A Novel Approach For The Assessment Of Ecological And Social Sustainability Of A RC Building Accounting For Seismic Risk

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SUMMARY:
A sustainable engineering decision-making strategy for design and assessment of civil infrastructures should take into account considerations regarding the society, the economy and the environment. This study presents a novel approach for the assessment of ecological and social sustainability of a case study building subjected to seismic actions during its service life. A methodology is presented that evaluates the time-dependent probability of exceeding a limit state considering the uncertainty in the representation of seismic action. The earthquake-induced damages are related to the environmental and social losses caused by the occurrence of the earthquake. A Life Cycle Assessment (LCA) of a case study building accounting for the time-dependent seismic reliability is conducted. LCA results revealed significant risk-based contributions for the rehabilitation phase due to the seismic induced damages. The time-dependent probability of collapse in a year can represent a benchmark indicator for human safety in the context of social sustainability.

Keywords: sustainability, time-dependent seismic risk, life cycle assessment, loss assessment

1. INTRODUCTION

The term “sustainable development” is introduced, as a result of debates between economists and ecologists, in a report entitled “Our Common Future” (The Brundtland Report 1987). In this report, a sustainable development is defined as a development that “meets the needs of the present without compromising the ability of future generations to meet their own needs”. The combination of sustainability and development aims at reconciling the economic growth in the classical sense with modern-day concern for the environment. This concept was also underlined by (Tiezzi 1984) who claims that one of the main characteristics of contemporary society is the contrast in time-scale between the evolution of the society (fast) and the environmental cycle (slow). A framework for sustainability assessment is made up of a set of objectives, sustainable variables/parameters, indicators and performance criteria. The key objectives for sustainable development are generally represented in terms of as a triple-bottom-line (TBL) strategy illustrated in Fig. 1. (Willard 2002), which is based on simultaneous realization of environmental, economic, and social goals. These objectives are usually established by the decision-makers, the community and the end-users.
Building sustainability is characterized by the interaction between the built environment and its economic, social and natural context. In particular, the economic aspects should be considered not only throughout the construction phase but also during the service life of the building in terms of building maintenance and preservation. These aspects can be evaluated by employing the Life-Cycle Cost (LCC) analysis taking into account both structural performance and energy efficiency criteria (Asprone et al. 2008, Kneifel 2010). The social dimension of sustainability for the built environment is often referred to as socio-political impacts, encompassing various issues such as, social acceptance, equity and opportunity, and adequate planning of social services (e.g., health, education and housing welfare) (Lee et al. 2010). Other aspects of sustainability in the context of construction works such as intergenerational equity, life quality index, risk acceptance with regard to decision making and lifecycle benefit-based design have been discussed by (Faber et al. 2004). Even though building

sustainability is a multi-facet concept, the attention is often focused on environmental aspects. This is due to the large impact of the city metabolism on the natural environment in terms of exploitation of the resources and consumption of energy. It is reported that as much as 40% of the world material consumption and 30-40% of the total energy demand and greenhouse gas emissions is related to the building sector, including housing (Pulselli et al. 2007, Nässén et al. 2007). Therefore, the construction industry assumes a central role in the quest for reaching a sustainable society within a reasonable period of time.

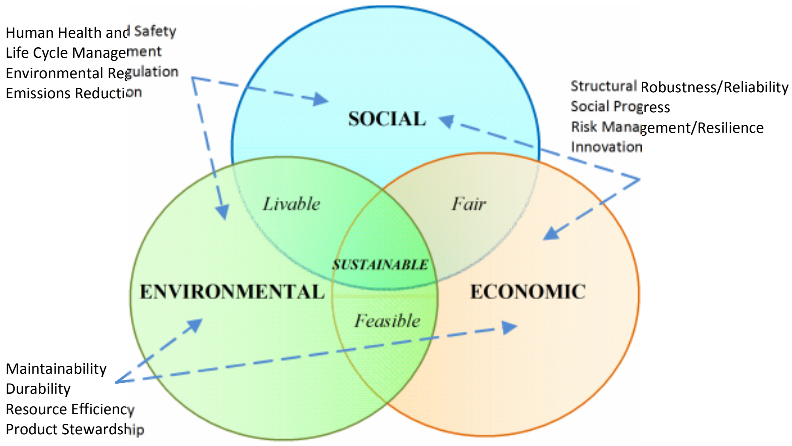


Figure 1. Triple Bottom Line (TBL) representation and sustainability requirements

2. INTEGRATING THE CONCEPT OF SAFETY IN THE FRAMEWORK FOR SUSTAINABILITY ASSESSMENT

Given that the sustainability assessment spans over the entire life cycle of a building, it should address all the critical actions to which the structure may be subjected. This is particularly relevant in regions characterized by high risk of natural hazards, such as, earthquakes, hurricanes, tornados, fires and floods. Moreover, the evaluation of sustainability in building sector is subjected to various sources of modeling uncertainties, such as, the resistance of the infrastructure, material mechanical properties, the duration of service life, etc. Hence, it is clear that achieving sustainability should entail probabilistic assessment of the safety of the entire system with respect to the critical actions to which it may be subjected. In light of these considerations, the risk-based sustainability assessment of a building encompasses the following general categories/phases: initial construction, damage-based repair and maintenance and final end of life replacement. These categories are elaborated in this section from economic, environmental and social point of view.
Studies by (Taghavi and Miranda 2003) investigated the initial cost contribution of different building components. They report that in a typical building, the structural system accounts for approximately 10%-20% of the construction cost. As far as it concerns the non-structural components, the contribution to initial construction costs depends on the functionality of the building; for instance, a hospital versus a residential building. Considering the consequences of seismic events on buildings, the resultant damage can affect the structural frame, non-structural components and building contents. Given the significance of the damaged-based repair costs, achieving a higher performance level for the building may play a fundamental role in reducing the overall life-cycle costs. The risk-based economic aspect of sustainability, is often quantified in terms of the expected loss, evaluated taking into account various sources of uncertainty, throughout the entire building lifetime as a function of the site-specific seismic hazard, structural performance and induced damage (Goulet et al. 2007;). Known the high social value of constructions, sustainability assessment should also address the social aspects; especially those related to the natural and man-made hazards. Given this consideration, the evaluation of the mean annual probability of collapse for a structure can represent an indirect evaluation of the

social worth of sustainability, since it denotes a measure of reliability, robustness and dependability of the structure. Moreover, the inconvenience perceived by the building inhabitants and the surrounding community is highly correlated to the down-time caused as a consequence of seismic events. From the environmental point of view the Life Cycle Assessment (LCA) framework is generally adopted in order to quantify the environmental loads in the construction industry during its entire life cycle, in other words, “*from the cradle to the grave*”. The state of the practice of LCA for buildings is based on the computation of the environmental flows for pre-defined life cycle phases. For instance, the probabilistic assessment of the environmental performance of a building should take into account the uncertainty in the evaluation of the environmental inflow as a result of the hazard-induced damage (related to both construction and end of life phases). The standard LCA procedure is part of the ISO 14040 series (ISO 14040:2006).
The aim of the present paper is to explore various aspects of the integration of risk assessment procedures in the ecological and social sustainability assessment of buildings. In particular a LCA of a reinforced concrete (RC) case study building has been performed using the IMPACT 2002+ methodology (Jolliet et al. 2003) taking into account the environmental and social expected loss due to the seismic risk during its lifetime.

2.1. Methodology

This section presents a step-by-step overview of the methodology introduced in the present work. First, the probabilities of exceeding a set of structural limit states are calculated during the infrastructure’s lifetime. Then, the expected life-cycle environmental impact indicators are calculated by taking into account the initial construction environmental impact, the additional impact related to the damage and repair operations depending on the damage level and/or the eventual end-of-life/recycling operations The calculations involved in this methodology are based on a presumed specific set of rules for the management of the structure. The methodology presented herein for the evaluation of expected life-cycle environmental impact can also be used for decision making between different seismic upgrading options while satisfying prescribed reliability constraints

2.2. Multi-hazard assessment of the limit state probability

Let T_{max} denote the service lifetime of the structure, N the maximum number of critical events that can take place during T_{max} and τ the repair time for the structure. The probability $P(\mathrm{LS};T_{max})$ of exceeding a specified limit state LS in time T_{max} can be written as:

$$P(LS;T_{\max}) = \sum_{i=1}^{N} P(LS \mid i) P(i;T_{\max}) \tag{2.1}$$

where $P(\mathrm{LS}|i)$ is the probability of exceeding the limit state given that exactly i events take place in time T_{max} (representing the fragility of the system) and $P(i;T_{max})$ is the probability that exactly i events take place in time T_{max} (representing the site-specific hazard for the system). In order to calculate the term $P(i;T_{max})$, it is assumed that the event/hazard in the lifetime of the structure is expressed by a Poisson probability distribution with a rate of occurrence equal to ν. Thus, the probability of having exactly i events in time T_{max} can be calculated as:

$$P(i;T_{\max}) = \frac{(\nu T_{\max})^i e^{-\nu T_{\max}}}{i!} \tag{2.2}$$

The term $P(\mathrm{LS}|i)$ is calculated by taking into account the set of mutually exclusive and collectively exhaustive (MECE) events that the limit state is exceeded (for the first time) at event j, j varying between 1 and i. The probability that the limit state is exceeded at event j is calculated by considering that the structure could have been damaged k times, k varying between 0 and $j-1$. Therefore, the evaluation of the term $P(\mathrm{LS}|i)$ requires the evaluation of the set of probabilities denoted by $P(C_j|k,i)$ that the limit state is exceeded for the first time at event j, given that exactly i events have taken place and as a result of which the structure is damaged exactly k times. The sequence of probabilities $P(C_j|k,i)$, $j=1,\ldots,i$ and $k=0,\ldots, j-1$, are also referred to herein as the structural fragility terms. The structural fragilities are denoted by $P(C_j|k)$. It is assumed that if the structure under repair is hit by another event, the repair operations are going to resume from zero. Further details about the adopted methodology are reported in (Jalayer et al. 2011).

2.3. Estimation of fragilities

The structural fragilities $P(C_j|k)$ are calculated as follows:
1. A non-linear static analysis of the structure subjected to seismic excitation is performed and the result is presented in the form of a static pushover curve (i.e., roof displacement versus base shear). The pushover curve is then transformed into that of an equivalent single degree of freedom (SDOF) structure known also as the equivalent SDOF capacity curve. The onset of different structural limit states is marked on the capacity curve.
2. A suite of M ground motion (GM) records is chosen for the site of the structure. The ground motions may be scaled in order to reflect (in an average sense) the expected intensity of ground motion at the site.
For each k value, $k=1,\ldots,i-1$, repeat steps 3 to 8 below:
3.Each of the ground motion records is transformed into a sequence of k (identical) ground motion records. This is used to emulate the fact that the structure may be damaged k times before being hit by that last event.
4. The equivalent SDOF structure is subjected to the suite of the GM records that are constructed as described in step 3 above.
5. The maximum and residual displacements and the residual strength of the equivalent SDOF system in response to the suite of records are recorded.
6. A linear least squares regression analysis of the (natural logarithm of) SDOF maximum displacement versus (natural logarithm of) earthquake intensity measure (i.e., first mode spectral acceleration) is conducted in order to estimate the median and the dispersion in the structural response for a given level of ground motion intensity given that the structure is damaged k times.
7. The limit state thresholds marked in step 1 and the median and dispersion estimates obtained in step 6 are used to calculate the structural fragility term $P(C_j|k)$ as a Lognormal cumulative distribution.
8. k=k+1 and go to step 3.

2.4. The probability of collapse in a year

In the previous sections, it is explained how the probability of exceeding the limit state LS can be calculated from Eqn (2.1). It is also of interest to calculate the probability of exceeding the limit state in a year. In general, the probability of exceeding the limit state in the time interval $[T, T + \Delta T\ ]$ can be calculated as:

$$P(LS;[T,T+\Delta T]) = P(LS;T+\Delta T) - P(LS;T) \qquad (2.3)$$

Therefore, the probability of exceeding the limit state in a year can be calculated from Eqn. (2.3), by setting ΔT equal to 1.

2.5 Expected life-cycle environmental impact

The expected life-cycle environmental impact indicators are calculated from the Eqn. (2.4):

$$E[L;T_{\max}] = E_0 + E_R \qquad (2.4)$$

where E_0 is the environmental impact of the initial construction phase (calculated deterministically) and E_R is the risk-based repair/replacement environmental impact taking into account the occurrence of the seismic events. The repair contribution E_R can be calculated from the Eqn. (2.5):

$$E_R = \sum_{n=1}^{N_{LS}} \sum_{t=0}^{T_{\max}-1} L_n e^{-\lambda t} [P(LS_{n+1};[t,t+1]) - P(LS_n;[t,t+1])] \tag{2.5}$$

where $P(\mathrm{LS}_n;[t, t+1])$ is the probability of exceeding the limit state LS_n in the one-year time interval [t, $t+1$] from Eqn (2.3), N_{LS} is the number of limit states ranging from the intact state of the structure up to the limit state of collapse, L_n is the expected environmental impact of restoring the structure from the limit state LS_n back to its intact state including repair operations. In the case of collapse limit state, L_n corresponds to the end-of life replacement. λ is the discount rate which is assumed equal to 0 and the term in the brackets of Eqn (2.5) is the probability that the structure is between limit states n and $n+1$.

3. CASE STUDY

The methodology presented herein is employed for the evaluation of the expected risk-based environmental impacts (the E_R term in Eqn. (2.5)) for the case-study building subjected to earthquakes. The case study building is a generic five-story RC frame structure with a lifetime of 100 years. Each storey is 3.00m high, except the second one, which is 4.00m high. The nonlinear behavior in the sections is modeled based on the concentrated plasticity concept. It is assumed that the plastic moment in the hinge sections is equal to the ultimate moment capacity in the sections which is calculated using the Mander model for concrete (Mander et al. 1998) and elastic-plastic model for steel rebar. The first-mode period of the case-study structure is equal to T =0.95s as reported in a previous work by the authors (Asprone et al. 2008). The sequence of structural limit states LS_n, n=1, . . . , N_{LS} are discretized as: intact, serviceability (operational level), onset of damage (immediate occupancy level), severe damage (life safety level), and collapse (collapse prevention level). The structural limit states are identified in terms of the maximum displacement of the equivalent SDOF system. The mean annual rate of significant earthquake events is assumed to be equal to $\nu = 0.20$ referring to the building site. Fig. 2 illustrates the static pushover curve calculated for the examined structure. The displacements marking the onset of different limit states are reported on the figure as circles. In particular, the maximum displacements (as in Fig. 2) for the equivalent SDOF system identifying the serviceability (SR), onset of damage (OD), severe damage (SD), and collapse (CO) limit states for structure are equal to: 0.01, 0.02, 0.03 and 0.10 m respectively. The seismic fragilities are calculated based on the procedure described in the previous section by selecting a set of ground motion records and applying it to the equivalent SDOF system.

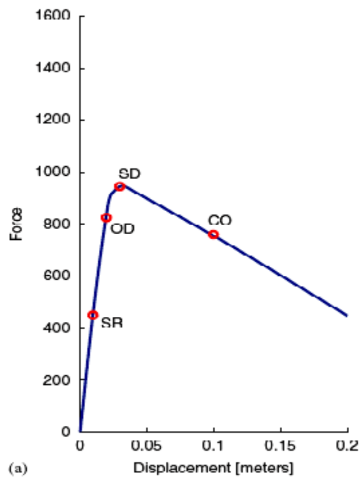


Figure 2. Pushover curves for the equivalent SDOF system: CO, Collapse; SD, severe damage; OD, onset of damage; and SR, serviceability

3.1. Damage evaluation

Evaluation of the seismic damage must take into account the performance of both structural and nonstructural components. In order to map out each limit state threshold to overall levels of structural and nonstructural damage, the FEMA specifications (FEMA 273 1997) are used as a reference since the general structural and non-structural components damage classification for each limit state is reported. The damage description corresponding to each limit state is applied to: vertical elements, horizontal elements, architectural components, mechanical-electrical-plumbing systems/components, and building contents. All these information have been taken into account in order to evaluate the expected damage and the related risk-based environmental impact during the lifetime of the case-study building.

3.2. Life Cycle Assessment of the case study building

The LCA of the case study building has been performed on the basis of the results reported in (DEQ 2010). The present study considers as functional unit the provision of 100 years of housing for the case study building (described in Section 3). The main goal of the assessment is to quantify the expected (potential) environmental loads related to seismic events which may potentially occur throughout the entire building life time and compare these results with the environmental loads/consequences related to the other different life cycle phases of the building. This goal is attained through the following procedure consisting of specific objectives:

- Create a LCA model for the case study where system boundaries are defined and building components are grouped into categories to which a mechanical and environmental performance is correlated;
- Identify different limit states and the corresponding levels of damage for the different categories of building components (as explained in Section 3 and 3.1 respectively);
- Relate the damage occurring for the different limit states and affecting the different categories of the building components to the environmental loads;
- Evaluate the total expected environmental load associated with the occurrence of seismic events, on the basis of the probabilistic approach reported in Section 2.1, by means of Eqn. 2.5;
- Perform the assessment according to a defined methodology to analyze and quantify the environmental consequences related to the case study, during its whole life cycle.

The boundaries of the study are intended to include all impacts within the production chain of the used materials, energy and processes that comprise the building life cycle. In particular, in order to include the total environmental impacts, the life cycle phases analyzed in the present study are grouped into four principal phases:

- *Pre-Use*: production of original materials, transportation, construction operations
- *Occupancy* (use): heating and cooling, electricity use, water use
- *Occupancy* (maintenance): production of replacement materials, transportation, maintenance operations
- *Post-Use*: dismantling/demolition, end of life

Moreover, for the purpose of the study and for the scheme of the proposed assessment, the building materials/components are divided and grouped into the following categories:

- Foundation
- Super structure: RC frame, Roof
- Nonstructural: Siding, Insulation, Interior, Trim, Door/Windows
- Water and electrical systems: Water, Trim, Ducting
- Major appliances

The LCA data for this work were collected from different databases. It is underlined that the study has been conducted using an assembly based pattern; to do this DEQ 2010 data have been considered for the LCI (Life Cycle Inventory). Further details of the assumptions made for the assessment and boundaries adopted are reported in DEQ 2010.

According to the damage descriptions corresponding to different limit states (FEMA 273 1997), for each limit state and for each building component category, it is assumed that the amount of new materials (and also the entity of transportation and construction operations) needed for restoring the original state of the building is computed as a percentage in weight of the quantities needed for initial construction (Table 1).

Table 1. Percentage of material components needed for the building rehabilitation depending on the limit state

	SR	**OD**	**SD**	**CO**
Foundation structures	0%	0%	30%	100%
Elevation Structures	0%	15%	60%	100%
Nonstructural	15%	35%	80%	100%
Water and electrical systems	0%	20%	75%	100%
Major appliances	0%	10%	50%	100%

As an example, the elevation structures, as reported in Table 1, may require an amount of additional materials and overall operations which is equal to 0%, 15%, 60% and 100% in weight of the initial ones in correspondence of SR, OD, SD, and CO limit states, respectively. Hence, the environmental load related to the computed new quantities is assessed by means of the common procedure of LCA, i.e. through the selected databases. It should be noticed that other sources of potential environmental impact related to the "unavailability" of the building as a consequence of seismic event are not taken into account in the present study. Following the proposed approach, these computed environmental loads are not taken as they are in light of the goal of the assessment, but they are treated according to the probabilistic methodology described in Section 2.5. In other words, the new computed environmental loads are multiplied by the probability of exceeding each limit state in a year (triggering an expected damage to the building), then summed up over all the limit states and finally integrated in time over the life span of the case study building, as in Eqn. 2.5. The outcomes of this procedure represent the (potential) environmental loads associated to the building rehabilitation which are expected to be generated during the entire life span as a consequence of the occurrence of seismic events in that period of time.

Hereby, in addition to the above-mentioned life cycle phases, an additional phase called as *Rehabilitation Phase* is considered in order to take into account the replacement/repair operations and raw materials, needed to restore the damaged building, as explained before.

Finally, in order to estimate the environmental performance of the structure under examination, the IMPACT 2002+ (Jolliet 2003) methodology was adopted which links all types of life cycle inventory results (elementary flows and other interventions) via 14 midpoint categories into four damage endpoint categories described as follows:

- *Climate Change* (CC): or global warming potential; substances known to contribute to the global warming are weighted based on an identified global warming potential expressed in kilograms of carbon dioxide equivalents ($KgCO_2e$).
- *Human Health (HH)*: it is a measure of the damage caused by the release of substances that affect human beings through toxicity, respiratory effects, UV radiations, and others. The meter used for measuring this kind of impact is the disability-adjusted life years (DALYs), which combines the resulting injuries and mortality rates into a single factor expressing an overall reduction in the life expectancy.
- *Ecosystem Quality* (EQ): it measures the potential damages affecting the health of an ecosystem through the release of substances that cause acidification, eutrophication, toxicity to wildlife, etc. These impacts are measured in units of potentially disappearing fractions (PDFs), which is expressed in term of the probability of species loss.
- *Resource Depletion* (RD): this damage category measures the depletion generated by the mineral extraction, nonrenewable resources consumption and over-use renewable resources (i.e., the consumption rate larger than renewal rate). These environmental impacts are measured in mega joules (MJ) expressing the amount of energy required to obtain an additional amount of the considered substance from the earth.

Since the goal of the study is to evaluate the role of potential environmental impacts in the rehabilitation phase (related to the building life time), the LCA results has been handled in terms of end point categories. In this way a more appreciable understanding of potential environmental consequences is possible since an effective comparison with the typical environmental building contributions can be performed.

4. DISCUSSION

The LCA results are illustrated in Fig. 3. As found in prior LCA results on housing (Ortiz et al. 2009), the major amount of the environmental impacts related to the entire lifetime of the house is due to the use of energy during occupation phase (between 50 and 70%). The normal use of a house (which includes consumption of heating fuel, water and electricity) is clearly the most prominent phase in the life cycle for all the four environmental impact categories studied. It should be mentioned that the sub-categories of the life cycle phases (such as transportation and construction related phases etc.) are not reported in a disaggregated manner since they contribute a relatively small amount (an overall contribution of 6% or less). Material production, both as the original (pre-use phase) and as replacement materials (maintenance phase) has a significant contribution (slightly higher than 40%) in the case of RD and HH impact categories. For other impact categories, the contribution of pre-use and maintenance phase is in the range of 25 to 30% (CC and EQ). The End of Life phase is relatively insignificant, for the majority of impact categories.

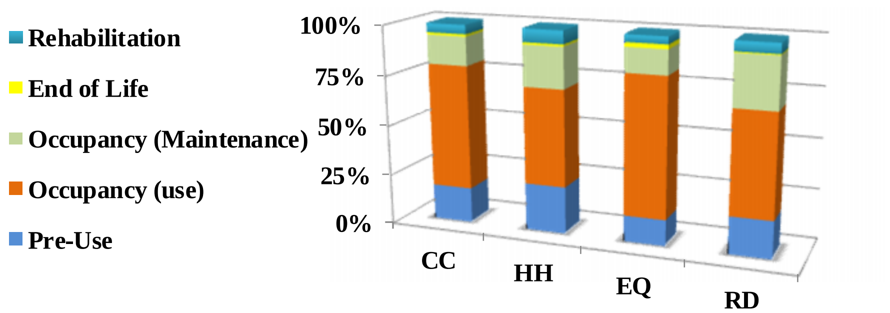
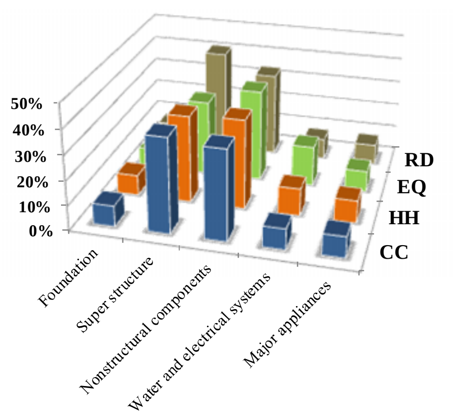
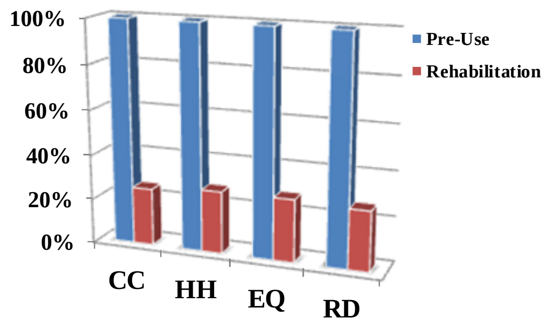


Figure 3. LCA results for the four damage categories: CC, Climate Change; HH, Human Health; EQ, Ecosystem Quality; RD, Resource Depletion



a)



b)

Figure 4. LCA results for the building components *a)* and LCA results comparing the rehabilitation phase and pre-use phase *b)*: CC, Climate Change; HH, Human Health; EQ, Ecosystem Quality; RD, Resource Depletion

Fig. 4 *a)* illustrates the LCA results in the Pre-Use phase for the four environmental impact categories disaggregated into building components. The major contributions come from the structural elements (super structure) and nonstructural components ranging between 30% (super structure for EQ impact category) and 41% (super structure for RD impact category). The remaining building components contribute to a lesser extent with roughly 10% for each type of building component and in each impact category. The LCA results demonstrate significant risk-based contributions for the rehabilitation phase due to the seismic events: in the case of HH impact category, the predicted impact associated to the rehabilitation phase reaches 6.5% of the overall impact. A comparison between the rehabilitation phase and pre-use phase is reported in Fig. 4 *b)*: around 25% of the initial environmental impact (reported as 100%) is expected to be a consequence of seismic damage occurring during the entire building lifetime. It should be remarked that the data obtained for the rehabilitation phase have been computed as averaged values throughout the service life and are strongly dependent on the seismic performance of the building. Hence, the environmental impact of a particular structural and/or nonstructural design choice can be regarded as a benchmark variable in decision making problems in a sustainable development context.

4.2. Social aspects

The risk to human life and social disruption from earthquakes are crucial factors for decision makers and political strategists. A review of the consequences of several large earthquakes demonstrates that the damage is typically concentrated in buildings. In particular, the residential sector constitutes as much as 90% of the total number of buildings damaged and as much as 50% of the total losses due to buildings damage (Comerio 1997). The social aspects of sustainability can be related to structural performance in terms of probability of collapse as a proxy for human safety. Focusing on the limit state of collapse CO, the probability of exceeding the collapse limit state in a year can be calculated by differentiation of $P(\text{LS}|\, t)$ with respect to time as stated in Eqn. 2.3.

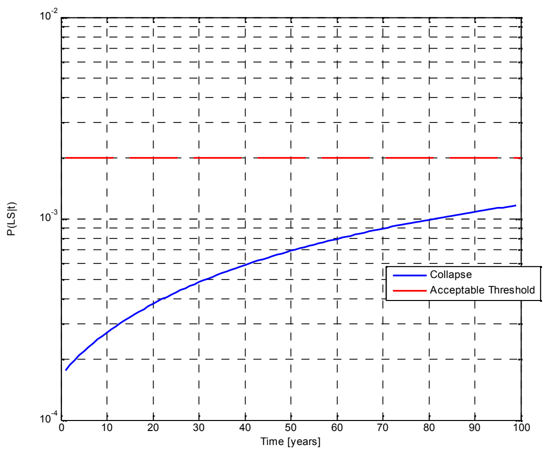


Figure 5. Probability of collapse for the examined structure

As a proxy for life safety considerations, the acceptable threshold of 2×10−3 can be set for the probability of collapse in a year (the reliability constraint) (Pate-Cornell 1994). The annual probability of collapse for the case study structure is plotted (blue curve) in Fig. 5 as a function of time against the acceptable threshold (red curve). This represents an indicator for social sustainability accounting for human safety. It should be re-emphasized that this time dependent indicator is strictly related to the seismic performance of the building.

5. CONCLUDING REMARKS AND RECOMMENDATIONS

This paper presents a preliminary effort for the sustainability assessment of structures subjected to seismic risk. A methodology is proposed for probabilistic Life Cycle Assessment of the structure taking into account the seismic risk-based time-dependent expected loss. The time-dependent

probability of collapse in a year, which is used as a proxy for life-safety/reliability considerations, is calculated taking into account the residual damage due to the sequence of earthquake events and the uncertainties in the seismic action during the service life of the building. The analysis revealed that the probability of occurrence of seismic events influences the LCA results for various life cycle phases of a building in terms of all four environmental indicators. It constitutes around 6% of the total environmental impact and around 25% of the impact load compared to the initial construction phase.
As a final point, authors want to emphasize that the present study highlights the need for a multi-criteria and multi-disciplinary decision making process that encompasses the design of structural systems, seismic hazard analysis, architectural considerations, local practices and the choice of building materials. The authors believe that the awareness of the relationship between risk, environment, and society with the common goal of reaching sustainable development should become a prerequisite for practitioners and operators in the construction industry.

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