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ORIGINAL PAPER

Feasibility of pre-earthquake strengthening of buildings based on cost-benefit and life-cycle cost analysis, with the aid of fragility curves

Andreas J. Kappos · E. G. Dimitrakopoulos

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Abstract There are two fundamental questions this article aims to deal with. First, whether a pre-earthquake strengthening of a large and heterogeneous building stock (the emphasis here is on building types common in S. Europe), is economically feasible or not, and second what is the optimal retrofit level for mitigating the seismic risk. To this purpose contemporary decision making tools, namely cost-benefit and life-cycle cost analyses, are tailored to the needs of the present study, and implemented with the aid of an ad-hoc developed new software application (COBE06). A method for estimating the reduction in structural vulnerability due to retrofit is proposed, as well as a methodology to determine the optimum retrofit level using the fragility curve approach. Finally, the proposed methodology is used in a pilot application that concerns the city of Thessaloniki, and results are drawn for the feasibility of strengthening the reinforced concrete building stock in this city.

Keywords Benefit-cost analysis · Pre-earthquake strengthening · Reinforced concrete buildings · Life-cycle cost analysis

Abbreviations

$C_{DI,k}$	Central damage index (of *k*th damage state)
DPM	Damage probability matrix
DS	Damage state
ESYE	Statistics agency of Greece
FEMA	Federal emergency management agency (USA)
FRP	Fiber reinforced polymers
I_{MM}	Modified mercalli intensity
D_{mv}	Mean damage factor
PGA	Peak ground acceleration
R/C	Reinforced concrete

A. J. Kappos (✉) · E. G. Dimitrakopoulos
Department of Civil Engineering, Aristotle University of Thessaloniki,
Thessaloniki, Greece
e-mail: ajkap@civil.auth.gr

R_L Retrofit level
SVHL Statistical value of human life

1 Introduction

Decisions regarding the seismic rehabilitation of existing buildings require both engineering and economic studies and consideration of social priorities. Pre-earthquake upgrading of a city's existing building stock is one of the most conflictual and difficult types of public policy decisions. Even in Californian cities, where the direct experience of disasters paved the way to seismic safety policy advances, the codes for upgrading of existing buildings took years to enact and the process was highly politicised (Comerio 1992). A decision regarding the feasibility of pre-earthquake strengthening of an existing building stock, should be based on the total risk (in monetary terms) for this stock, taking indirect (or associated) costs into account, in addition to the direct costs referring to the repair of damaged buildings, calculated using currently available procedures such as the damage probability matrices (DPMs) and the fragility (or vulnerability) curves. The estimation of the indirect costs presupposes the knowledge of variables such as the use of buildings under consideration, economic information specific to the building (replacement value, rental income, value of personal property etc.) as well as of general character (discount rate, planning horizon, net present value coefficient and, of course, the statistical value of human life). Valuable data sets regarding these factors are included in a report by FEMA (1992) but they strictly apply only to the US, particularly to California. On the other hand, in Europe most of this data is either missing or in a form different from that required for a seismic risk analysis.

Benefit/cost ratios, estimated by dividing the expected present value of future benefits by the costs required for rehabilitating a certain class of buildings are a key parameter in establishing priorities for pre-earthquake strengthening projects. If these ratios are greater than one, prospective strengthening against earthquake is economically justified. In the past, and in the absence of other information, the methodology suggested by FEMA (1992) for calculating benefit/cost ratios was followed, even outside the US; it is clear, though, that at least the basic economic data, such as replacement value or rental income should always be adjusted to reflect local economic conditions. A first effort to adopt the FEMA227 procedure to the needs of the cost-benefit analysis of a European building stock was made by Kappos et al. (1995), who introduced some local economic data and DPMs, and applied the procedure to the reinforced concrete buildings of Thessaloniki, Greece.

The work presented herein moves a step forward in several aspects. First of all by introducing the additional concept of life-cycle cost analysis to determine the optimal level of retrofit. Also, by using recently derived by the first writer and his associates fragility curves covering all common types in Greece i.e. both reinforced concrete (R/C) and unreinforced masonry (URM), and indeed most of the typologies found in S. Europe (Kappos et al. 2006). Furthermore, this article presents a method for estimating the lifetime total expected cost of a retrofit utilising fragility curves. Finally, valuable insight regarding retrofit benefits, as assessed from benefit-cost analysis, can be gained from the work presented herein, for instance that the feasibility of a retrofit scheme is determined more by its ability to reduce structural damage for moderate rather than intense earthquakes, at least in the common case of areas of moderate seismic hazard, as the one studied herein.

2 Procedure and implementation of cost-benefit analysis

In cost-benefit analysis, the potential seismic strengthening of a building stock is viewed as an economic investment and as such it is considered to be feasible if the expected benefits exceed the total cost of the investment, or in other words if the benefit/cost (B/C) ratio is greater than one. In Fig. 1 the structure of this methodology is displayed.

Two discrete steps shown with ellipses can be recognised, wherein the required information for the analysis is estimated. In most cases hazard is described by a probabilistic model (hazard curves) and vulnerability by sets of fragility curves appropriate for the building stock under consideration. Two more steps denoted with rectangular boxes are also shown that correspond to decisions necessary to (seismically) upgrade an existing building such as the retrofit method, the associated cost, and several others (presented in later Sections), and to economic data. The evaluation stage follows, wherein, based on the benefit-cost ratio, the decision regarding the feasibility of retrofitting is made, and finally the life-cycle cost concept is adopted to determine the optimal level of retrofit.

2.1 Necessary data—seismic hazard in Thessaloniki

In Fig. 1, ellipses correspond to parameters with significant uncertainty that does not depend on the decision maker. The uncertainties involved stem either from factors that are either inherently random (or aleatoric) or from a lack of knowledge and/or crudeness in modelling (or epistemic), and are dependent on the modelling procedure (Ellingwood and Wen 2005).

The seismic hazard (magnitude, frequency of occurrence, epicentre etc.) is among the 'aleatoric' uncertainties and therefore is declared in Fig. 1 with an ellipse. Usually in large scale benefit-cost analyses, such as the present one, seismic hazard relationships are used that correlate the frequency of occurrence of a seismic excitation with a given (or greater) macroseismic intensity e.g. I_{MM} (Modified Mercalli Intensity). In this study Eq. 1 proposed by Papaioannou (2004) for the Thessaloniki area is first used:

$$\log N = 2.55 - 0.61\, I_{MM} \tag{1}$$

This equation was derived from the distribution of macroseismic intensity values observed in Thessaloniki (Papazachos et al. 1999). In the course of a sensitivity analysis two more seismic intensity equations have been used:

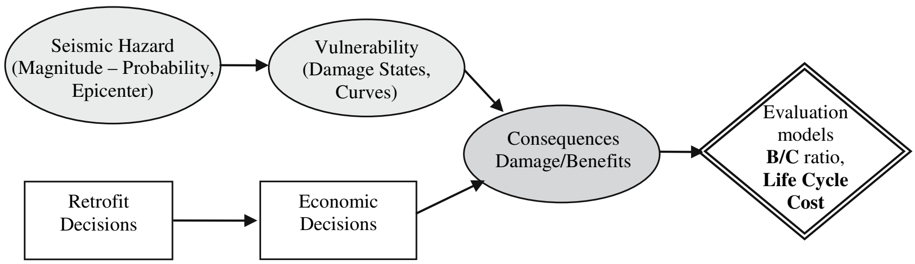

Fig. 1 The general structure of cost-benefit analysis (adapted from Alesch et al. 2003)

$$\log N = 4.79 - 0.92 I_{\mathrm{MM}} \quad (2)$$

$$\log N = 5.02 - 1.01 I_{\mathrm{MM}} \quad (3)$$

Equation (2) is based on probabilistic estimation of the seismic hazard using the "Frisk88M" algorithm from a recent study in ITSAK (Papaioannou 2004). Equation (3) is the one used in Kappos et al. (1995) during the first benefit/cost analysis in the Greek area and stems from calibration studies of the Greek Seismic Code (NEAK) in use at that time; although it is an older one, because it represented a broader concensus among seismologists (a need dictated by the requirement to provide a feasible solution to the seismic action definition in the then forthcoming new seismic code), it was deemed appropriate to consider it, along with the more recent ones. All three relationships refer to annual probability of exceedance and implicit is the assumption that earthquake occurrences follow a Poisson process.

The three equations give substantially different results for high-seismic intensities ($I_{\mathrm{MM}} >$ VIII), but this differentiation is within the scatter accepted for the estimation of macroseismic intensity. It is worth noting that the highest intensity ever observed in Thessaloniki was IX, from the seismic event of 1759 (Papazachos and Papazachou 1997). Regarding the aforementioned three relationships, notice that the highest probabilities of occurrence of strong earthquakes result from Eq. 1, the lowest from Eq. 3 which is based on the data available in the early 90s, while Eq. 2 yields intermediate results. The inherent uncertainty of all three relationships for intensities higher than VIII is strongly emphasised (data are clearly insufficient for this range of I_{MM}).

2.2 Vulnerability data

The second group of data, shown in Fig. 1 also within an ellipse since it is the second source of uncertainty (epistemic), refers to the vulnerability of structures. Initially in benefit-cost analysis (FEMA 1992), damage probability matrices (DPMs) based on expert judgment were used, and such matrices are still used in some seismic loss estimation studies. The current trend, though (e.g. Grossi 2000), is to express vulnerability in terms of fragility curves (or corresponding DPMs) based on analytical and/or statistical data, rather than expert judgment, both for structural and non-structural elements (Ferrito 1997, Shinozuka et al. 2000).

In the study area (Thessaloniki) such data is available from the work of Penelis et al. (1989) and Kappos et al. (2004a, b, 2006). The former involves the database created from the statistical data collected after the 1978 Thessaloniki earthquake, while the latter concerns fragility curves derived for all common typologies of R/C buildings in Greece, using a combination of analysis and the aforementioned statistical data; this is the so-called 'hybrid' approach proposed by Kappos et al. (1998, 2004a, b). Therefore, these curves and the associated DPMs are indeed specific to Greece in general and Thessaloniki in particular. It is noted that a DPM for a certain building type is derived from the corresponding set of lognormal fragility curves (each related to a different damage state); for each of the six discrete PGAs that correspond to the macroseismic intensities from VI to XI (intensity and PGA were correlated using the Koliopoulos et al. (1998) empirical relationship, see also Kappos et al. (2004a, b)), the entries to the pertinent column of the DPM are calculated by taking the difference of the cumulative probability corresponding to the thresholds of each damage state. Another advantage of these DPMs, in contrast to those based on expert

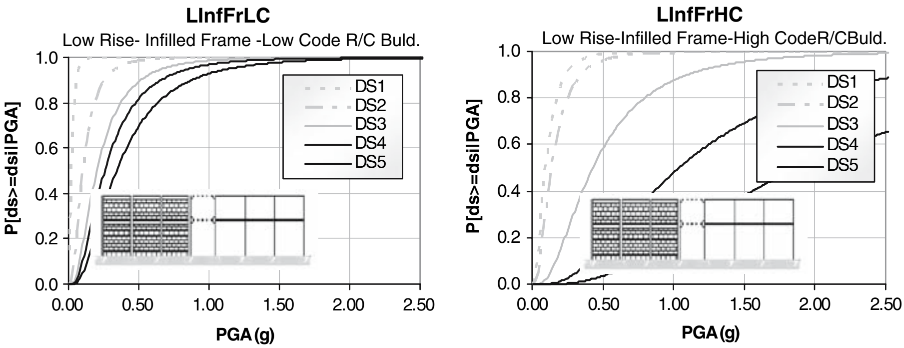

Fig. 2 Fragility curves for low-rise infilled frame structures, low-code (left) and high-code

judgement, is that they are derived from continuous fragility curves and hence they can be computed for any seismic intensity.

These fragility curves (a sample is shown in Fig. 2) are expressed as cumulative log-normal probability functions and correlate peak ground acceleration (PGA) to the probability that a building type exceeds a particular damage state. Five damage states (DS1–DS5) have been used (in addition to the no damage state DS0); they are shown in Table 1 both in descriptive terms and as loss indices (ratio of repair cost to replacement cost). In implementing the cost-benefit analysis DPMs are preferably used; hence the aforementioned fragility curves were converted to DPMs in the usual way, taking also into account the empirical relationship of Koliopoulos et al. (1998) for correlating intensity and PGA.

From the structural type point of view, all common R/C building types found in Thessaloniki are addressed. They are of three different configurations, namely: infilled frames and dual (frame + shear wall) systems with and without pilotis (soft ground storey) type. Referring to the height of the buildings, 2-storey, 4-storey and 9-storey R/C buildings were considered as representative of low-, medium- and high-rise buildings, while regarding the level of seismic design, both low (early seismic codes—1959 Greek Code) and high (modern seismic codes—2000 Greek Code which is similar to the 1995 code) were considered; note that in the study by Penelis et al. (1989) pre-code (pre-1959) buildings were found to perform similarly to low-code ones, hence the same curves were used herein for both types. The nomenclature used for the building types is also presented in Table 1.

Referring to the fragility curves for low-rise infilled frame buildings (a very common type in S. Europe), shown in Fig. 2, it is worth pointing out that, as found by Kappos et al. (2004a, b, 2006) and verified from observation of past earthquake damage, the effect of seismic design level was much more pronounced in the case of frame buildings than in the case of dual ones.

2.3 Retrofit decisions

In this study the feasibility of a pre-earthquake strengthening of the old (i.e. designed according to the 1959 Greek Code) R/C buildings of Thessaloniki is examined. It is noted that these buildings constitute the majority of the city’s building stock (Fig. 3), since almost 70% of the buildings were constructed prior to 1984 (ESYE 2005), when seismic regulations in Greece were revised, and hence are more vulnerable than post-1984 buildings, as also confirmed in recent earthquakes (Kappos et al. 2004a, b).

Table 1 Damage grading and loss indices (left), and nomenclature used for building types (right)

Damage state	Damage state label	Range of loss index-R/C	Central damage index (%)	Nomenclature (based on height, structural system, seismic code)		
DS0	None	0	0	Height	Structural system	Seismic codes
DS1	Slight	0–1	0.5	*L*—low rise	*InfFr*—infilled frame	*LC*—low code
DS2	Moderate	1–10	5	*M*—medium	*PilFr*—pilotis frame	*HC*—high code
DS3	Substantial to heavy	10–30	20	*H*—high	*PilDu*—dual with pilotis	
DS4	Very heavy	30–60	45	e.g. LInfFrLC: low-rise, infilled frame low-code buildings		
DS5	Collapse	60–100	80			

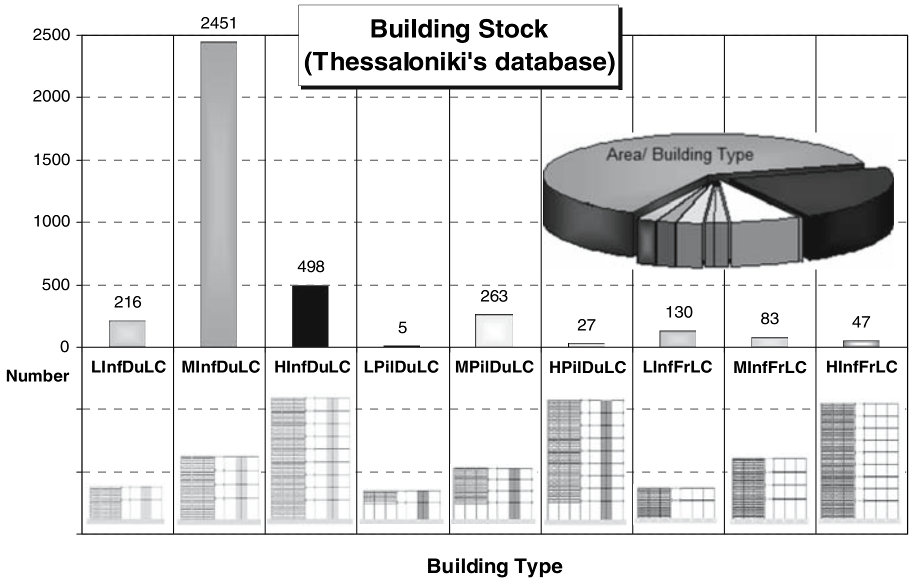

Fig. 3 Building stock: number of buildings and area per building category

A substantial number of seismic rehabilitation techniques is currently available (e.g. see Penelis and Kappos 1997). This study addresses a large and inhomogeneous building stock, hence it is not feasible to examine in detail each retrofit method (e.g. R/C or FRP jackets, steel plates, addition of new R/C walls, etc.), and its implications with respect to reducing the vulnerability of the building; therefore some simplifying assumptions had to be made.

For a retrofit scheme, that upgrades an existing old building to the level of seismic performance of modern (high-seismic code) buildings, the direct cost of the rehabilitation per m^2 of building area was taken as 12% of the building's replacement cost per m^2 (i.e. €90/m^2). The direct cost covers all expenses for materials and the rehabilitation work, and obviously depends on the type of the strengthening method (some methods are less labour-intensive than others, but may involve more expensive materials e.g. compare R/C and FRP jacketing). In assessing the total retrofit cost, the indirect cost was also taken into account, which covers the expenses regarding the engineer's fee ant the cost of issuing a permit for construction works, and was taken equal to 20% of the direct cost (FEMA 1992).

2.4 Economic data

Regarding the necessary economic data, it must be emphasised that first of all they are hard to acquire, at least in a form suitable for a benefit-cost analysis, while on the other hand, they are of major importance for the quality of the output of any decision-making methodology.

These data either concern buildings (FEMA 1992, see also Table 1) or are of general nature. The values selected are drawn from a wide variety of sources, among which is the database created after the Thessaloniki 1978 earthquake (Penelis et al. 1989, Kappos et al. 1995), and information from an ongoing research programme (see "Acknowledgements") that concerns basic economic parameters, such as replacement and retrofit cost for buildings, based on data collected after the 1999 Athens earthquake. As is well known, these parameters must always be representative of the study areas, for instance it would be inappropriate to use for Greece retrofit cost data from the US. Also general economic data have been collected from the National Statistics Agency of Greece (ESYE), such as the percentage of ownership by occupants of dwellings, and business turnover in the study area. Finally, whenever no other possibility existed, relevant information from FEMA (1992) was used after being adjusted to the basic economic parameters of Greece.

From the data concerning buildings, the most important is the replacement cost (R_V) which was estimated as 750€/ m^2 (average value for the study area). The term "replacement" stands for the replacement of the function provided by a building which must be demolished, by a new building. Using this parameter, building damage is calculated as the product of the replacement value times the area of the building times the mean damage factor (D_{mv}) of the damage probability matrix that describes the vulnerability of the building; D_{mv} is the sum of the products $D_{CI,k} \cdot P_k$, where $D_{CI,k}$ is the central damage index of the kth damage state (see also Table 1) and P_k is probability of kth damage state being reached.

All types of economic losses, the formula used for estimating each of them, and the basic value used in the analyses presented herein, are summarised in Table 2. Index "j" in

Table 2 Basic economic data used in benefit-cost analysis

Symbol	Cost	Equation	Basic value
C_j^{dam}	Damage of buildings	Replacement cost (R_V) × Floor area × Mean damage factor (D_{mv})	R_V = €750/m^2 (Greece 2005)
C_j^{ren}	Rental loss	Rental rate × Gross leasable area × Loss of function (time)	€4.0/m^2/month (0.5% R_V)
C_j^{rel}	Relocation expenses	Relocation cost × Gross leasable area × Loss of function (time)	€15.0/m^2/month (2.0% R_V)
C_j^{loc}	Loss of contents	Personal property value × Floor area × D_{mv}	€225/m^2 (30.0% R_V)
C_j^{inc}	Income loss	Business turnover × Gross leasable area × Loss of function	€2.4/m^2/day (0.3% R_V)
C_j^{HF}	Human fatality	Statistical value of human life × Expected deaths	€500,000/person (upper bound)
C_j	Total cost:	$C_j = C_j^{dam} + C_j^{ren} + C_j^{rel} + C_j^{loc} + C_j^{inc} + C_j^{HF}$	

all parameters of Table 2 indicates that losses are calculated for each macroseismic intensity *j* (from 6 to 11); intensities from 6 to 8 are the most critical for the results due to the high probability of occurrence of these intensities. High intensities (>9) have a very low probability of occurrence in Thessaloniki and most areas in Greece (and Europe).

Among the economic data of general nature, the statistical value of human life deserves special attention due to its high importance and uncertainty. From the available estimation methods described in FEMA-227 (1992), the "courts awards approach" was adopted in this article, which is based on the indemnities paid in cases of death from the state or insurance companies, since it was deemed as the most reliable and objective one. However, indemnities paid to the relatives of victims in Greece vary considerably from case to case. From a limited-scale survey conducted in Greek mass media, the reported values of indemnities varied from as low as €50,000 (victims of the 1995 Aegion earthquake), to as high as €1,450,000 (occupational accident at a construction site in 2005); it is important to note that typically the high sums decided by the first-degree court, are substantially reduced following the appeal. As a rule, these indemnities are considerably lower than those reported for other countries such as the US, where they range from 1 to 5 million dollars (€0.8–4 million) in 2000 rates (Zerbe and Falit-Baiamonte 2001). To cope with this difference, a sensitivity analysis was carried out, with values of €50,000 and 500,000 (upper bound) for human life in Greece, as well as analyses without accounting for the value of human life.

The remaining required economic data are: (a) the discount rate used to convert costs (losses) due to future earthquakes into present (monetary) value. As this rate decreases, future benefits increase and so do the benefit/cost ratios (see Sect. 3.2). As basic value in the analyses 4% is chosen, while rational values for the discount rate ranging from 3 to 6% (FEMA 1992) are considered appropriate for modern Greece. (b) The design time period, or planning horizon, of the pre-earthquake strengthening programme is the time during which the economic benefits of the retrofit are considered. Typical planning horizons for common buildings vary from 20 to 40 years (this is equivalent to assuming an average remaining life of the building stock from 30 to 10 years, assuming the commonly adopted, conservative, value of 50 years. design life of common buildings, in practice useful life is 60 years or more); a sensitivity analysis is presented in Sect. 3.2. (c) "Salvaged value" is the increase in the building value due to seismic strengthening, viewed within a benefit/cost analysis as a future benefit (converted to present values), that decreases the retrofit cost by 10% (FEMA 1992).

2.5 Estimating the efficiency of strengthening

2.5.1 Reduction of structural vulnerability

Pre-earthquake strengthening reduces the seismic vulnerability of structures, however a quantification of this decrease (or the efficiency of retrofit) is not an easy goal. There are two procedures available in the literature to tackle this challenge.

The first procedure is the one originally introduced by FEMA (1992), wherein the efficiency of the retrofit was estimated based on "expert judgment" tables adopted from ATC-13 (1985). This method is still used in the absence of other data/information, but is considered as a compromise solution, since the dispersion in the results is high (Grossi 2000). On the other hand, to date, published data on the vulnerability of structures to various levels of seismic intensity is scarce and even less data is available on the effects of structural mitigation on damage reduction.

The second method used to estimate the vulnerability of retrofitted buildings is the "analytical" one i.e. through static or dynamic analyses (usually, and preferably, inelastic). This method, though, is applicable only in building-specific studies (Wen and Kang 2001), or when a specific retrofit method is evaluated (Smyth et al. 2004), which does not fall within the scope of this article.

In the present study that deals with the entire R/C building stock in the city of Thessaloniki, with emphasis on older buildings designed prior to 1984 (when the Greek Seismic Code was revised and modern design concepts were introduced). As mentioned earlier, from the work of Kappos et al. (2004a, b), fragility curves specific to Greek R/C buildings and also considering the effect of seismic design level (low-code, high-code), were available, so here a third method for estimating the efficiency of seismic retrofit is proposed. It is assumed that using one of the available seismic retrofit methods, the vulnerability of a 'low code' building is mitigated so as to match the vulnerability of the same type 'high code' building; it is noted that often this is a stated goal in the design of the retrofit, although it is equally common to adopt somewhat lower performance objectives for old buildings, compared to newly designed ones. The practical implication of this assumption is that the vulnerability of the retrofitted building is expressed through the fragility curve of the same type, high-code, building; or, from another perspective, that the efficiency of the retrofit (R) can be estimated from the decrease of the corresponding damage probabilities (e.g. $R^{\mathrm{Full}} = D_{\mathrm{mv}}^{\mathrm{HC}} - D_{\mathrm{mv}}^{\mathrm{LC}}$) among the two fragility curves of the low-code (before retrofit) and high-code (after retrofit) building, hence the failure probabilities become smaller after the retrofit (Fig. 4).

As a further development, considering that strengthening of an old (low-code) building can aim at enhancing the structural performance up to an intermediate level, lower than the one corresponding to high-seismic codes, the concept of "retrofit level" R_{L} is introduced; this is defined as the increase in the damage mean values due to an 'intermediate' retrofit ($D_{\mathrm{mv}}^{\mathrm{After\ R}} - D_{\mathrm{mv}}^{\mathrm{Before\ R(LC)}}$) with respect to the ones after full retrofit (high-code performance levels), see Eq. 4.

$$R_{\mathrm{L}} = \frac{D_{\mathrm{mv}}^{\mathrm{After\ R}} - D_{\mathrm{mv}}^{\mathrm{Before\ R(LC)}}}{D_{\mathrm{mv}}^{\mathrm{Full\ R(HC)}} - D_{\mathrm{mv}}^{\mathrm{Before\ R(LC)}}} = \frac{R}{R^{\mathrm{Full}}} \Rightarrow D_{\mathrm{mv}}^{\mathrm{After\ R}} = D_{\mathrm{mv}}^{\mathrm{Before\ R(LC)}} + R^{\mathrm{Full}} \cdot R_{\mathrm{L}} \qquad (4)$$

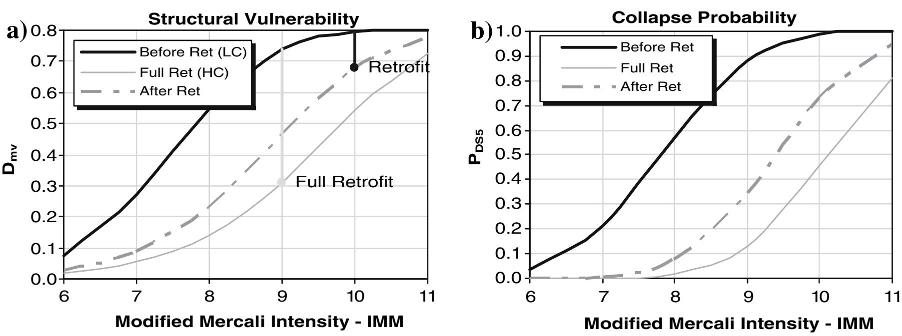

Fig. 4 Efficiency of seismic strengthening. Mitigation of structural vulnerability after full or intermediate retrofit in terms of (**a**) Mean damage factor and (**b**) Collapse probability

Hence, retrofit Level R_L ranges from 0 (no retrofit) to 1 (retrofit to high-code level); it can also take values greater than one expressing strengthening of old structures to performance levels higher than the ones prescribed by modern seismic codes.

Again the vulnerability of the retrofitted buildings is illustrated by the corresponding fragility curves and the efficiency of the seismic retrofit (R) from the difference (decrease) of the corresponding damage probabilities among the two fragility curves (Fig. 4).

Note that, in principle, a building might switch category after it is retrofitted (e.g. when adding shear walls to an R/C frame building); however, given the rather crude way the effect of retrofit is modelled in the present study, such refinements are not considered herein. To this end, it may be interesting to extend, in a future study, the concept of the 'retrofit level' in order to include the change of structural category after retrofit e.g. by using the fragility curve (if available) of the modern (high-code) building that belongs to the category after retrofit as the 'Full Retrofit' fragility curve.

2.5.2 *Mitigation of casualties*

Regarding the human fatalities (deaths and severe injuries) caused by building collapses during earthquakes, the method proposed by Coburn and Spence (2002) has been used, that enables a straight correlation of casualties with the vulnerability and the function of the buildings. Thus, the number of casualties (K_s) is given by:

$$K_S = F \cdot [M_1 \cdot M_2 \cdot M_3 \cdot (M_4 + M_5 \cdot (1 - M_4))] \tag{5}$$

- F: the total area of collapsed buildings; it is calculated by multiplying the area of each building category in the study area with the corresponding probability of collapse (damage stage DS5).
- M_1: is the occupancy rate (number of people/m^2 of building area). A mean value for Thessaloniki is 0.025 (thus 40 m^2 per inhabitant).
- M_2: a coefficient that depends on the use of the building at the time the earthquake strikes. Considering that 80% of the buildings in the study area—city of Thessaloniki—are used as residential and 20% as non-residential according to (ESYE), M_2 is 0.52 if the earthquake occurs at 12:00 h and 0.65 at 24:00 h, respectively.
- M_3: is the ratio of inhabitants trapped in the building due to collapse, taken as 0.30
- M_4: is a coefficient that correlates collapse with casualties (deaths), for R/C buildings taken as 0.4 (Coburn and Spence 2002).
- M_5: stands for deaths due to collapses, taken as 0.7 for R/C buildings, also taking into account that in Greek cities adequate rescue teams can be organised, based on experience gained from recent earthquakes (Vacareanu et al. 2004).

This methodology is incorporated in the developed analysis algorithm, in lieu of tables based on "expert judgment", hence the reduction in the number of fatalities is proportional to the reduction in structural vulnerability; this is believed to be an improvement of the original (FEMA 1992) methodology.

2.6 Evaluation methods: cost-benefit analysis

The next step involves the evaluation of the mitigation alternatives that is usually comprised by two different tasks. The first is expressing all consequences (benefits, costs) in

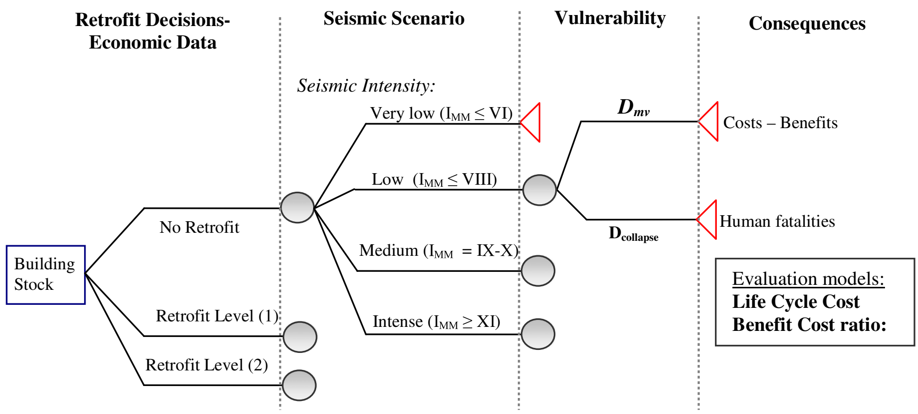

Fig. 5 Decision tree of cost-benefit analysis

terms of the same units (typically monetary), and the second one is converting all monetary values to present time, so the various consequences can then be summarised. The available methods can be classified either on the basis of whether they assume that the annual probabilities of future earthquakes are constant or not (Takahashi et al. 2004), or on the basis of whether the efficiency of the retrofit is time-independent or not (Frangopol et al. 2001; Nuti and Vanzi, 2002). If these probabilities are constant per year (time-invariant), future benefits are also constant per year; this is the assumption of benefit/cost analysis according to FEMA (1992), adopted also in this article.

So for every combination of seismic intensity (j), mean damage factor ($D_{\mathrm{mv},j}$), and retrofit level, consequences are expressed in terms of the same units, as Fig. 5 illustrates. The expected annual benefits (B_0), which are constant per year, are calculated, and then the benefits over the planning horizon (B_t), in present monetary value are estimated, according to equations:

$$B_0 = \sum_{j=VI}^{XI} N_j R_j C_j \ , \ B_t = B_0 \frac{1-(1+\lambda)^{-t}}{\lambda} \tag{6}$$

where N_j is the expected number of earthquakes annually yielded by Eq. 1 to 3, R_j the efficiency of retrofit as estimated according to Sect. 2.5.1. and C_j the total loss (see Table 2), all three for seismic intensity j, t is the planning horizon and λ the discount rate.

The economic efficiency of a pre-earthquake strengthening of a building stock can then be determined in terms of the net present value of the investment of the retrofit. If the expected benefits exceed the total cost, the net present value is positive (benefit/cost ratio greater than one) and the retrofit investment is economically justified. The benefit/cost ratio is expressed as the present value of the benefits (in monetary terms) expected to accrue (due to the retrofit) over the planning period plus the present value of the cost of the deaths avoided (V_{DA}), if the cost of human life is included in the analysis, divided by the total retrofit cost (R_{C}) minus the (present) salvaged value of the building (V_{S}) i.e. the increase in the price of the building due to the retrofit:

$$B/C = \frac{B_t + V_{\mathrm{DA}}}{R_{\mathrm{C}} - V_{\mathrm{S}}} \tag{7}$$

2.7 Evaluation methods: life-cycle cost analysis

Occasionally the problem is not whether potential strengthening is economically feasible or not, but rather the decision for strengthening has already been made and the question is what level of strengthening should be chosen. In these cases another, similar to "benefit-cost analysis", decision-making tool can be used, in order to balance the initial cost of the retrofit against the cost that might incur as a consequence of failure, thus determining the optimal retrofit level. This procedure is called Life-Cycle Cost analysis, and is based on consideration of initial costs and lifetime costs over the structure's lifetime (Wen and Kang 2001; Frangopol et al. 2001; Liu et al. 2003) or the time horizon of strengthening; in this approach the optimal design is the one that yields the minimum Life-Cycle Cost.

The analytical expression for the total lifetime expected cost over a time horizon (t), for a single hazard with respect to a design variable vector (X), can be obtained from equation (Wen and Kang 2001):

$$E[C(t,X)] = C_0 + (C_1P_1 + C_2P_2 + \ldots + C_kP_k)\frac{N}{\lambda} \times \left(1 - e^{-\lambda t}\right) + \frac{C_m}{\lambda}\left(1 - e^{-\lambda t}\right) \quad (8)$$

In the case addressed herein, the retrofit level R_L is used as design variable (X), the single hazard is the earthquake hazard, and time horizon is the planning horizon of the retrofit. The notation E[ ] declares that the cost $C(t,X)$ is an expected value; C_0 = initial cost for new or retrofitted facility; C_k = kth damage—state failure cost, in present monetary value; P_k = probability of kth damage state being reached at time of the loading occurrence, λ = discount rate/year; k = total number of damage states under consideration and C_m = operation and maintenance costs per year.

Regarding Eq. 8, it must be noted that it is the closed form of a more general equation, provided also by Wen and Kang (2001), applicable when the hazard occurrences are modelled by a simple Poisson process with occurrence rate of N/year and for resistance that is time-invariant (i.e. deterioration of structural resistance with time is ignored). Also, the damage state probability P_k, as well as, the efficiency of retrofit are assumed to be time-invariant as already mentioned in Sect. 2.6, so the use of Eq. 8 is legitimate. Finally, implicit in Eq. 8 is the assumption that the structure will be restored to its original condition after each hazard occurrence.

Now, if C_k is assumed to be a product of the central damage index (of kth damage state—$D_{CI,k}$) times the monetary cost per loss category ($C_k = \bar{C} \cdot D_{CI,k}$, where, in the case of building damage, for instance, $\bar{C}$ would be the product of the replacement value times the floor area of the buildings examined), then by definition the sum in parentheses in Eq. 8 is equal to the product of the total cost times the mean damage factor D_{mv}, since:

$$\begin{aligned}(C_1P_1 + C_2P_2 + \ldots + C_kP_k) &= \bar{C} \cdot D_{CI,1} \cdot P_1 + \bar{C} \cdot D_{CI,2} \cdot P_2 + \ldots + \bar{C} \cdot D_{CI,k} \cdot P_k \\ &= \bar{C} \cdot D_{mv}\end{aligned} \quad (9)$$

Hence, taking into account Eq. 9 and ignoring maintenance cost, Eq. 8 becomes:

$$E[C(t,R_L)] = C_0 + \bar{C} \cdot \frac{1 - e^{-\lambda t}}{\lambda} \sum_{j=VI}^{XI} N_j \cdot D_{mv,j}, \quad (10)$$

where $D_{\mathrm{mv},j}$ is the mean damage factor and N_j the number of earthquake occurrences per year, both for seismic intensity j. In the form of Eq. 10, the total lifetime expected cost is based on the mean damage factor, thus, Eq. 10 allows a straightforward incorporation of a damage probability matrix, and hence the associated fragility curve, into life-cycle cost analysis.

3 Application

The results presented herein concern the feasibility of a pre-earthquake strengthening of buildings. The building stock under consideration includes the old (low-code) R/C buildings in Thessaloniki; results presented in the following refer specifically to the buildings included in the database described earlier, but the conclusions drawn refer to the entire city since a representative sample is considered. Numerical calculations required for “Benefit/cost” and “Life-Cycle Cost” analysis, were carried out using the ad hoc developed Visual Basic program “COBE06”. It is pointed out that the answer sought within this article is not which building should be strengthened to withstand a specific earthquake scenario (or the seismic action in specific zones of a microzontation map), but rather to prioritise old buildings in the city on the basis of their relative vulnerability. Of course, one could proceed further and set a second set of priorities e.g. by selecting for pre-earthquake strengthening the most vulnerable buildings that are located in the zones with the higher-expected seismic action.

3.1 Distribution of losses

In Fig. 6, economic losses for earthquakes with macroseismic intensities “j” from VI to XI are presented, i.e. these results are independent of the seismic hazard in the study area. Note that the vertical axis in the diagrams, which refers to losses, is in logarithmic scale.

The following losses are shown in the figure, rated according to their relative importance (and excluding casualties in this case): (1) Building damage (noted as “Build. Dam.”), (2) Personal property losses (“L.Cont.”), (3) Loss of income (“Inc.Los.”), (4) Relocation expenses (“Rel.Exp”) and finally (5) Rental losses (“Rent.Los.”). As expected all losses increase monotonically for higher-seismic intensities.

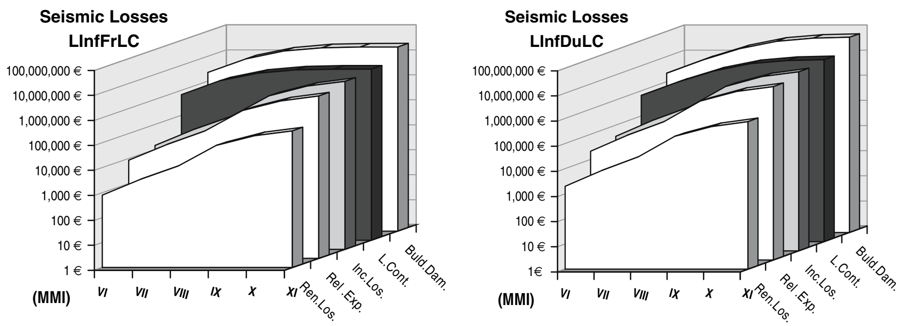

Fig. 6 Distribution of seismic losses with respect to seismic intensity and type of damage for LInfFrLC and LInfDulLC buildings, based on a 40-year planning horizon

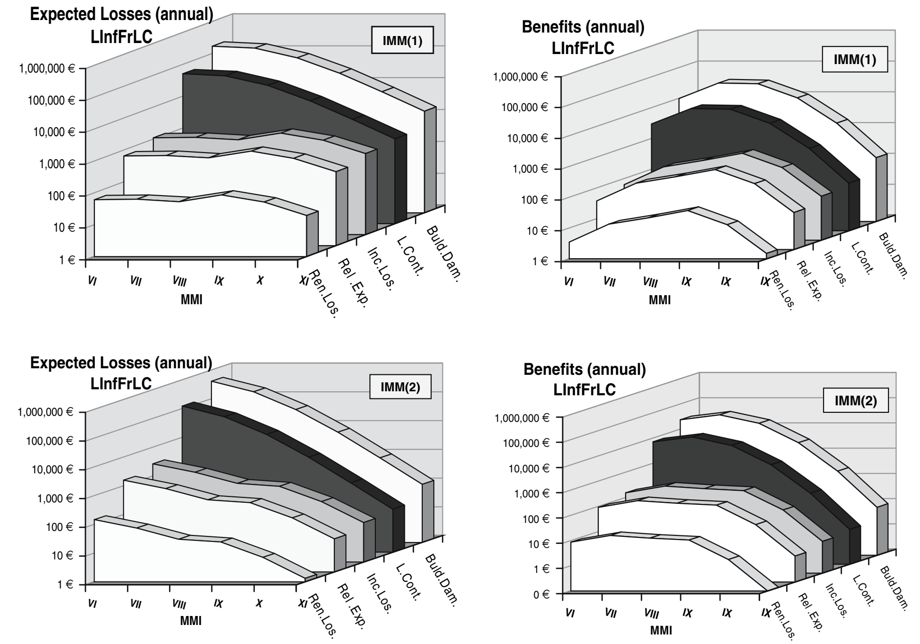

Fig. 7 Distribution of expected (annual) losses and (annual) benefits with respect to seismic intensity and type of damage, for Low rise-Infilled Frame-Low Code buildings (LInfFrLC), based on Eqs. 1 and 2 for I_{MM} and 40-year planning horizon

Personal property losses (“L.Cont.”) are calculated according to FEMA (1992) as 30% of the cost of building damage, while, as shown in Fig. 6, the sum of these two losses is at least one order of magnitude higher than the remaining losses. Accurate estimation of building damage is crucial for the reliability of the results, pointing to the need for the best feasible estimation of structural vulnerability and the role of the epistemic uncertainties (such as lack of knowledge, ignorance or coarse modelling) inherent in the process of loss estimation.

The expected annual losses due to earthquake hazard are displayed in Fig. 7. These results account for the annual probability of earthquake occurrence, hence (unlike those in Fig. 6) depend on the seismic hazard in the studied area (two scenarios of seismic hazard are considered i.e. Eqs. 1 and 2).

The relative importance of “expected losses” is the same as in Fig. 6 (“seismic losses”). However the variation of losses with respect to seismic intensity is very different, since in Fig. 7 maximum losses are expected for small and moderate intensities (from I_{MM} = VI to IX); this, of course, is due to the high probabilities associated with these intensities (see Eqs. 1–3 referring in Thessaloniki). It is also noted that since the reduction of the expected losses will determine the economic efficiency of the retrofit, the latter, as evaluated from a benefit/cost analysis, is determined more by its ability to mitigate structural damage for moderate rather than intense earthquakes; this is an important observation from a practical point of view.

Retrofit benefits (Fig. 7, right column) are calculated based on the losses that are expected to be avoided. Again the rating of benefits per category is the same as in the previous cases, whereas the variation with seismic intensity is different. Benefits are maximised almost in all cases for moderate intensities (VII–VIII). This trend can be justified looking at Fig. 4, where the mitigation of structural vulnerability due to strengthening, as assumed in this article, is illustrated. This mitigation is more evident for moderate intensities (I_{MM} = VII–VIII) than for smaller or higher ones, hence the retrofit yields larger benefits; it is recalled here that since no specific retrofit scheme is examined in this study, the fragility curve of a low-code retrofitted building is the fragility curve of the same type high-code building. Again, as the variation of benefits implies (Fig. 7), a successful retrofit scheme should aim at a higher reduction of structural vulnerability for small intensities (I_{MM} = VI), in order to maximise the expected benefits.

3.2 Benefit to cost ratios (not including casualties)

In Fig. 8 benefit to cost ratios are plotted for all building types not considering casualties and assuming a planning horizon for the strengthening of 40 years. For all building types benefit/cost ratios are smaller than unity, therefore strengthening is not deemed economically beneficial. It is noted, nevertheless, that in buildings with dual system the benefit/cost ratios are considerably smaller than for buildings with frame system.

In the insert of Fig. 8 the effect of time horizon and discount rate on benefit/cost ratios is shown. As expected, benefits increase for longer planning horizons, for instance benefit/cost ratios are about 30% higher for a planning horizon of 40 years compared to those for 20 years. Note in this respect that in Greece the seismic code was substantially upgraded in 1985 (this could be considered fairly representative of the situation in other European countries, although differences in code updating practices do exist), hence seismically deficient structures are today 20 or more years old; therefore, 30–40 years is a rational selection of planning horizon, noting that 60 years can be considered as a typical time life for 'normal' buildings.

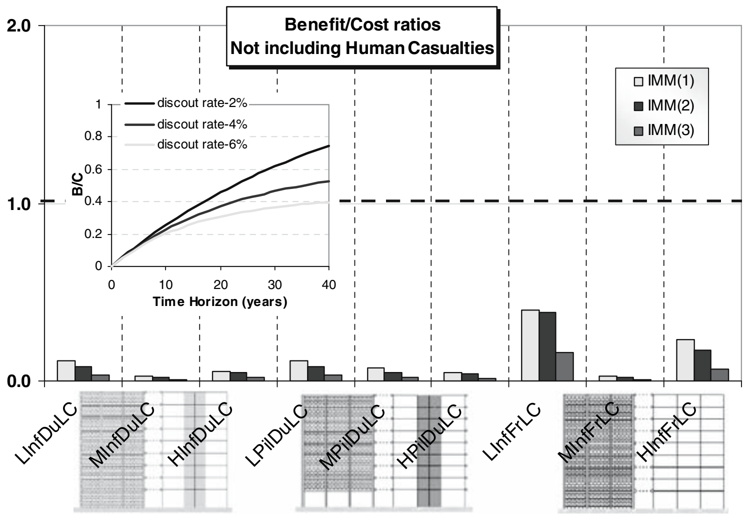

Fig. 8 Benefit to cost ratios for all building types examined, without considering casualties and for 40 years planning horizon. In the small diagram the effect of time horizon and discount factor on benefit-cost ratios is displayed

3.3 Benefit to cost ratios (including casualties)

Benefit/cost ratios were also calculated in the case study including casualties (i.e. the cost of life, as discussed in Sect. 2.4). More specifically, casualties that are expected to be avoided due to seismic retrofit are assessed and expressed in monetary terms using the statistical value of human life, hence benefits increase and so do the benefit/cost ratios (Eq. 4); casualties that are expected to be avoided are defined as those expected before retrofit minus those expected after retrofit (see Sect. 2.5.2).

The results in Fig. 9 were derived for a planning horizon of 40 years and a statistical value of human life equal to 500,000€, which should be deemed as an upper bound by the Greek standards, but a conservative value for other western countries (see Sect. 2.4). In this case, low-rise as well as high-rise (infilled) frame buildings appear as appropriate candidates for strengthening, since the associated benefit/cost ratios are greater than one, almost regardless of the seismic hazards relationship used (Eqs. 1–3). If the seismic hazard scenario described by Eq. 1 is adopted, low-rise buildings with dual system, either pilotis (soft storey) or infilled, might also appear (albeit marginally) as candidates for strengthening. It is noted that also in the analysis reported in Fig. 9, strengthening is clearly more feasible in the case of frame buildings compared to the ones with dual system.

When human casualties are included in the analysis, the statistical value of human life becomes a parameter of paramount importance. This is clear in Fig. 10, where the variation of benefit-cost ratios with respect to SVHL (varies from 0 to 500,000€) for all building types is shown. For a SVHL = 0€ the results have already been shown in Fig. 8, while for a SVHL = 500,000€ they are also presented in Fig. 9 as “$I_{MM}(1)$”.

Benefit/cost ratios increase linearly with respect to SVHL, since retrofit-related benefits are estimated as the casualties that are (expected to be) avoided times the SVHL (V_{DA} in Eq. 6). Expected casualties are estimated for each building category, based on the function of the building, its collapse-probability, and its total area. Hence, for building types with very low collapse probabilities before retrofit, as in the case of the high-rise dual buildings, the influence of SVHL on the results is minor. On the other hand, if the collapse probability

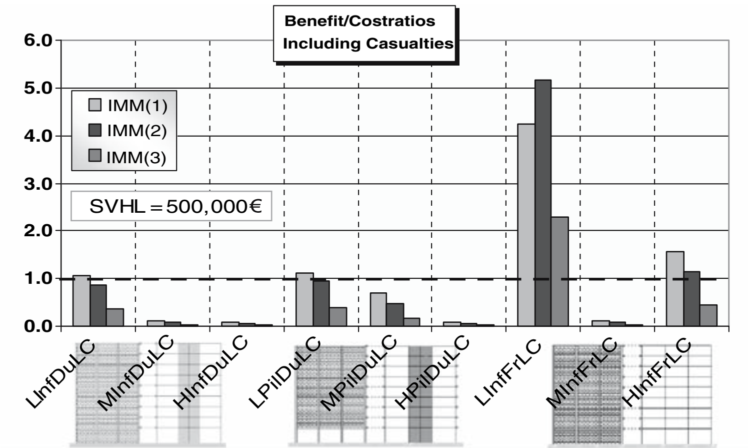

Fig. 9 Benefit-cost ratios for all building types examined considering human casualties (SVHL is taken as €500,000) and for 40 years time horizon

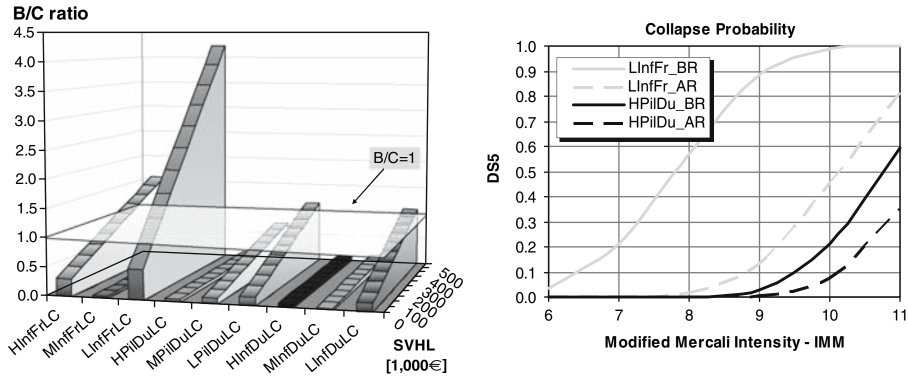

Fig. 10 Benefit/cost ratios for all building types examined ($I_{MM}(1)$ scenario), as a function of the Statistical Value of Human Life considered (SVHL varies from €0 to 500,000)

after retrofit is drastically reduced, as in frame buildings, the higher the value of SVHL assumed, the more feasible strengthening becomes.

It is also clear from Fig. 10 (left) that for the most realistic statistical value of human life by the Greek standards, i.e. €50,000, no building type yields a benefit/cost ratio higher than unity, which means that strengthening is not considered economically feasible for any building type.

3.4 Life-cycle cost analysis

Another interesting issue to be addressed is the level of strengthening that should be chosen. Using the concept of "retrofit level" introduced in Sect. 2.7, making use of fragility curves, the optimal retrofit level can be defined as the one that yields the minimum total lifetime (expected) cost. In the following, the total lifetime cost is calculated for every retrofit level (from Retrofit Level = 0–"no retrofit" to Retrofit Level = 1–"full retrofit", i.e. strengthening up to High-code performance levels), based on the assumption that the retrofit cost increases linearly according to the associated retrofit level from 0 for Retrofit Level = 0, to 90€/m^2 (12% of the building's replacement cost per m^2) for Retrofit Level = 1. Thus, the minimum lifetime cost determines both the "retrofit level" and the associated cost of the optimal retrofit. Note that costs reported herein refer to the total building area per building type. Discount rate and planning horizon are assumed to be 4% and 40 years, respectively, while when casualties are taken into account (thick lines in the figures), the statistical value of human life considered is 500,000 (the upper bound value).

It is first recalled that benefit-cost analysis has indicated that low-rise infilled frame buildings were the ones with the highest benefit/cost ratios. The results of life-cycle cost analysis reported in Fig. 11 show the optimal retrofit level for this class of buildings. It is 0.4/0.5/0.7 when the value of life is not taken into account, and 0.5/0.8/0.8 when it is, for seismic hazard according to Eqs. 3, 1 and 2, respectively. Translated into retrofit costs these are 36/45/63 (€/m^2) and 45/45/72 (€/m^2) respectively (building replacement cost per m^2 is assumed as 750 €/m^2).

The above imply that the optimal retrofit level, as well as the associated cost, are considerably lower than the one considered within the scope of benefit-cost analysis (Sects.

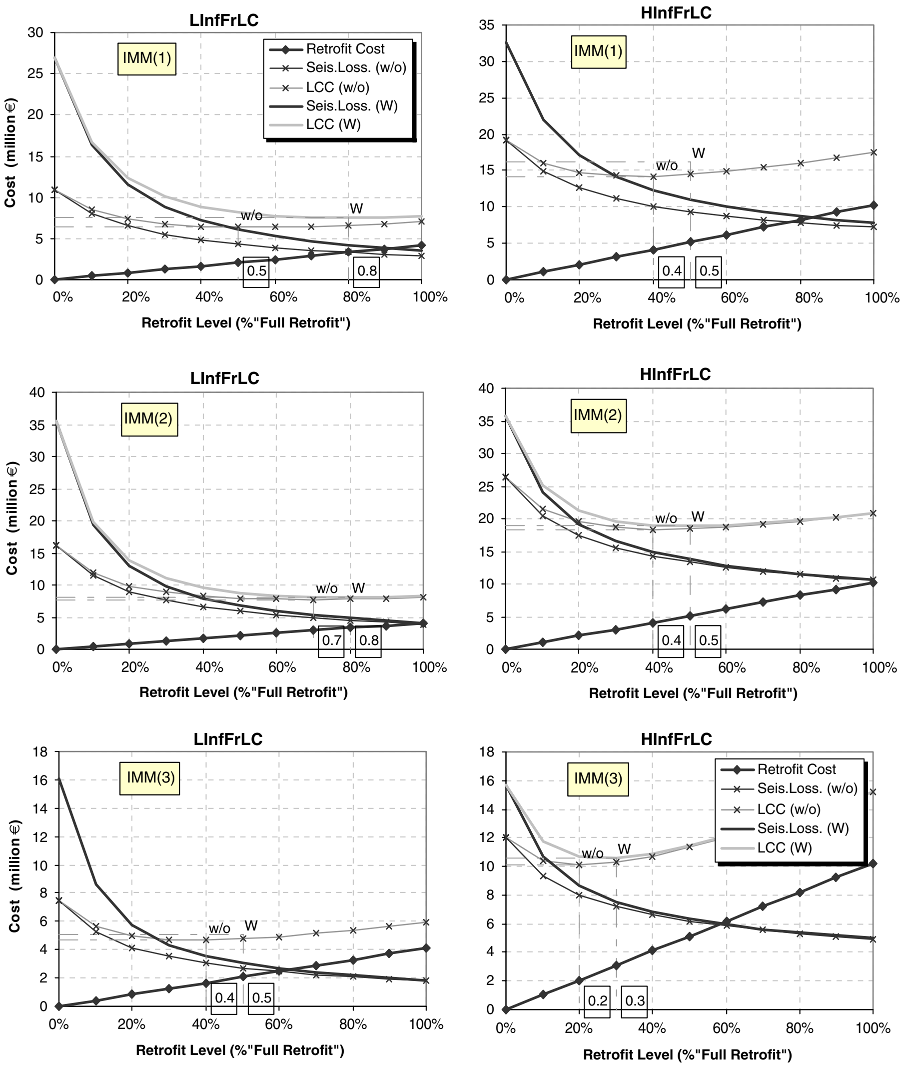

Fig. 11 Life-cycle cost analysis, for low-rise (left) and high-rise (right) infilled frame, low code buildings

3.2 and 3.3), which was strengthening of the old (low-code) buildings up to high-code performance levels (the cost associated with that particular choice of retrofit level was estimated as 90€/m^2).

In all cases examined the optimal retrofit level is higher when the seismic hazard is estimated using Eq. 2, lower for Eq. 1, and the lowest for Eq. 3; these results are consistent with the occurrence probabilities of earthquakes with intensities greater than VII (I_{MM} VIII) resulting from each of Eqs. 1–3. As expected, the optimal retrofit level is higher when the seismic hazard is higher.

When casualties are taken into consideration, seismic losses (denoted as "Seis.Loss. (W)" in the figures) are, of course, higher than when they are neglected ("Seis.Loss. (w/o)"); therefore the optimal retrofit level is slightly higher. In some cases, such as

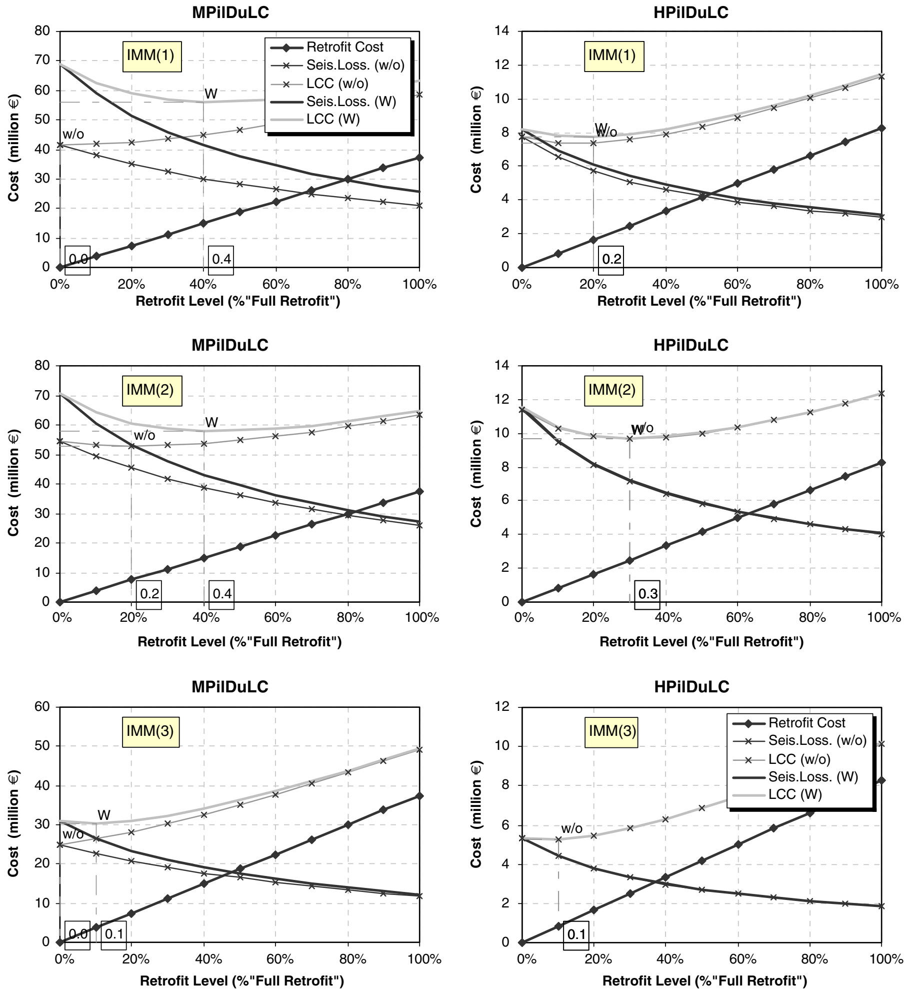

Fig. 12 Life-cycle cost analysis, medium (left column) and high-rise (right column) low code-buildings with dual system and pilotis (soft story)

"HInfDu" (high-rise infilled dual) buildings no significant human losses were expected, thus the optimal retrofit levels were practically the same, both with and without considering casualties.

It is clear from the comparison of Fig. 11 and Figs. 12 and 13, referring to frame and dual systems respectively, that the optimal retrofit level in the case of frame buildings is consistently higher. This conclusion is in agreement with the observation that the effect of seismic design level is much less prominent in the case of (old) buildings with walls than those with frames only (Kappos et al. 2004a, b, 2006). Interestingly enough, in most cases the optimal retrofit level of high-rise buildings was lower than the one estimated for the corresponding low-rise ones. As far as the medium-rise infilled buildings with dual system "MInfDuLC" are concerned, the status quo seems to be the proper choice, since the "no retrofit" scenario yields the minimum life-cycle cost.

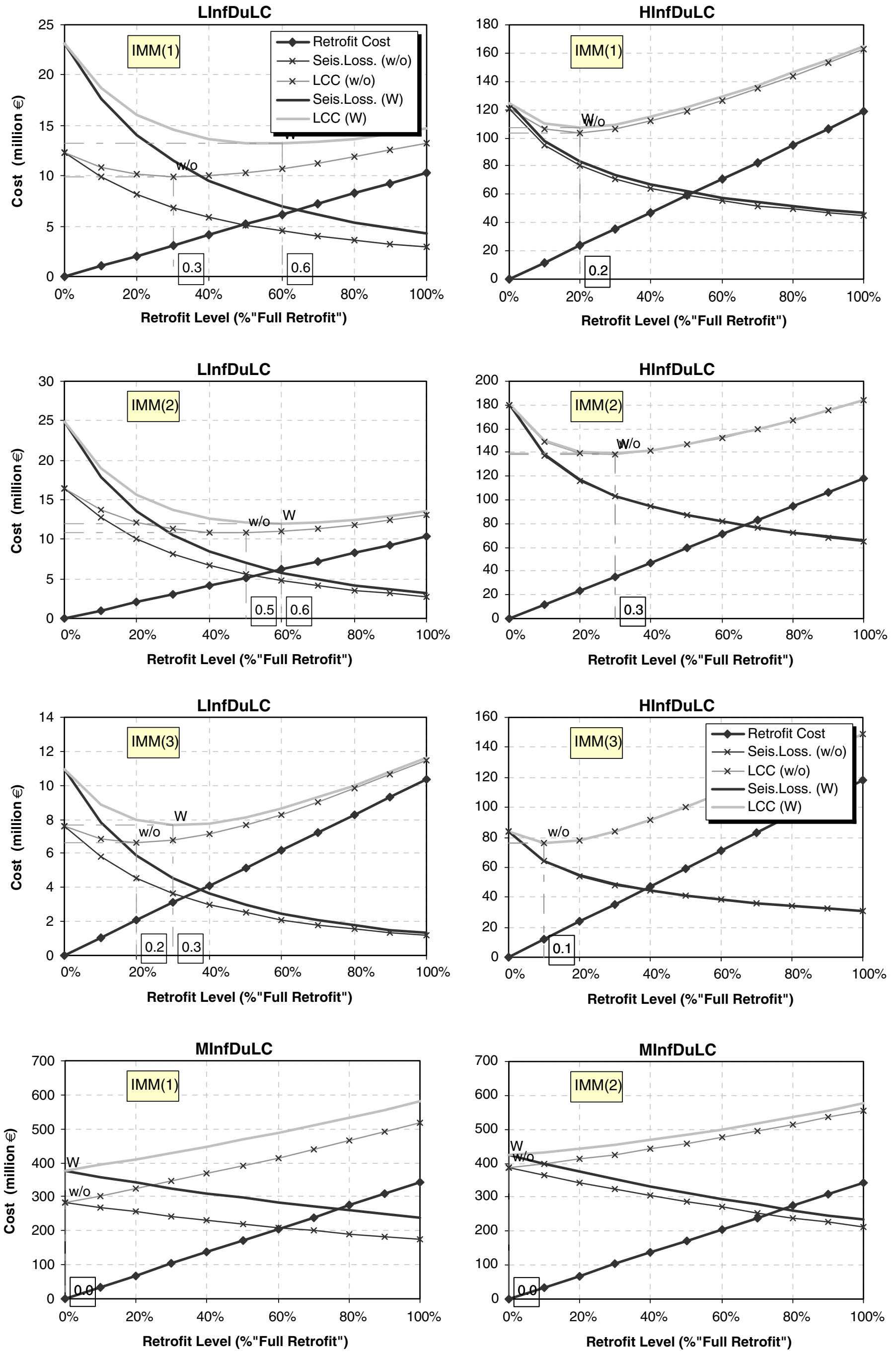

Fig. 13 Life-cycle cost analysis, low (left column), medium (bottom) and high-rise (right column) low code-infilled buildings with dual system

4 Conclusions

The feasibility of pre-earthquake strengthening of an actual, heterogeneous, building stock, including the old R/C buildings of Thessaloniki, has been analysed. To this purpose contemporary decision making tools, namely cost-benefit and life-cycle cost analyses, were tailored to the needs of the present study, and implemented with the aid of an ad-hoc developed new software application (COBE06). Decision making regarding pre-earthquake strengthening, is an inherently multidisciplinary task and the required data was collected from a wide variety of sources after rather strenuous efforts. Fragility curves produced specifically for the aforementioned buildings types (which are common in many areas of S. Europe) were utilised in order to assess building damage before retrofit and define both the mitigation of structural vulnerability due to retrofit and the optimal retrofit level.

Also, useful insight was provided regarding the significance and the characteristics of various types of earthquake losses. The rating of damage types according to their importance (not including casualties) showed that losses due to building damage are the most important and hence special attention must be paid when assessing them. It has been shown that the feasibility of the retrofit, as it is viewed within a benefit-cost analysis, is affected more by its ability to reduce structural damage for moderate rather than intense earthquakes, since moderate earthquakes have a higher probability of occurrence.

It was seen that casualties influence benefit/cost ratios more when collapse probability is drastically reduced due to retrofit. Problems in adequately quantifying the statistical value of human life were discussed; the reference value used (€500,000) is an upper bound by the Greek standards, but is a rather conservative value for other western countries (e.g. the US). Nevertheless it amplified, in some cases up to 8 times, the benefit/cost ratios, thus shifting the outcome of the analysis towards the feasibility of retrofit, particularly in the case of R/C buildings without walls (i.e. infilled frame systems). Even in the case that casualties are overestimated, a massive strengthening scheme encompassing all old R/C buildings is not deemed to be economically feasible in Thessaloniki, whereas it might be considered for some particular classes such as the low-rise frame buildings.

Regarding the optimal retrofit level of a potential strengthening, as estimated through life-cycle cost analysis, it was found in all cases to be lower than that corresponding to upgrading the old (low-code) buildings to currently adopted (high-code) performance levels. In some cases, such as the medium-rise infilled buildings with dual system, the status quo seems to be quite appropriate.

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