Assessing Environmental Impact of Earthquake-Induced Damage for an Italian Case-study Building

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ABSTRACT: This study assesses environmental impacts due to the repair of earthquake-induced damage considering an old reinforced concrete (RC) frame representative of those built in Italy before the 1970s. Such impacts, expressed in terms of embodied carbon, represent a considerable component of buildings' life-cycle embodied carbon in seismically-prone regions. Embodied carbon is the term for greenhouse gas emissions associated with manufacturing and using a product/service. In the case of materials for building repairs, this includes extraction, manufacturing, transporting, construction, maintenance, and disposal. The seismic damage sustained by the case-study frame is first evaluated using the FEMA P-58 methodology. Specifically, the frame's nonlinear response is analysed against increasing ground-shaking intensities, followed by estimating the damage incurred by its individual components via ad-hoc fragility models. Damage is then converted to embodied carbon by calibrating consequence models specifically developed for Italian structural and non-structural building components. This is accomplished by: 1) collecting environmental-impact data from Italian manufacturers of relevant construction materials and; 2) defining suitable structure-specific damage levels and the required repair work for every component. Results show that the embodied carbon induced by seismic damage throughout the case-study building's life cycle might exceed 25% of that generated during its initial construction (pre-use phase).

1. INTRODUCTION

The construction industry is amongst the largest contributors to a variety of serious environmental impacts, including climate change, causing 36% of greenhouse-gas emissions in the EU (European Commission 2013). This becomes a more critical issue in earthquake-prone regions, where seismic damage could occur during the entire life cycle of structures. The environmental impacts in this case stem from the repair activities required to reinstate structural and non-structural components to their original condition, which includes restoration, material production, debris removal, or complete building demolition if the damage is irreparable.

The past few decades have witnessed a broad implementation of performance-based earthquake engineering (PBEE). Such a seismic assessment framework integrates hazard, structural, damage, and loss analyses to provide stakeholders with an improved characterisation of seismic performance in terms of meaningful decision variables (repair costs, downtime, and environmental impacts). The PBEE concept was then refined in the FEMA P-58 guidelines (FEMA 2012) by introducing a state-of-the-art methodology, which quantifies the overall seismic loss sustained by a building via aggregating losses incurred by its individual structural and non-structural components.

Most of past research on PBEE and seismic risk assessment quantified repair costs, downtime, and casualties (*e.g.,* O'Reilly et al. 2018; Perrone et al. 2020). Conversely, most of sustainability studies focused on evaluating the environmental impacts at different life-cycle phases for buildings outside seismically active regions by performing the so-called life-cycle assessment (LCA) (*e.g.,* Basbagill et al. 2013; Xia et al. 2020).

Nevertheless, the recent growing interest in building sustainability in earthquake-prone areas has resulted in several studies assessing the environmental impacts of seismic damage and proposing probabilistic LCA frameworks that account for such damage as part of buildings' life-cycle phases (*e.g.,* Arroyo et al. 2015; Chiu et al. 2013; Menna et al. 2013; Padgett and Li 2016). For instance, Welsh-Huggins and Liel (2017) integrated sustainability concepts with the first version of the FEMA P-58 approach via a manual procedure that extracts material quantities needed for the repair to be used within LCA to address the effects of seismic damage. The second FEMA P-58 version (FEMA 2018) provided a substantial advancement in this direction because it explicitly accounted for earthquake-induced environmental impacts by providing consequence models that quantify such impacts for both structural and non-structural components when subjected to different damage states (DSs). However, those models are solely applicable for buildings in the USA. They were also developed using approximate methods that rely heavily on expert judgement, making them more suitable for preliminary assessments.

The majority of the above work pertains to buildings in the USA, whilst the number of studies available for Italy (and Europe) -the focus of this study-, is still limited. Napolano et al. (2015) and Menna et al. (2016), for instance, performed LCA to assess the environmental impacts of retrofitting Italian masonry structures but did not consider any seismic damage. Belleri and Marini (2016) proposed consequence models consistent with the FEMA P-58 approach to assess the environmental impacts of repairing several Italian building components. However, the definition of DSs and required repair actions in those models was based entirely on the FEMA P-58 database that solely applies to the USA. On the other hand, Clemett et al. (2022) evaluated the environmental impacts of seismic damage for an Italian school building retrofitted via multiple strategies. Still, they used consequence models developed for buildings in the USA rather than Italy.

Based on the previous discussion, this study develops FEMA P-58-compatible consequence models that quantify the environmental impacts of repairing multiple seismic damage levels (*i.e.,* DSs). Those models are specific to building components in Italy (and the Mediterranean area), including structural/non-structural components, and services (*e.g.,* plumbing, electricity, tiling). The environmental impacts are measured here through embodied carbon, which quantifies the total greenhouse gas emissions resulting from the production of any material, converted to carbon dioxide equivalents (CO_2eq). This metric is among the critical ones for quantifying the global warming potential. The developed consequence models are then adopted within the FEMA P-58 approach to perform a risk-based assessment in terms of embodied carbon for a case-study reinforced concrete (RC) frame representative of those built in Italy before the 1970s.

2. SCOPE DEFINITION

Sustainability is typically assessed under a full LCA framework, which incorporates the overall environmental impacts related to different phases of a building's life cycle. Those phases, as per the European Standards (EN 15978 2011), include: 1) material production; 2) construction process; 3) actual use; and 4) end of life. Each one of these stages has a separate set of various modules.

For structures prone to earthquake damage, the embodied carbon stems from the repair work required to restore affected building components, which could be considered as part of the use phase within the life cycle. This part includes production of materials needed for the repair work and the construction activities. It also involves end-of-life activities like demolition and disposal of damaged building components. Interestingly, the material production here is expected to represent the vast majority of embodied carbon generated by the repair activities, as suggested in the Climate Emergency Design guide introduced by the Low Energy Transformation Initiative (LETI 2020).

Following the discussion above, it is essential to clarify that the scope here is not performing a full LCA that tackles all life-cycle phases, as this has been extensively addressed in the literature. Instead, this study aims to develop consequence models that quantify embodied carbon resulting exclusively from repairing seismic damage within Italian residential RC buildings. This covers the material production and construction processes, in addition to end-of-life activities like demolition, processing, and waste disposal. The embodied carbon of the material transportation during construction/end-of-life phases is not addressed due to its high variability and relatively trivial contribution (*e.g.,* Monahan and Powell 2011).

3. METHODOLOGY

This study performs a risk-based assessment of embodied carbon for a case-study RC frame using the FEMA P-58 component-based approach. The adopted methodology incorporates the following steps: 1) definition and modelling of a case-study building; 2) assessment of its nonlinear dynamic response by analysing hazard-consistent ground-motion records; 3) compiling an inventory of all damageable structural/non-structural components with their fragility models and embodied-carbon consequence models; 4) performing FEMA P-58 analysis to quantify the environmental impacts induced by earthquake damage expressed in terms of embodied carbon. More details are provided in the following sub-sections.

3.1. Case-study Building and Modelling Strategy

A five-storey infilled RC frame in L'Aquila, Italy, is selected as a case study. This frame is designed to resist gravity loads only to represent those built in Italy before the 1970s. The nonlinear response of the frame is simulated by creating 2D models via OpenSees (McKenna 2011). All RC structural members are modelled as beam-column elements with finite-length plastic hinges addressing the nonlinear flexural response via moment-curvature relationships (Priestley et al. 2007). The potential shear mechanisms are accounted for by adding shear springs in series to beam-column elements (Zimos et al. 2015). Joint failure is also considered by assigning a rotational spring in each zone of beam-column joint (O'Reilly and Sullivan 2019). Lastly, masonry infills are modelled as equivalent diagonal double struts (Liberatore and Decanini 2011). Figure 1(a-b) depicts the layout of the case-study frame and the nonlinear modelling strategy for beam-column elements. More details on that can be found in Aljawhari et al. (2022, 2023).

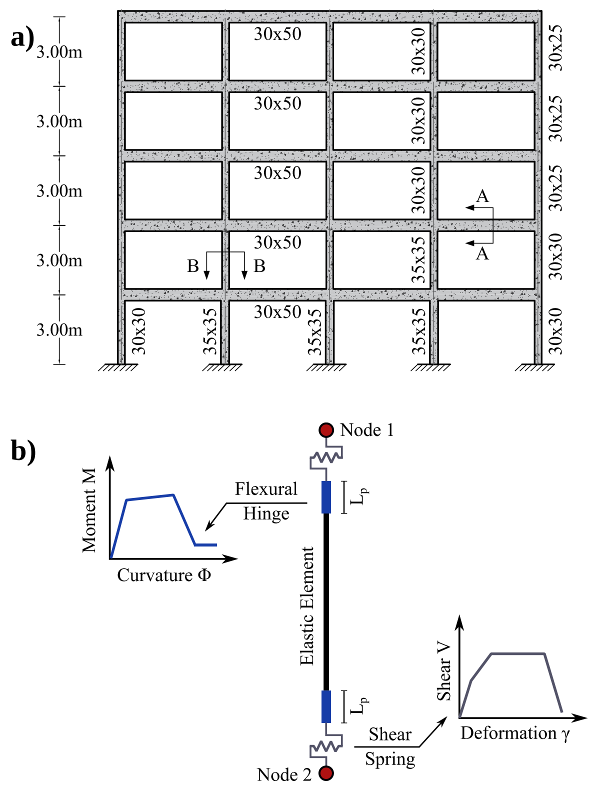

Figure 1:a) layout of the case-study frame; b) beam-column numerical modelling strategy.

3.2. Dynamic Analysis and Record Selection

The dynamic response of the case-study frame is assessed by performing nonlinear time-history analysis (NLTHA) using the multi-stripe analysis (MSA) approach (Jalayer and Cornell 2009). In such an approach, the building is subjected to ground motions with discrete levels (stripes) of ground shaking, expressed in terms of a suitable intensity measure (IM). The IM selected here is the geometric mean of spectral acceleration values (avgSa), which is calculated over periods ranging from $0.2T_1$ to $1.5T_1$, where T_1 is the first-mode period (Kazantzi and Vamvatsikos 2015). This study defines 12 stripes reflecting avgSa levels with return periods from 30 to 4975 years. For each stripe, a set of 35 records consistent with the seismic hazard of L'Aquila are selected following the procedure discussed in Aljawhari et al. (2023).

Figure 2 shows the MSA results in terms of avgSa and the respective maximum interstorey drift ratio (MIDR), which serves as a strong proxy for global structural and non-structural damage. The analysis cases in Figure 2 are also classified based on the global DS sustained by the structure, which could be slight (DS1), moderate (DS2), extensive (DS3), and near collapse (DS4). The MIDR thresholds corresponding to the onset of each DS were defined by Aljawhari et al. (2023) through pushover analysis. It can be observed that the case-study frame experienced high DSs (*i.e.*, DS3-DS4) in more than 55% of the analysis cases, indicating its weak seismic performance.

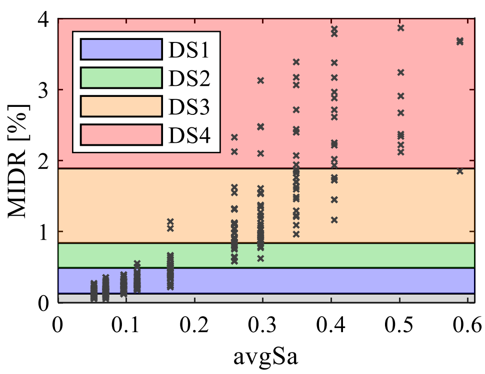

Figure 2:MSA results and global DS classification.

3.3. Inventory of Relevant Building Components

To implement the FEMA P-58 risk assessment approach, a comprehensive inventory of all the damageable building components, along with their fragility and consequence models must be first identified. Table 1 provides a summary of all the adopted components and reference studies for their fragility models, specifically developed for Italian (and Mediterranean) RC buildings.

The main challenge, however, represents the unavailability of consequence models for Italian building components, which convert the damage quantified by the fragility models to embodied-carbon estimates. Hence, FEMA P-58 compatible models are developed in the current study to allow performing a reliable risk-based embodied carbon assessment, as discussed in the next sub-sections.

Table 1: Damageable building components and reference studies of their fragility models.

Components	*Type*	*Reference*
External joints	*Structural*	*Cardone (2016)*
Internal joints	*Structural*	*Cardone (2016)*
External infill walls	*Non-structural*	*Del Gaudio et al. (2019)*
Internal partitions	*Non-structural*	*Del Gaudio et al. (2019)*
Tiles, heating, plumbing	*Services*	*Del Gaudio et al. (2019)*

3.3.1. Embodied carbon of building materials

Seismic damage of building components needs a series of complex repair activities; thus, a reliable embodied-carbon evaluation procedure must be adopted considering all the construction materials potentially involved in such a process. This study implements the embodied carbon factors (f_{CO_2eq}) for this purpose, which calculate the embodied carbon associated with the production of various construction materials, expressed as kilograms (kgs) of CO_2eq per material unit quantities (*e.g.*, ton, m^3) (*e.g.*, Hammond and Jones 2008). Those factors are multiplied by the amounts of repair materials to obtain the overall embodied carbon.

f_{CO_2eq} values are country-specific, meaning that they must be obtained from manufacturers of construction materials in Italy. This information is acquired from the Italian Environmental Product Declaration platform (EPDItaly) (EPDItaly 2022) that offers data published by almost 60 Italian manufacturers and more than 230 product classes. Accordingly, all the data on relevant construction materials are gathered and then utilised to derive average f_{CO_2eq} values, in addition to standard deviations (σ) to consider their variability. Table 2 reports such parameters for a few construction materials common in almost all repair works (*e.g.*, concrete, steel rebar, bricks). The remaining ones are not shown here for brevity.

Table 2: Embodied-carbon factors of the main construction materials for repairing seismic damage.

Material	f_{CO_2eq} *in* $kgCO_2eq$	σ	*Unit*
Concrete	*299.00*	*113.00*	m^3
Reinforcement	*729.00*	*94.00*	*ton*
Bricks	*240.00*	*56.00*	*ton*
Cement	*733.75*	*132.00*	*ton*
Tiles	*15.90*	*6.04*	m^2

3.3.2. Consequence models for the non-structural building components

Non-structural components incorporate external infill walls made of double-leaf clay bricks and internal partitions composed of single-leaf brick walls. Those components might experience three different DSs: Light diagonal cracking patterns (DS1), extensive cracking (DS2), and crushing of a major part of the infill wall (DS3) (Cardone and Perrone 2015). To quantify the embodied carbon resulting from the repair of such DSs, a set of repair activities must be identified. The required material quantities are then estimated for those activities. Both the repair activities and material quantities are based on Del Gaudio et al. (2019).

The embodied-carbon consequence can then be derived by multiplying the estimated quantity of each material involved in the repair work at every DS by its corresponding f_{CO_2eq} value in Table 2. To address the geometric variability of infills, different combinations of wall heights and lengths are simulated via Monte Carlo sampling, considering a uniform distribution. A similar number of f_{CO_2eq} realisations is also sampled to account for their variability. The contribution of demolition and waste disposal is added separately, assuming 3.40 $kgCO_2eq$ for each m^2 of de-construction and a rate of 0.013 $kgCO_2eq$ for 1 kg of waste material (RICS 2017), considering a recycling ratio of 90% (Napolano et al. 2015). The derived consequence models are given in Table 3 as median values in $kgCO_2eq$ and their dispersion (β), assuming a lognormal distribution. Such a distribution is recommended and tested by the FEMA P-58 guidelines (FEMA 2018). The values are normalised by 1 m^2 of infill-wall area.

Table 3: Embodied-carbon consequence models for the non-structural components.

DS	*Parameter*	*External infills*	*Internal partitions*
DS1	*Median in* $kgCO_2eq/m^2$	*14.82*	*14.68*
	Dispersion β	*0.34*	*0.34*
DS2	*Median in* $kgCO_2eq/m^2$	*35.49*	*28.48*
	Dispersion β	*0.28*	*0.28*
DS3	*Median in* $kgCO_2eq/m^2$	*147.93*	*81.73*
	Dispersion β	*0.30*	*0.28*

3.3.3. Consequence models for the services

Services include plumbing, heating, wall/floor tiles, and electrical systems. In Italian residential buildings, services are embedded within infills, thus allowing to correlate their damage to the DS incurred by the infill itself (Cardone and Perrone 2017). The activities needed to repair the different DSs of services are obtained from De Risi et al. (2020). Material quantities needed for the repair are estimated by first dividing the building to two “ideal” rooms: a generic room and a bathroom; each one requires a different set of repair activities based on the DS, as discussed in De Risi et al. (2020). Next, Monte Carlo sampling is adopted to generate numerous combinations of geometric dimensions for the two room types and to sample f_{CO_2eq} values to account for their variability. The resulting consequence models are then derived by multiplying material quantities with the f_{CO_2eq} values at each DS. Table 4 reports those models, normalised by 1 m^2 of the building plan area. The demolition/disposal effects are added separately.

Table 4: Embodied-carbon consequence models for the services (heating, tiles, plumbing, electricity).

DS	*Parameter*	*Services*
DS1	*Median in* $kgCO_2eq/m^2$	*0.00*
	Dispersion β	*N.A.*
DS2	*Median in* $kgCO_2eq/m^2$	*60.29*
	Dispersion β	*0.34*
DS3	*Median in* $kgCO_2eq/m^2$	*156.45*
	Dispersion β	*0.28*

3.3.4. Consequence models for the structural building components

As for the previous building components, estimating earthquake-induced embodied carbon for structural components requires defining multiple DSs and a set of repair actions representative of the Italian construction practice/industry. Such information is determined based on Cardone (2016), assuming three different DSs: light cracks (DS1), moderate cracks and spalling (DS2), and major spalling with potential crushing (DS3). Those DSs are illustrated in Figure 3 for external joints.

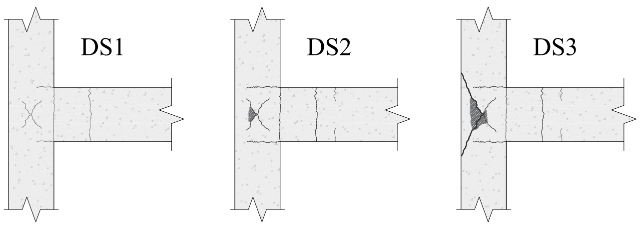

Figure 3:Illustration of DSs for external RC joints.

Upon estimating all the material quantities needed to repair each DS, they are multiplied by the corresponding f_{CO_2eq} values in Table 2. The effects of demolition and disposal are added separately (in a similar manner to that used for the non-structural components). It should be noted that the variability of geometric features is considered by sampling a combination of beam/column section dimensions and span lengths. f_{CO_2eq} samples are also generated to address their potential variability. The derived embodied-carbon consequence models for structural components are reported in Table 5.

Table 5: Embodied-carbon consequence models for the structural components.

DS	*Parameter*	*External weak joints*	*Internal weak joints*
DS1	*Median in $kgCO_2eq/m^2$*	*201.19*	*358.48*
	Dispersion β	*0.30*	*0.29*
DS2	*Median in $kgCO_2eq/m^2$*	*321.29*	*574.35*
	Dispersion β	*0.29*	*0.28*
DS3	*Median in $kgCO_2eq/m^2$*	*652.46*	*1054.74*
	Dispersion β	*0.30*	*0.29*

4. RISK-BASED EMBODIED CARBON

After compiling the inventory of all damageable building components and deriving the necessary consequence models, it is possible to run a full risk-based assessment of earthquake-induced embodied carbon for the frame, adopting the FEMA P-58 approach. All the calculations are performed via the Performance Assessment Calculation Tool (PACT) developed by FEMA (2018). One required input for PACT is the embodied carbon related to building replacement. This is set equal to 385 $kgCO_2eq$ per 1 m^2 of floor area, including demolition and disposal (Blengini 2009). PACT also requires an embodied-carbon threshold above which the building is likely to be demolished and replaced rather than repaired. This threshold is set as 60% of the embodied carbon related to building replacement (*e.g.*, Cardone and Perrone 2017; Clemett et al. 2022).

Figure 4 illustrates the "environmental" loss curves, which express the mean annual frequency of exceeding any embodied carbon value (λ_{CO_2}), taking into account the contribution of all hazard levels. It is noted that low hazard levels with return periods less than 475 years have the largest contribution to the total loss curve (dotted line). Next, the so-called expected annual environmental loss (EAL_{CO_2}) is reported in Figure 4. This constitutes a very useful environmental-impact indicator of the average embodied carbon incurred on a yearly basis due to earthquake damage, considering different ground-shaking scenarios. A value equal to 3250 $kgCO_2eq$ is found as seen in Figure 4. Assuming that the case-study frame has a 50-year service life, then the embodied carbon emitted upon the repair of seismic damage reaches nearly 26% of that produced during the initial construction phase.

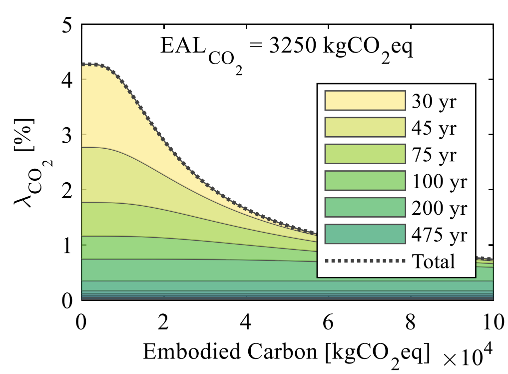

Figure 4:Environmental loss curves and EAL_{CO_2}.

Lastly, the relative contributions of structural and non-structural damage, collapse, and large residual drifts to the resulting embodied carbon at different hazard levels are shown in Figure 5. It is observed that the collapse and excessive residual drifts become significant from hazard levels with return periods as low as 475 years, indicating the high susceptibility of the case-study frame to damage and loss. It is also noted that the damage of non-structural components dominates the low hazard levels below the 475-year return period.

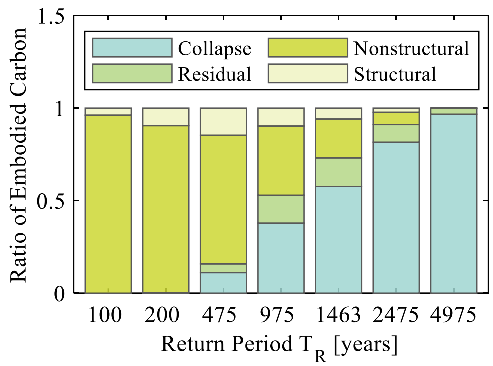

Figure 5:Environmental loss curves and EAL_{CO_2}.

5. REMARKS AND CONCLUSIONS

This study performed a risk-based environmental impact assessment via the state-of-the-art FEMA P-58 approach to evaluate the embodied carbon induced by the repair of seismic damage for an old archetype RC frame located in L'Aquila, Italy. This involved assessing the nonlinear dynamic response of this case-study frame by analysing hazard-consistent ground-motion records. A set of consequence models that estimate the embodied carbon resulting from the repair of Italian building components (*i.e.*, structural, non-structural, and services) at various DSs were also derived by gathering embodied carbon factors pertaining to construction materials from Italian manufacturers, followed by defining a set of DSs and their repair actions to estimate the needed material quantities. The following observations can be highlighted:

- Most of the earthquake-induced embodied carbon is caused by repairing non-structural components (including services), especially at low/frequent ground-shaking intensities.
- The embodied carbon emitted from seismic damage throughout the building's life service could exceed 26% of that produced during the initial construction (pre-use phase).
- The above number might remarkably increase when looking at more vulnerable structures (*e.g.*, unreinforced masonry) or regions with higher seismicity (*e.g.*, Patras, Greece).

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