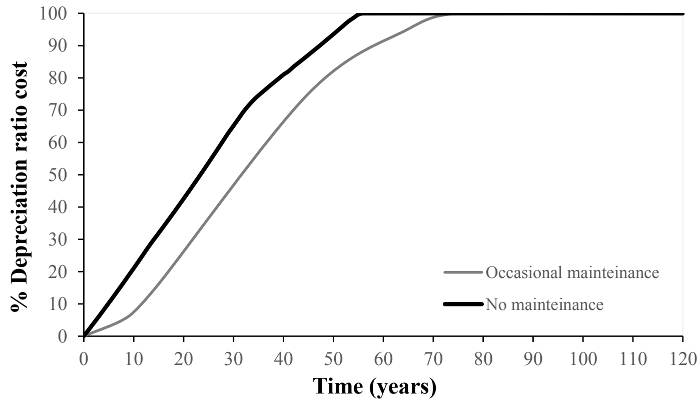

Figure 7. Life-Cycle Cost Value Models of an existing residential RC building considering two different maintenance processes.

The potential effect on residual economic life due to building seismic risk level for life safety performance level has been evaluated.

For example, a building situated in Italian seismic zone characterized by a reference macro-seismic intensity for life safety performance level of VIII ESM98 grade (10% of probability in 50 years), and characterized by vulnerability typical of BareFrame, InfillFrame, PilotisFrame 4 story Old-Code types respectively, has been considered.

In Figure 8, the effects on residual economic life resulting of building seismic risk level have been displayed. Mathematically, the modification of life-cycle cost value model has been obtained adding the expected value of ratio cost (related to VIII ESM98 seismic intensity range of seismic direct economic losses model) at a specific ordinate of building life-cycle cost value model (for example in this case at the sixteen year after the built). In this way, the cycle-life cost value move up of the expected ratio cost (repair cost/reconstruction cost), and the residual economic life proportionally reduces.

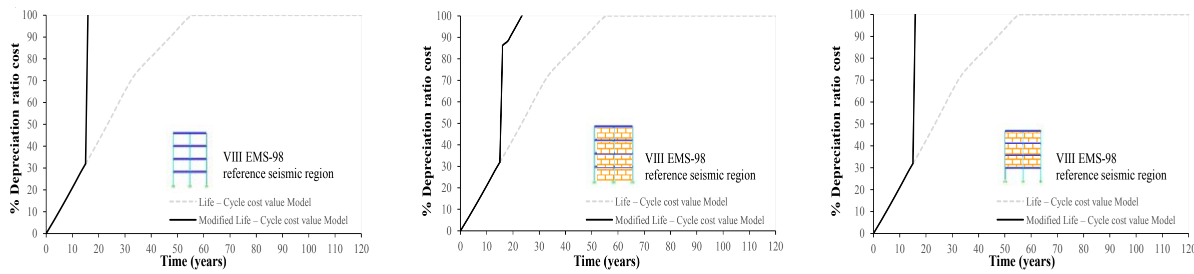

Figure 8. Life – Cycle cost value Model Modified taking into account the monetary losses resulting from seismic risk level for life safety performance level for BF-IF-PF 4 storey Old Code types.

The Figure 8 highlights as the seismic risk level of an existing RC building (BareFrame and PilotisFrame) designed only to gravity load implies an instantaneous and strong reduction of residual economic life after a reference earthquake. However, InfillFrame type highlights a less reduction of residual economic.

These integrated models represent a strong input for owners-investors to found themselves retrofitting interventions in peace-time, avoiding the economic disadvantages due to the reduction-annulment of building economic life as a result of seismic damage, that could be recovered only with high economic investment, in some cases even higher than that required for retrofitting.

4 CONCLUSION AND WORK IN PROGRESS

In this paper, a new procedure for definition of Seismic Direct Economic Losses Model has been presented and applied. The Seismic Direct Losses Models have been defined convolving Fragility Curves and Repair Cost Functions.

Novel Repair Cost Functions have been defined based on a translation process of analytical damage distribution in a global ratio cost. In this way have been defined Damage Consequence Models for the main performance groups

The translation process and the Damage Consequence Models have been empirical validated based on data of L'Aquila reconstruction process. Then, the defined DCMs and the simple assignment and assembly methodology are able tools to provide a realistic quantification of economic consequence of structural performance. In this way, the accuracy of structural performance play a key role.

The proposed approach for Seismic Direct Losses Models could be considered an improvement that the classic and convention ones based on expert vulnerability and damage-cost indexes. On the other hand, the novel approach is more easy and practical than those based on elements fragility curves.

In this work, a first attempt of using of Seismic Direct Economic Losses Model in evaluation of economic feasibility of retrofitting intervention on existing RC buildings has been presented. Innovative and strong multidisciplinary models based on integration of Life-Cycle Economic Value Model and Seismic Direct Economic Losses Model have been defined. These latter could be considered as innovative tools able to encourage the single owners-investors to be leader in mitigation process, in order to minimize the negative seismic financial effects that is one of their primary objectives.

In next work, further efforts and developments will be performed in order to obtain a better estimation of effect of seismic risk on building residual economic life.

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