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SEISMIC LOSS AND LIFE-CYCLE COST ASSESSMENT FOR REINFORCED CONCRETE STRUCTURES

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ABSTRACT

Over the recent years, issues pertaining to the sustainable development of structures have come into focus. Sustainability in development takes into consideration not only the present needs, but also the ones of the forthcoming users of a building. A crucial part is the estimation of the costs related to the erection and use of the structure and finally its decomissioning. Thus, a cradle-to-grave cost estimation of a building, i.e. a complete definition of all the costs during its lifespan, is a crucial part of sustainable design and construction. In order to obtain all the pertinent costs, a critical parameter to consider is the repair and maintenance cost. This becomes very important in seismically active regions where rare events may enforce total asset loss, while the occurrence of even low-intensity events, may cause significant non-structural and building content loss. Our objective is to investigate seismic losses for low/midrise reinforced concrete (RC) frame buildings of the southern of Europe and the Mediterranean where significant seismic activity is observed. As an example an actual building built in Greece in 1950's is presented. Using state-of-art approaches allows to account for structural member losses as well as non-structural components and contents, offering a holistic view of the lifetime hazard represented by older non-ductile RC frame buildings.

INTRODUCTION

In seismically active regions the earthquakes that may occur during the lifetime of a structure are related to significant costs due to the repair needs that may arise. Strong ground motion will inevitably damage structural members, especially in the case of old, insufficiently sized buildings. Apart from structural damage, the earthquake-induced ground motion will also cause non-structural damage to the internal partitions and the cladding of the building that may also need to be repaired or replaced to allow its continued operation. Furthermore, damages to mechanical equipment, HVAC (heat-ventilation-airconditioning) installations and the contents associated with the use of the building, (bookcases, shelves, computers etc) need also to be addressed and may prove to be a cost that should not be neglected.

Recent earthquakes affecting urban areas have had enormous economical impact, showing that despite the progress achieved in the seismic design of structures, something is still missing. The level of structural safety achieved by pertinent code provisions has certainly led to safer designs. The concepts of capacity design and careful detailing of structural members have led to safe buildings that minimize casualties and allow their timely evacuation. Still, this is not enough. Recent seismic guidelines (FEMA-356, 2000) propose instead an array of probabilistically-defined requirements, schematically shown in Fig.1, that offer a characterization of the desired structural performance for

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different seismic intensity recurrence intervals. Fig.1 presents a detailed view of the requirements set for rare events (safety) and for more frequent ones (operability), while more extended description of the desired building performance is provided in Table.1. Lately, focus has been shifting to the latter category of events, as current design codes have not yet addressed issues related to the repair and retrofitting cost of a structure (Ramirez and Miranda, 2009).

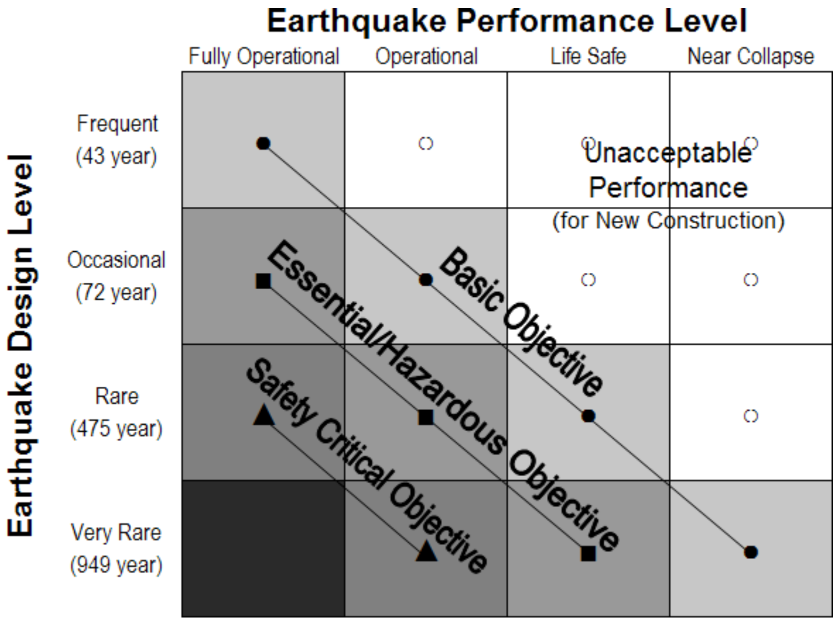


Figure 1: Recommended seismic performance objectives for buildings as per FEMA-356 (2000).

Economic losses due to earthquake damage are often crippling. For example, estimates by Hall (1995) show that the 1994 Northridge earthquake led to losses that exceeded \$25 billion. According to Benuska (1990), the 1982 Loma Prieta earthquake resulted to property damage that ranged between \$6 billion and \$13 billion. Thus, it is clear that apart from the death toll, the impact of economic losses due to earthquakes should be also quantified and taken into consideration. Therefore, as a first step towards evaluating the sustainability of existing buildings, focusing on Southern Europe and the Mediterranean, we shall embark on an investigation of the seismic losses incurred by one of the most characteristic building types of this region, namely, the reinforced concrete frame. For this purpose, the state-of-art loss assessment framework of FEMA P-58 (2012) shall be adopted and subsequently adapted to reflect the characteristics of the region of interest.

SEISMIC LOSS ASSESSMENT FRAMEWORK

The best known current paradigm for assessing earthquake losses is captured by the Cornell and Krawinkler (2000) framing equation that has been adopted by the Pacific Earthquake Engineering Research (PEER) Center (Aslani and Miranda 2005, Mitrani-Reiser 2007):

$$\lambda(DV) = \iiint G(DV \mid DM) \cdot \left|\mathrm{d}G(DM \mid EDP)\right| \cdot \left|\mathrm{d}G(EDP \mid IM)\right| \cdot \left|\mathrm{d}\lambda(IM)\right| \tag{1}$$

IM is the Intensity Measure that monitors the level of seismic loading; typically, chosen to be the first mode spectral acceleration $S_a(T_1)$. EDP represents one or more Engineering Demand Parameters that measure structural response given the IM. For example, these can be the peak floor acceleration (PFA), the maximum interstorey drift ratio (IDR) and the residual drift at each story, as adopted by FEMA P-58 (2012). Finally, DV is one or more decision variables that are meant to support decision-making by stakeholders. According to PEER, these comprise the triptych of monetary losses, downtime and casualties. $G(\cdot)$ represents the complementary cumulative distribution function, and $\lambda(\cdot)$ is the function of the mean annual frequency of exceeding values of its argument.

These quantities are incorporated in Eq.(1), integrating hazard analysis with structural analysis data, damage and loss assessment to assist in the decision-making process schematically shown in Fig.2 by Mitrani-Reiser (2007).

Table 1: Description of the building performance for each objective set by FEMA-356 (2000).

Damage Control and Building Performance Levels				
	Target Building Performance Levels			
	Collapse Prevention Level (5-E)	Life Safety Level (3-C)	Immediate occupancy Level (1-B)	Operational Level (1-A)
Overall Damage	Severe	Moderate	Light	Very Light
General	Little residual stiffness and strength, but load-bearing columns and walls function. Large permanent drifts. Some exits blocked. Infills and unbraced parapets failed or at incipient failure. Building is near collapse.	Some residual strength and stiffness left in all stories. Gravity-load-bearing elements function. No out-of plane failure of walls or tipping parapets. Some permanent drift. Damage to partitions. Building may be beyond economical repair.	Mo permanent drift. Structure substantially retains original strengt5h and stiffness. Minor cracking of facades, partitions and ceilings, as well as structural elements. Elevators can be restarted. Fire protection operable.	No permanent drift. Structure substantially retains original strength and stiffness. Minor cracking of facades, partitions and ceilings, as well as structural elements. All systems important to normal operation are functional.
Nonstructural components	Extensive damage.	Falling hazards mitigated but many architectural, mechanical, and electrical systems are damaged.	Equipment and contents are generally secure, but many not operate due to mechanical failure of lack of utilities.	Negligible damage occurs. Power and other utilities are available, possibly from stand by sources.
Comparison with NEHRP provisions for the Design Earthquake	Significantly more damage and greater risk.	Somewhat more damage and slightly higher risk.	Less damage and lower risk.	Much less damage and lower risk.

Probabilistic seismic hazard analysis (PSHA, Cornell 1968, Esteva 1968) essentially simulates the occurrence of earthquakes along the faults influencing a specific site to extract λ(IM), i.e., the Mean Annual Frequency of exceeding any given level of seismic intensity. The connection of IM and EDP essentially requires a comprehensive structural analysis for the estimation of G(EDP|IM), best exemplified by Incremental Dynamic Analysis (IDA) as described by Vamvatsikos and Cornell (2002). IDA subjects a structural model to nonlinear time history analysis under a suite of ground motion records scaled to multiple levels of the IM. It thus manages to offer a complete estimate of the distribution of any EDP given the IM. In order to associate the derived EDPs with structural damage, fragility functions are employed. Thus, rather than mapping EDPs to a continuous IM, these component-specific functions (or distributions) associate EDP levels with discrete Damage States (DSs) of the component. The initiative to create these fragility functions came early in order to serve the needs of seismic risk estimation for nuclear power plants (Kennedy and Ravindra 1984). This research effort has been continued until recently. For example, Porter et al. (2007) suggested methods for deriving consistent fragility functions while considering all sources of uncertainty. Such component-level fragilities should be distinguished from building-level fragilities that are parameterized on the IM, rather than the EDP, and refer to an entire building, rather than a specific component. Such building-level fragilities (e.g. Jeong and Elnashai 2007, Kazantzi et al. 2008, 2011) have found widespread use in performing simplified large-scale assessments of loss, yet they are being phased out in favor of specialized component-level ones, at least for single buildings. For each component and damage state, a corresponding cost function is needed to allow for a comprehensive cost analysis of repair actions and losses. By integrating losses over each level of the IM, one can generate the so-called vulnerability functions that can provide a complete probabilistic characterization of seismic loss at each level of the IM. By convolving the vulnerability with the seismic hazard curve, we essentially get the result of Eq.(1).

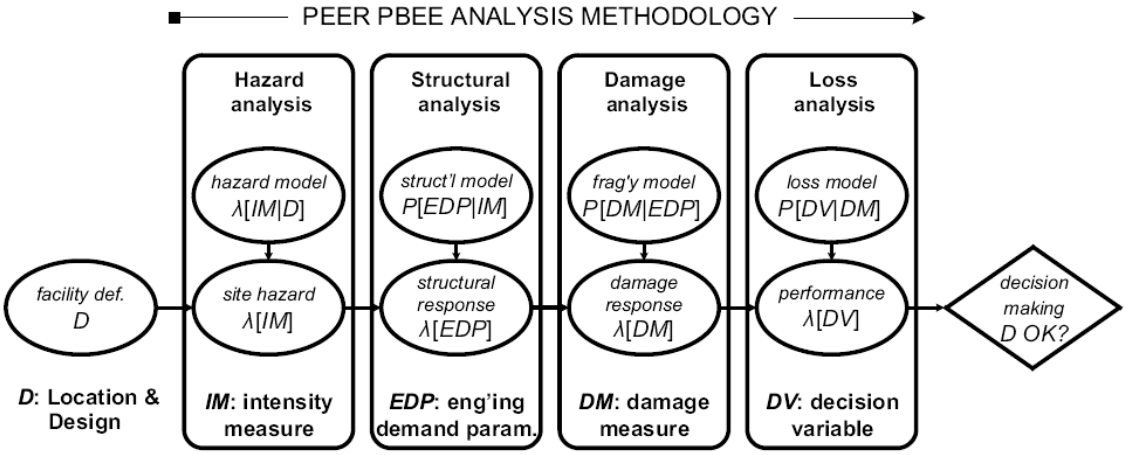


Figure 2: PEER defined decision-making process by Mitrani-Reiser (2007)

The US Federal Emergency Management Agency (FEMA) veered research efforts to the creation of a complete and a comprehensive tool that will allow the estimation of the seismic losses due to earthquake-induced loads. The result of this effort is the FEMA P-58 (2012) set of guidelines that based on the fragility functions developed and together with the companion software (PACT tool), currently form the state-of-the-art in the probabilistic estimation of the seismic loss for buildings. As recognized in the introduction of FEMA P-58 (2012), the driving force for writing these guidelines was the need to provide insurance companies and stakeholders an estimation of the estimated annual losses due to seismic damage. Apart from the structural components, FEMA P-58 (2012) also considers losses due to non-structural components like furniture and equipment. Moreover, estimation is also provided for the time that will be required for a building to remain non functional in order for the repairs to take place. The latter is crucial for industrial facilities and for commercial buildings. Furthermore, in order to estimate the probability of human losses, population models that vary according to the hour of the day and the day of the week are also included.

With FEMA P-58, engineers are called to group all the building components affecting the seismic repair cost in fragility groups. These are groups of components that are expected to exhibit the same behaviour and sustain comparable damage. These groups are assigned the same fragility functions and the amount of damage that they will sustain is governed by the same EDP. The EDP's used are: a) interstorey drift ratio, which affects mainly the structural components, b) the peak floor acceleration, which is used to assess damage in suspended equipment, i.e. HVAC, and furniture and c) the residual drift, mainly used to predict whether the building will be repaired or replaced. The EDPs required to assess the final seismic repair cost may arise from a set of IDA curves that have been estimated for the specific building and site.

The fragility functions of FEMA P-58 (2012) describe the damage of every component recommending several discrete damage states. Once the EDP levels are defined by one of the above procedures, the damage probability of each component is estimated. Then for every component, through the connection of each damage state with a repair cost distribution (also provided by the component datasheets of FEMA P-58 (2012), multiple realizations of component loss are calculated. Since both the definition of the damage states and the definition of the repair cost are probabilistic (through a mean, standard deviation and a normal or lognormal distribution) their sampling is performed via Monte Carlo simulation. Finally, all component repair costs are combined and the distribution of the seismic loss is calculated for the entire building at each level of the IM.

The FEMA P-58 (2012) procedure allows the disaggregation of the statistically expected cost component-wise, as demonstrated by Mitrani-Reiser (2007) and Aslani and Miranda (2005). The disaggregation of the cost due to collapse and non-collapse damage as well can be also easily accommodated. This information is especially useful in the decision-making procedure shown in

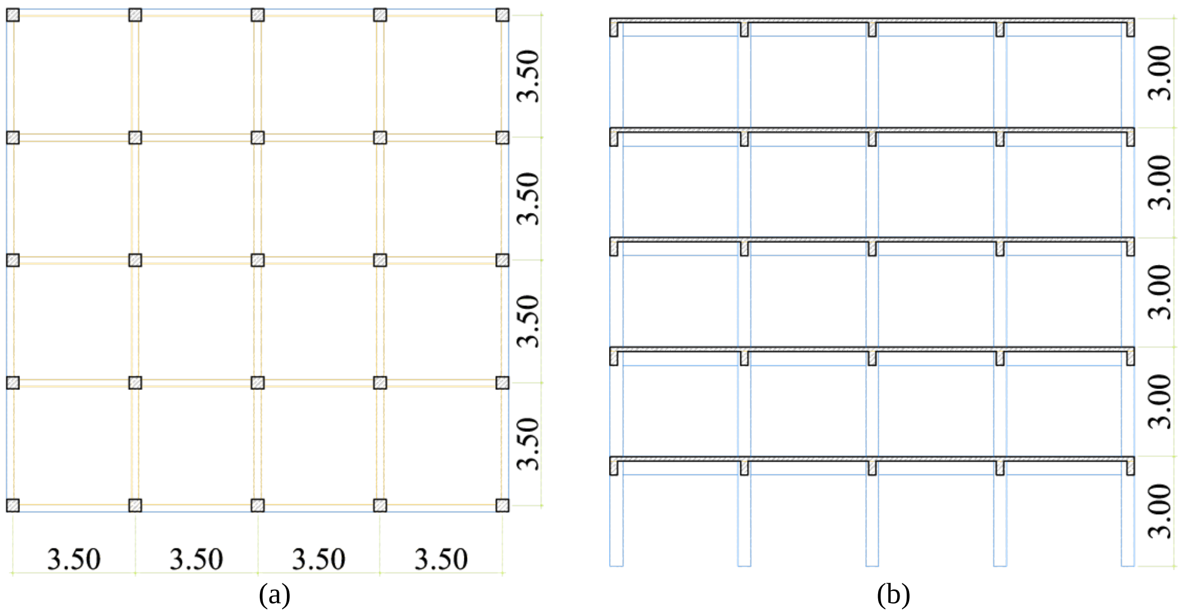
Fig.2. This procedure may also allow engineers to decide on whether to proceed by retrofitting the structure or recommend its demolition.

The combination of the ATC-58 guidelines along with the PACT tool provides engineers with the means to assess the cost of the statistically anticipated seismic damage. Thus a solution can be achieved in the problem faced by owners and stakeholders as well as insurance companies on the expected seismic losses. Yet, these tools are readily available only with out-of-the-box data covering the United States, thus an adaptation to the costs encountered in other seismically active regions is needed (FEMA 2012). Scope of the present work is to provide a framework for the cost assessment of the seismic losses for structures located in the south of Europe, i.e. a seismically active region. The cost estimation is carried out accounting for local data, providing thus a region specific estimation.

REINFORCED CONCRETE FRAME CASE STUDY

In order to carry out the seismic loss assessment for reinforced concrete structures in our area of interest, the 5 storey reinforced concrete building shown in Fig.3 is selected as working paradigm. The building was constructed in the 1950's and is a typical example of urban buildings of that period in Greece (and probably most of the Mediterranean). The columns of the first three storeys have 35x35cm sections and in the upper two storeys are reduced to 30x30cm sections. The beams have a 20x50cm section in all storeys. The materials used were 15MPa concrete and 220MPa reinforcing steel. The above correspond to a typical building design with weak columns and strong beams widely used in south Europe between 1950's and 1980's. Although the combination of strong beams and weak columns does not allow significant non linear behaviour to take place during the dynamic loading of the building, the specific configuration is selected since it is representative of many buildings of the European south built before the capacity design widespread adoption. It should be noted, though, that the presence of adequate transverse reinforcement in the columns and joints (indicative of the better construction standards of the era) has been hypothesized, thus avoiding the appearance of brittle shear failures.

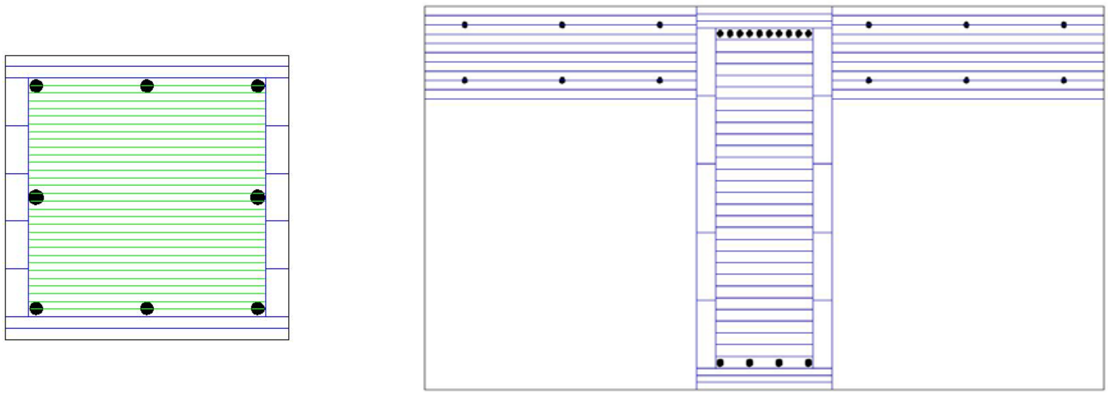
The building has been partially refurbished and now serves as an office building. During the refurbishment process, all internal and external infills were removed. The exterior of the building was covered by curtain walls and internally gypsum partitions were installed. Thus, only the concrete load bearing elements as well as the in situ cast staircases remain from the initial structure.



(a) (b)

Figure 3: (a) Plan and (b) elevation of the RC building (dimensions in meters)

A detailed model with fiber elements for each different section, as shown indicatively in Fig.4, was built in OpenSees (2010) and used in the analyses. Differences in concrete quality in the core and the cover of the section were allowed for and thus for each section two concrete areas are modelled with fibers: one corresponding to the core of the section having confined concrete properties and one corresponding to the cover of the section having unconfined concrete properties. The reinforcing bars of each section were also modelled with steel fiber elements that allow for elastoplastic behaviour with an ultimate ductility to represent fracture in tension and bar buckling in compression.



(a) (b)

Figure 4: Fiber meshing of column (a) and beam (b) sections

STRUCTURAL ANALYSIS

Initially and in order to evaluate the building's behaviour, a static pushover analysis was carried out with triangular loading. The storey drifts versus the base shear were obtained as shown in Fig.5. The building cannot be categorized as having classical soft-story behaviour. Still, the irregularity observed in the interface of the 3rd and 4th story, where the columns' section is reduced, together with the weak-column strong-beam design, defines these stories as the weaker link. Thus, when one of the two yields at a story drift of about 1%, it essentially attracts all excessive deformation. As shown in Fig.5, all other stories start unloading at the same time. For the triangular load pattern, the critical one happens to be the 3rd story. It eventually deforms without bounds and leads to global collapse. Still, different load patterns (and different ground motions) may point to either the 3rd or the 4th as the culprit for collapse.

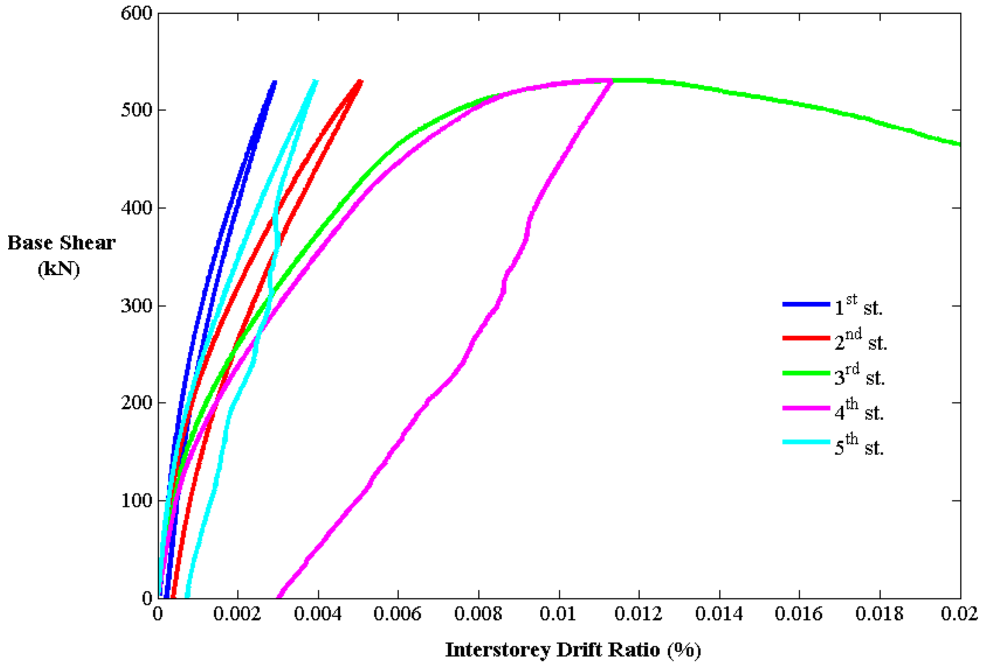


Figure 5: Storey drifts obtained by static push over analysis with triangular loading

As prescribed in the ATC-58 guidelines, a set of IDAs were performed to assess the buildings dynamic behaviour. A suite of 22 far field events from various seismically active areas were employed, comprising the FEMA P695 (2009) far field set. Each event has two horizontal components and as a result forty four records in total are used. For each IDA, the Intensity Measures are scaled based upon the 1st eigenmode's spectral acceleration, i.e. $SA(T_1)$, assuming damping equal to 5%. The EDPs obtained from each analysis for each storey were the IDRs shown in Fig.6 and in percentile form in Fig.7, as well as the PFAs for each storey.

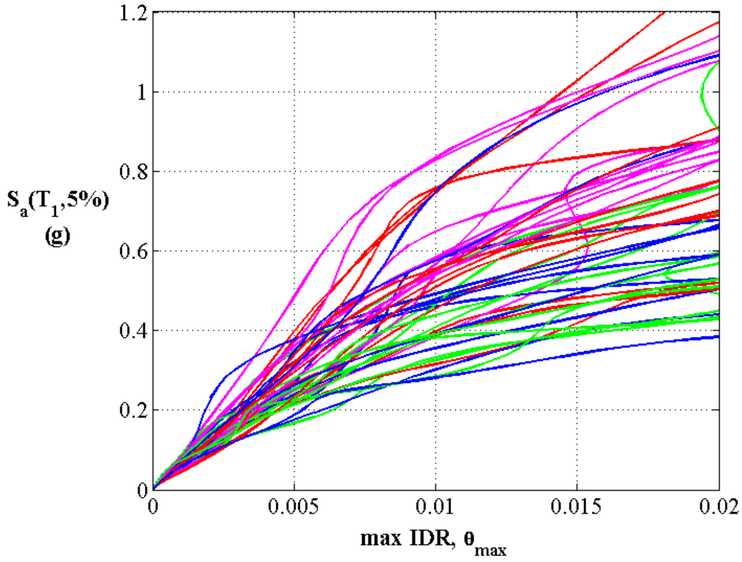


Figure 6: Maximum storey drifts obtained by IDA

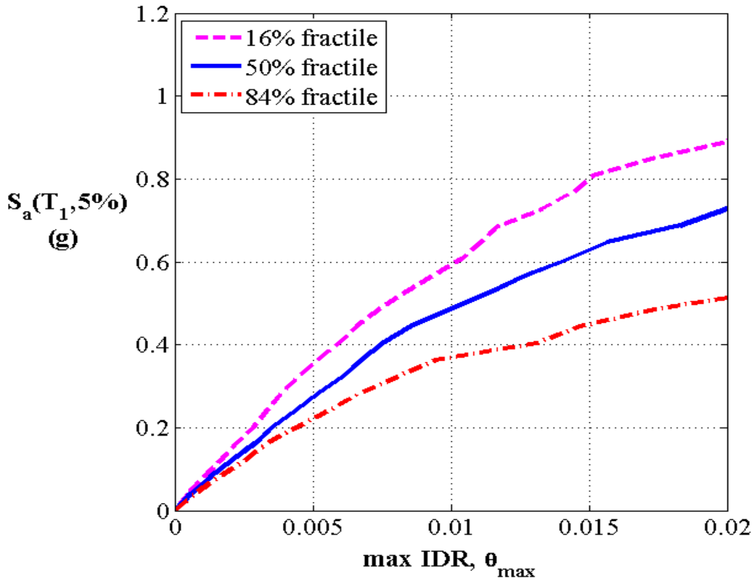


Figure 7: Fractile IDA curves of the maximum story drift

LOSS ASSESSMENT

Following the procedure outlined in FEMA P-58 (2012), an inventory of the structural and non structural members as well as the contents of the building and their possible damage states was formed. This inventory was based on the component descriptions offered by the PACT tool and is shown in Table.2. Each entity of the structure liable to sustain damage was associated with its own fragility function and thus a definition of its discrete damage states with an EDP obtained by the IDAs, whether this was the IDR or the PFA, was achieved. As the whole seismic loss estimation procedure is of probabilistic nature, these fragility functions are defined through a probability density function which for the specific case is a lognormal distribution. The mean values and the dispersions provided by FEMA P-58 were utilized here also since they are fairly representative of the behaviour of each specific component of the structure. With the EDPs recorded at each IM level, it is thus feasible to obtain an estimation of the probability of being in each damage state, as described from the associated component fragility function.

Then, and in order to obtain the estimation of the cost due to the repairs of the components of the structure, each component damage state is also associated with a cost function. The cost functions have either normal or lognormal distributions, according to the definitions of FEMA P-58. As the building is situated in Greece rather than the USA, the means/medians (but not the dispersions) of the FEMA P-58 cost functions were modified to account for the local market prices. This was carried out using the procedure suggested in the guidelines for conversion to local costs. More specifically, for each component the cost of each damage state is divided to labor cost and unit repair cost, with the nature of the repair works determining the contribution of each part to the total. The two constituents are adapted to reflect the hourly labor cost of Greece and the corresponding unit repair cost.

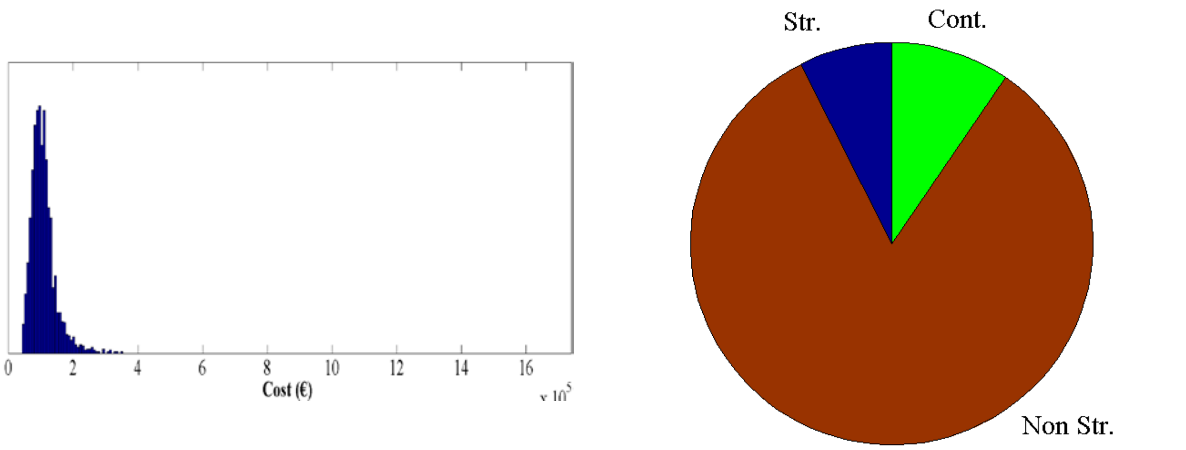
In order to obtain a more consistent estimation of seismic losses, the estimates are conditioned on whether collapse has occurred. When collapse occurs, the building is assumed to be demolished and a new one with exactly the same size and characteristics is constructed in the place of the initial. In this case the cost is the one of the new construction (cost replacement new), which is taken as a nominal one based on local construction costs for office buildings. The cost replacement new is also used in place of the repair cost, even when no collapse has been registered, whenever the former exceeds the latter. Essentially we are assuming the owner to be a "rational agent", acting only with monetary criteria in mind, without any other considerations (e.g., of historical value).

Table 2:Description of the fragilities used in the loss assessment of the RC building.

FEMA P-58 ref.	Description	EDP	Quantity
B1041.031a	Concrete beam-column joints, beam on one side	IDR	16 per story
B1041.031b	Concrete beam-column joints, beam on both sides	IDR	9 per story
B2022.001	Curtain walls	IDR	16 per story
C2011.021b	Cast in place concrete stairs	IDR	1 per story
C1011.001a	Wall partitions	IDR	2 per story
C3032.001a	Suspended ceiling	PFA of floor above	9 per story
D1014.022	Hydraulic elevator	PFA	1 in total
E2022.023	Desktop electronics	PFA	18 per story
E2022.106b	Bookcase	PFA	18 per story

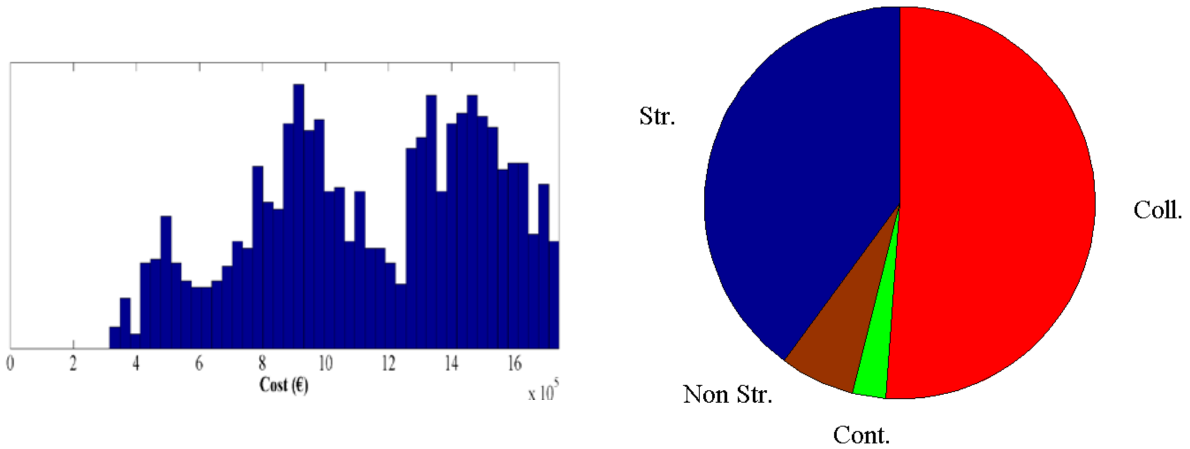
Indicatively, results are presented for three IM values. The first one corresponds to $SA(T_1)$ equal to 0.31g, representing thus a frequent earthquake for which pertinent code provisions would require limited damage as shown in Table.1 in fields 1-B and 1-C. The second level corresponds to $SA(T_1)$ equal to 1.15g, i.e. close to the design earthquake for the specific building having T_1=0.6sec. As described by Table.1, FEMA-356 would require compliance with the life safety criterion as of field 3-C, but it would accept that the building may be beyond economical repair. Finally, the third level with $SA(T_1)$ equal to 2g corresponds to a rare large-magnitude earthquake with a low annual frequency of exceedance. The results for each of the three cases are presented in histograms showing the distribution of the final cost in Euros. Furthermore, pie charts are obtained showing the split of the overall mean loss to the cost of building collapse and the repair cost of structural/ non structural/content components. As expected, the histograms in Fig.8(a), Fig.9(a) and Fig.10(a), show a clear shift of the bar plots to the right, i.e. to higher costs for increasing intensity measures. This is inevitable since the amount of structural elements damaged increases, and this is where the majority of the invested value lies for this office building. As can also be observed from the cost breakdown shown in the pie charts of Fig.8(b), Fig.9(b) and Fig.10(b), the distribution of the cost also changes as the intensity of the ground motion increases. More specifically, in small intensities the repair costs arise mainly due to repairs and replacement of non-structural elements and gradually the cost is governed by the cost needed to repair structural elements and finally the cost is pretty much defined by the replacement cost of the building since the percentage of collapses increases.

In order to obtain a clear understanding of the change in the cost distribution for different values of the IM, the 16, 50 and 84 percentile cost curves are shown versus $SA(T_1)$, in Fig.11. The cost increases as the first mode spectral acceleration increases as well, and the rate of increase changes as different types of elements, i.e. structural/non-structural, are damaged. Thus, as the structural elements begin to sustain damage, the increase in the total cost is more intense in comparison to the low $SA(T_1)$ region where the cost mostly arises from the need to replace contents and non-structural elements. Finally, for large values of $SA(T_1)$, the number of collapses is critical and as a result the cost gradually stabilizes into the replacement cost of the building as demonstrated by the nearly vertical percentile curves of Fig.11.



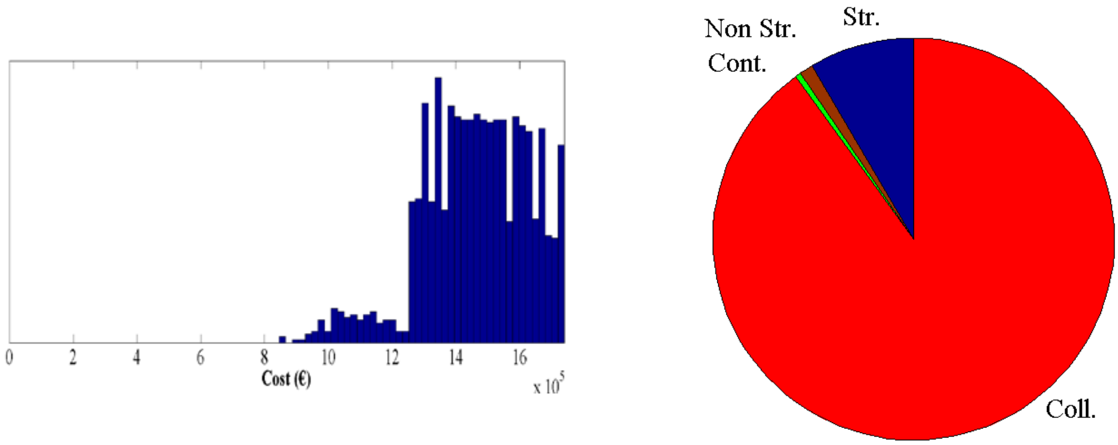
(a) (b)

Figure 8: Cost distribution for $SA(T_1)$=0.31g in histogram form (a) and cost breakdown (b)



(a) (b)

Figure 9: Cost distribution for $SA(T_1)$=1.15g in histogram form (a) and cost breakdown (b)



(a) (b)

Figure 10: Cost distribution for $SA(T_1)$=2g in histogram form (a) and cost breakdown (b)

Due to the lack of capacity design, the building exhibits early collapse at low levels of $SA(T_1)$. This is evident from the pie chart of Fig. 9(b) where for an IM level akin to the design earthquake, a large percentage of records causing collapse are observed in the analysis. As a result, the cost is governed by the replacement cost of the building. In the case of a building designed according to modern structural codes, e.g. incorporating capacity design, this behavior is not expected to appear at the design level ground motion. In such a case the cost breakdown in the pie charts of Fig.9(b) would be mostly driven by component repair costs, with the collapse part being significantly smaller. The results of Fig. 8(b) and Fig. 10(b), though, representing much lower and much higher intensities, respectively, may not appear to change as much.

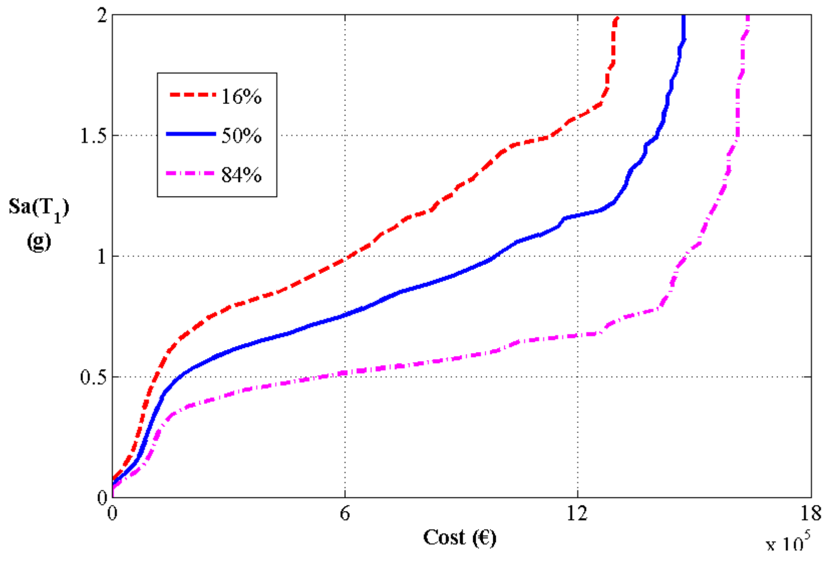


Figure 11: Loss 16/50/84% curves, showing the distribution of repair cost as a function of the IM level

CONCLUSIONS

An investigation into the use of the FEMA P-58 approach for assessing losses of buildings in Southern Europe has been presented. As a testbed. a reinforced concrete frame building constructed in the 1950s was selected. It is a typical example of existing non-ductile structures, designed and constructed before the era of capacity design throughout the Mediterranean. Subsequent analyses confirm the expected susceptibility of the structure to lateral loads. A reduction in column dimensions and reinforcement at the 3rd and 4th floor leads to early damage localization and to the formation of a story mechanism.

Application of FEMA P-58 was based on repair and replacement cost data that were chosen to reflect local market prices and labor costs. A detailed inventory of the components of the structure liable to be damaged during an earthquake was made, and a comprehensive probabilistic assessment was carried out. The outcome clearly supported the structural analysis findings, indicating that non-structural damages govern losses for frequent serviceability level earthquakes, but structural losses and collapse reconstruction costs become dominant for rarer ground motions, even less intense than current design-level events. This is in stark contrast with the expected outcome for modern buildings, highlighting the potential for crippling losses in older non-ductile buildings that tend to form the majority of the building stock in many countries.

ACKNOWLEDGMENTS

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