



Influence of Seismic Design Decisions on the Life Cycle Environmental Impact of an RC Building

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Abstract. Buildings constitute a significant share of global energy-related carbon emissions due to emissions during their use and manufacturing of the construction materials. Additionally, emissions related to the repair of seismic damages also contribute to the total emissions in seismically active regions. This study focuses on the impact of a significant seismic design decision, namely, the selected ductility class, on the expected total life cycle environmental impact of reinforced concrete (RC) buildings. The proposed life cycle assessment framework evaluates the environmental impacts during the construction and those related to repairing potential seismic damages during its service life. Three case study RC building models that are designed for different ductility classes are considered in the investigation. Expected emissions due to seismic damage are obtained probabilistically by integrating the structural fragility with the seismic hazard at the site. As a result, the considered environmental impact accounts for the entire service life of the building, including any potential seismic events that may cause damage to the structure. The environmental impact of seismic damage is calculated by considering the emissions related to the repair/replacement of structural elements, non-structural elements, and major appliances. The results show that the building designed for a higher ductility class has a lower expected life cycle environmental impact, even in regions of high seismic activity. Furthermore, it was observed that the contribution of non-structural elements to the total seismic repair emissions was considerably high for the considered case study building.

Keywords: Cost-Benefit Analysis · Environmental Impact Assessment · Loss Assessment · Seismic Design · Sustainability

1 Introduction

In recent years, the effects of the global climate crisis have become more apparent, leading to a sense of responsibility across all fields. Recently, the building sector has been identified to have significant impact on the environment, particularly in terms of its contribution to global greenhouse gas emissions. The buildings operation and construction combined is responsible for a significant proportion of global energy consumption and emissions, accounting for approximately 30% of total final energy consumption and 27% of emissions within the energy sector [1]. The environmental impacts of buildings can be examined in two main components: operational emissions that are emitted during use

(e.g. heating, cooling) and embodied emissions that are caused by construction (e.g. production and transportation of materials). Unlike operational emissions, civil engineers have control over embodied emissions. Strategies such as minimizing material usage, using environmentally friendly materials, and making seismic design decisions aimed at reducing environmental impacts can be implemented when designing structures.

Engineers who design buildings are often required to comply with building codes, while having some degree of choice in their design decisions. These decisions can affect both the cost of the building and its embodied environmental impacts. Additionally, such decisions also affect the emissions resulting from any necessary repairs due to seismic effects. Considering the environmental impact of these decisions can significantly influence overall environmental impact. In particular, it is necessary to consider the expected lifetime environmental losses due to seismic effects. To minimize total losses, striking a balance between the effects of initial safer designs and future repairs resulting from seismic events is crucial to optimize the environmental impact. There are several studies in the literature that compare different decisions, considering seismic effects, to evaluate the total environmental impact of buildings such as choosing the suitable structural system [2, 3], adopting various strengthening options [4, 5], and alternative seismic design levels [6–8].

In building design, the assumption of ductility class directly affects the amount of construction materials consumed. The design code recommends engineers to use a smaller reduction factor (R) when a lower ductility class is selected. Using a smaller R leads to the design of structures with greater resistance capacity in terms of higher total design base shear. Designing structures with higher resistance capacity requires more construction material and thus increases embodied emissions and environmental impact. However, these structures are likely to remain elastic and sustain less damage under frequent shaking. On the other hand, the increase in the elastic resistance capacity reduces the resource consumption associated with repairs. Therefore, while increasing embodied environmental impacts of the structure, it decreases the environmental impacts of repair caused by seismic damage. This study aims to present an approach that balances the environmental impact of a building for different ductility classes.

2 Environmental Impact Assessment

The approach applied to calculate the environmental impacts of buildings is described in this section. Environmental impacts from buildings are classified into two main categories: emissions generated during construction and emissions resulting from seismic damage. Operational emissions (e.g. heating, cooling and lighting) which occur during building use, are not covered in this study since they are not directly affected by the details of the structural system. The emissions generated by the building are presented by calculating emissions related to structural elements, non-structural elements, and major appliances separately. Total environmental impacts (E_T) can be determined by considering both the embodied environmental impact (E_E) and the environmental impact related to the repair and replacement of materials due to seismic damage (E_S) as shown in Eq. (1).

$$E_T = E_E + E_S \quad (1)$$

A life cycle assessment (LCA) approach for calculating the total environmental impact is presented here. LCA is a methodology used to calculate the environmental impacts of a product or service throughout its entire life cycle, from the production of raw materials to disposal. The LCA approach, which also considers the environmental impacts of three structural components, selected GWP (global warming potential) as the environmental impact category and evaluated the environmental impact category in units of kg CO₂e.

This study analyzed embodied emissions (i.e. product stage, construction, end of life) and emissions from seismic damage (i.e. use stage) in four main categories. The extraction, manufacturing, and transportation of raw materials were grouped as the product stage (a.k.a. cradle-to-gate). The transportation to the construction site and the construction process at the site were grouped as the construction stage. Seismic repair and replacement of materials due to seismic damage were classified as the use stage. Demolition of the building and final disposal were grouped as the end-of-life stage. The environmental impacts of structural elements were assessed by considering the product, construction, and end-of-life stages, while for the non-structural elements and major appliances only the product stage was considered.

2.1 Embodied Carbon Emissions

Environmental impacts resulting from the construction of structures are classified as embodied emissions. As shown in Eq. (2), the effects of these emissions are examined in three main components: embodied emissions of the structural ($E_{E,ST}$), the nonstructural ($E_{E,NS}$), and the major appliances ($E_{E,MA}$). These effects include those resulting from the structural system, member dimensions, etc., determined during the structural design, the effects caused by materials used for non-structural elements, and effects of household appliances that can be referred to as major appliances.

$$E_E = E_{E,ST} + E_{E,NS} + E_{E,MA} \quad (2)$$

Structural Elements. In this study, the components constructed using concrete and steel reinforcement, are considered as the structural elements. The LCA results for these elements were adopted from Zabalza Bribián et al. [9], which utilized the Ecoinvent v2.0 database [10] to provide the carbon emissions results (per kg) for concrete and reinforcement steel using European averages. The average values can be tailored to each European country based on specific characteristics (energy mix, production technology, etc.), but such country specific estimates were not adopted in this study due to the difference having a low impact on the results (as shown later). The LCA stages for structural materials are material production, transportation from the production facility to the construction site, construction and demolition of the building, and final disposal of the product. The reference LCA results for concrete and steel reinforcement are 0.137 and 1.526 kg CO₂e/kg, respectively. The total embodied emissions contribution based on the amounts of these materials used for all three case designs can be calculated as follows:

$$E_{E,ST} = L_R \bullet Q_P \quad (3)$$

The LCA result of the used impact category (GWP; kg CO₂e/kg) and the total amount of material used (kg) are represented by L_R and Q_P , respectively.

Non-structural Elements. Calculating the total environmental impacts of non-structural elements is a complex task, but their contribution to total embodied emissions is also quite significant, so their inclusion in calculations may be critical. In this study, emissions of non-structural elements were obtained from Atmaca [11]. He conducted a study investigating the optimum insulation thickness used to reduce energy consumption and emissions per square meter. In this study, he focused on the stages of construction, operation, and demolition to estimate the energy use, carbon emissions, and costs of two residential buildings in Turkey, over a 50-year lifespan. Carbon emissions from non-structural elements in of the buildings (BT1) analyzed by Atmaca were calculated as 81.4 kg CO₂e/m². Carbon emissions of the nonstructural elements were calculated by proportioning the floor area of the BT1 building to the floor area of the case-study building in this paper. Embodied carbon emissions from non-structural elements are considered the same for each building. However, it should be noted that these values do not take into account the demolition stage of non-structural elements (i.e. cradle-to-gate only).

Major Appliances. In the event of a building collapse or damage, major appliances present in every home typically gets severely damaged, which can result in both economic and environmental loss. Studies in the literature indicate that the contribution of major appliances to the environmental impacts due to seismic damage is lower compared to structural and non-structural elements [12]. However, examining the effects of this can also provide insight for future studies. Using the SimaPro v9.2.0 software [13], the total environmental impacts caused by the production of major appliances were calculated. Some elements present in every household were selected based on engineering judgment. The demolition stage was not included and carbon emissions resulting from the production of major appliances were calculated. It is assumed that the major appliances are common in the alternative buildings considered here and have the same emission values.

2.2 Seismic Repair Emissions

The environmental impact of a structure subjected to seismic events is determined by the extent of the damage sustained. A building will require repairs when it is damaged, depending on the extent of the damage. It is assumed that the structure is repaired to its original, undamaged state whenever it is damaged at any point during its lifetime.

Probabilistic damage analysis is necessary to determine the environmental damage that the structure may suffer due to seismic events. The framework for calculating the expected environmental impact of earthquakes on the building over its entire life cycle is based on the equation proposed by Smyth et al. [14] for estimating the economic loss.

Smyth et al.'s expected loss calculation assumes that the structure will only be repaired or replaced once during its lifetime. Costs will only be incurred if a disruptive earthquake occurs for the first time within the considered time horizon. Therefore, the resulting expected loss is a lower bound estimate of the possible losses. In a probabilistic

framework, the total life cycle environmental impacts related to damage can be estimated using Eq. (3) by combining the expected hazard at the building site with the structural capacity of the building. More information about the equation can be found in Smyth et al.’s study. The equation is, as follows:

$$E_S = \sum_{T=1}^{T^*} \sum_{m=1}^{n_m} \frac{E_m}{(1+d)^{T-1}} \int_{im_{min}}^{im_{max}} [\hat{R}(im + dim, T) - \hat{R}(im, T)] P(DS = d_m | IM = im) dim$$

In this equation, d_m represents the level of damage that has occurred. E_m is the amount of emission required to repair the structure when damage- m is sustained, n_m is the total number of different damage levels, T^* is the lifespan of the building, d is the annual discount rate used to calculate the present value of impacts over the lifetime of the building. $P(DS = d_m | IM = im)$ is the probability that a particular damage level (d_m) will occur given a specific level of ground motion intensity (im), $\hat{R}(im, T)$ is the probability that a certain level of ground motion (im) will be exceeded at the site given that no earthquakes have occurred in the previous ($T-1$) years.

In this study, the discount rate (d) used in Eq. (4) is set to zero. While cost studies often use a discount rate to convert future impacts to net present value, it may not be appropriate to do so when considering the environmental impacts. Unlike the common financial assets, the effects caused by a unit emission do not loose or gain value in time. Therefore, the effects of these environmental impacts will not be converted to net present value in this study.

In the calculation of expected losses, the quantity of repairs required for each damage level is necessary. As it is difficult to precisely determine the necessary repairs/replacements for each building, expressing it as a percentage of the initial construction cost is a practical approach. The study by Menna et al. [12], which includes the percentage of materials needed for building repair based on damage limit levels, has been used as a reference for calculating E_m . Restoration to the original state corresponds to seismic-induced emissions. The recommended percentages for structural, non-structural, and major appliances are given in Table 1. E_m values can be obtained by multiplying the initial material quantities found for each building component by the given percentages.

Table 1. Percentage of materials needed to bring buildings back to original states [12].

Component Type	Operational (%)	Immediate Occupancy (%)	Life Safety (%)	Collapse Prevention (%)
Structural	0	15	60	100
Non-Structural	15	35	80	100
Major Appliances	0	10	50	100

3 Case Study

The proposed framework for assessing the environmental impact is applied to a case study of building made of reinforced concrete by considering two different levels of ductility. The building is assumed to be located in an area with a high seismicity. The architectural design of the building in the case study was selected to be representative of typical urban residential buildings built today, and it was assumed to be a six-story reinforced concrete structural wall building (see Fig. 1). It is assumed that the building is located in Mahmutbey, Istanbul and the site is in soil class ZC according to TBEC (2018) [15].

Three different structural designs were developed in total. Two of the buildings were designed for a high level of ductility, while one was designed according to the provisions for limited ductility. Design R4 represents the case with limited ductility using a behavior factor R equal to 4. The other two buildings were designed with a high ductility level, R equal to 7. Designs R7a and R7b have the same structural system behavior factor with a high ductility level. However, there is a difference in the longitudinal reinforcement ratio in the boundary regions along the critical height of the shear walls. The main difference between buildings with the same design conditions is the structural resistance capacity. Geometry, material properties, and soil conditions are assumed to be the same for all buildings. In this study, the foundation of the buildings were not considered in the evaluation and it is assumed that their difference was negligible. Floor slabs were assumed to be 20 cm thick and had $8\phi/180$ reinforcement. Concrete with a compressive strength of 35 N/mm^2 and reinforcement with a yield strength of 420 N/mm^2 were used for all three case study buildings. Such material strengths are common in the newly constructed buildings.

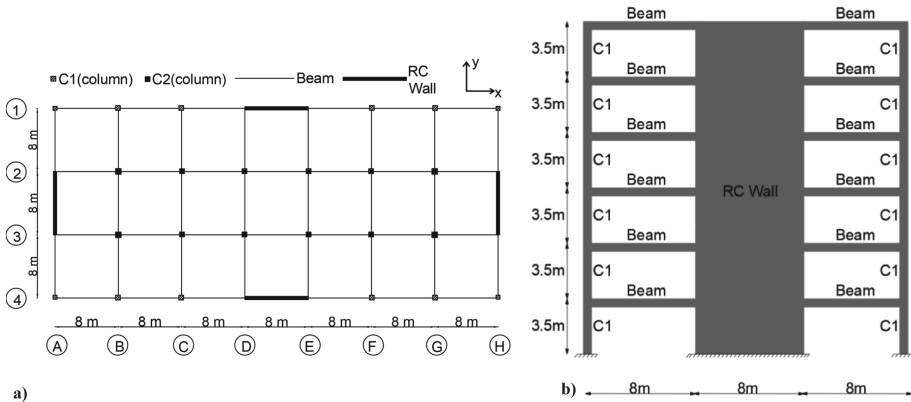


Fig. 1. a) Plan view and b) A-A axis of case study buildings.

Table 2 illustrates the longitudinal reinforcement ratio, transverse reinforcement ratio, and section dimensions of the structural elements of the building, which were designed with the aim of achieving cost-effectiveness. The reinforcement ratios specified for the walls correspond to the reinforcement along the critical height and the wall boundary. The columns, beams, and shear walls possess rectangular cross-sections

(shown in Fig. 1a). Elements that have similar reinforcement and section properties are identified by the same label. The critical height of the shear wall was established as 10.5 m, which corresponds to the height of the first three floors across all the buildings. The length of the wall boundary for all buildings was calculated to be 2 m.

Table 2. Section dimensions and reinforcement ratios for structural elements.

Design	Member	Section (cm × cm)	LRR (%)	TRR (%)
R4	C1	60 × 60	1.69	0.65
	C2	75 × 75	1.08	0.52
	Beam	60 × 75	1.19	0.25
	Wall	35 × 800	3.67	0.30
R7a	C1	60 × 60	2.18	0.65
	C2	70 × 70	1.60	0.56
	Beam	60 × 75	1.05	0.25
	Wall	30 × 800	2.02	0.26
R7b	C1	60x60	2.18	0.65
	C2	70 × 70	1.60	0.56
	Beam	60 × 75	1.05	0.25
	Wall	30 × 800	1.67	0.26

3.1 Nonlinear Modelling Approach

In an effort to reduce the overall duration of the analysis, 2-D models were generated by taking into consideration only the structural elements located within the A-A axis of each structure (as shown in Fig. 1b). Nonlinear analyses were conducted using the OpenSeesPy software version 3.4.0.1 [16]. Force-based elements were employed to model the columns and beams [17]. This model assumes that plastic behavior is concentrated along the length of the plastic hinge. The formulation proposed by Priestley et al. [18] was used to calculate the length of the plastic hinge. The moment curvature behavior model proposed by Takeda et al. [19] was adopted for columns and beams to account for the stiffness degradation behavior under post-yield cyclic loading. In the Takeda model utilized in this study, the pinching factors were set to 1, the damage factors were set to zero, and the beta parameter was defined as 0.5. A two-dimensional Multiple-Vertical-Line-Element-Model was generated using the MVLEM element command for simulating the flexure-dominated RC wall behavior.

Pushover Analysis. The displacement-controlled pushover analysis method was employed to determine the damage states of the buildings. The results of the pushover analysis for the three buildings are shown in Fig. 2. These curves represent the variation

of normalized base shear (base shear force divided by the building weight) with Maximum Interstory Drift Ratio (MIDR). Immediate Occupancy (IO), Life Safety (LS), and Collapse Prevention (CP) limit states were identified in accordance with TBEC (2018), obtained from the pushover analysis results. In regards to the environmental impact assessment, the environmental impacts resulting from seismic damage were based on a study by Menna et al. [12], which considers four different limit states. As such, an Operational (OP) limit level was added in addition to those specified in the regulations. Within the scope of this study, it is assumed that the MIDR for the OP limit state corresponds to half of the MIDR value at the IO level.

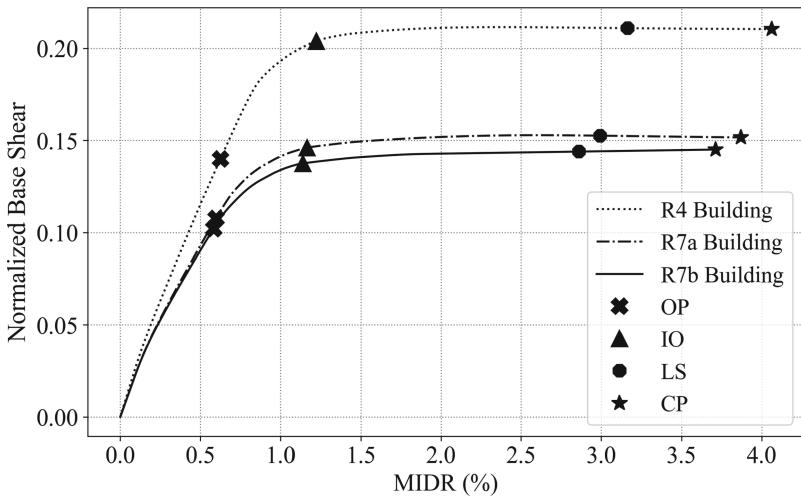


Fig. 2. Limit states and pushover curves of case study buildings.

The modeling of the nonlinear behavior of the structure and the characteristics of ground motion are crucial factors in determining the structural capacity against seismic action. In order to capture the variability of the causative excitation, a set of 22 strong ground motion pairs were selected from the Pacific Earthquake Engineering Research Ground Motion Database (<https://ngawest2.berkeley.edu/>). The selection of the ground motion records was based on the distance, magnitude, and soil conditions that are relevant to the site in question.

Loss Assessment. In this study, the fragility curves of the buildings were integrated with the derivative of the seismic hazard curve calculated for the site to estimate environmental losses caused by seismic effects. The hazard curve provides the probability of exceeding that intensity for a range of peak motion intensities. Peak ground velocity (PGV) was chosen as the intensity measure, and the hazard curve (see Fig. 3a) proposed by Akkar et al. for Istanbul (cited in Duran [20]), was utilized. Fragility curves model the expected seismic resistance of a structure and display the probability of exceeding a certain level of damage state (DS) as a function of ground motion intensity measure (IM). The level of damage was determined using MIDR. For each PGV value, the MIDR values obtained

from time history analysis were compared to the MIDR values specified for the previously defined structural damage limits. The maximum likelihood method was used to estimate the fragility function parameters. The resulting fragility curves for the three buildings for each damage level are illustrated in Fig. 3b using these parameters.

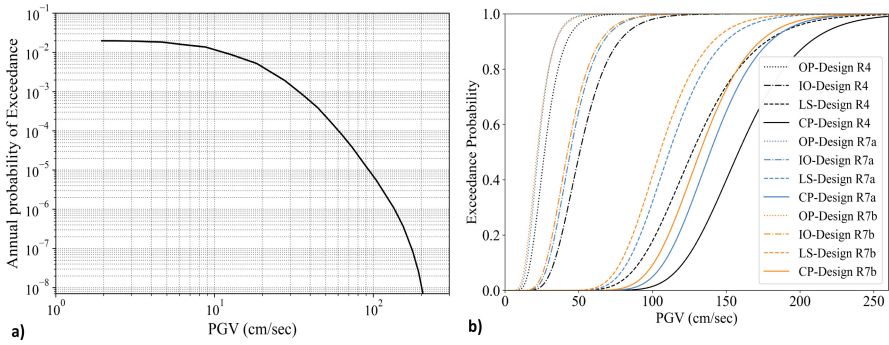


Fig. 3. a) Annual Hazard Curve for Istanbul and b) Building Fragility Curves.

4 Results

The consequences of the environmental impacts caused by the structures during their lifetime due to construction and potential seismic damage are discussed. The expected annual environmental impacts associated with damage levels resulting from the integration of structural capacity and earthquake hazard at the building site are depicted in Fig. 4. It is determined that damage levels categorized as LS and CP have a limited impact on the overall expected annual emissions resulting from repair efforts. Figure 4 illustrates that the OP and IO damage levels have the greatest contribution to the environmental effects caused by seismic damage. For the case study buildings, in accordance with the current design code, the contribution of further damage states to the overall loss is minimal.

The lifespans of the case-study buildings were assumed to be 50 years. The total environmental impacts per square meter for the buildings over their 50-year lifespan are presented in Table 3 and Fig. 5b. The Design R4, with higher resistance capacity than others, exhibits significantly lower environmental impacts related to seismic events. However, when the total environmental impact of the buildings, including building components and seismic damage, is considered, it can be seen that the Design R4, despite its higher resistance, has a greater overall environmental impact than the Design R7a. Therefore, it can be concluded that reducing emissions associated with repair works alone does not compensate for the increased resources required to construct a stronger structure. When R7a and R7b designs are compared, it can be seen that the small increase in total reinforcement ratio in buildings with similar ductility level reduces the environmental impacts caused solely by seismic events. However, ultimately it leads to an increase in overall environmental impacts since more material is consumed in their construction.

Furthermore, the structural elements of the building were found to have the largest impact on emissions among building components.

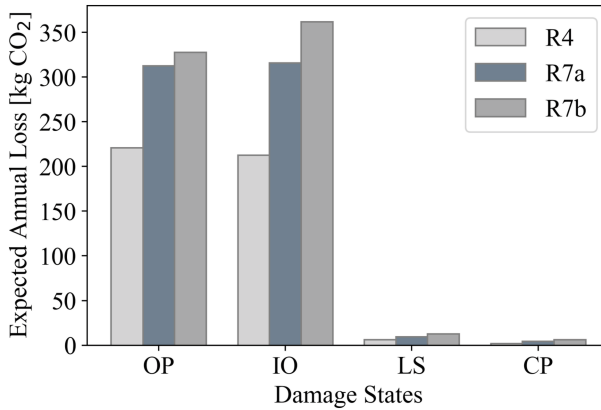


Fig. 4. The expected annual environmental loss for each damage level.

Table 3. Total environmental impacts over the 50-year lifespan (kg CO₂e/m²).

Design	Concrete	Steel	Non-Structural	Major Appliances	Seismic Damage	Total Impact
R4	123.6	91.4	81.5	7.0	1.8	305.2
R7a	121.9	75.9	81.5	7.0	2.6	288.8
R7b	122.0	73.8	81.5	7.0	2.8	287.0

The environmental impacts caused by seismic activity on buildings are presented as per component basis in Fig. 5a. The seismic environmental effects, in the order of magnitude from the most significant to least, are non-structural elements, structural elements, and major appliances. It has been observed that the environmental effects related to the repair of non-structural elements after an earthquake are greater than the total of all other elements, this is because non-structural elements will require repair and replacement at even at lower intensity levels when structural damage is limited.

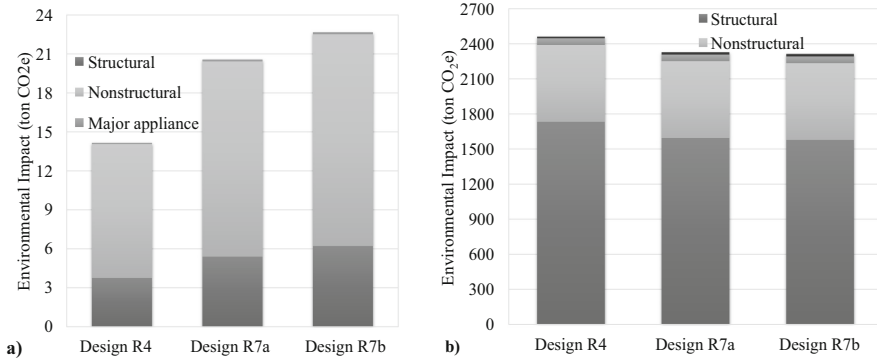


Fig. 5. a) Contribution of components to seismic repair emissions and b) Total environmental impact results for case study buildings.

5 Conclusions

This study presents a comprehensive approach to evaluate the relationship between the environmental impact of a building design and the chosen ductility class. This approach evaluates the emissions from initial emissions of the construction and potential seismic repairs throughout its lifetime, taking into account structural components, non-structural components, and major appliances. Specifically, the relationship between the selected ductility class and the total life cycle environmental impact is evaluated for a multi-story residential reinforced concrete building. The findings of this research can be summarized as follows:

It is determined that damage levels LS and CP have a limited impact on the overall expected annual emissions resulting from repair efforts. Figure 4 illustrates the lower damage levels have the greatest contribution to the environmental effects caused by seismic damage. For the case study buildings, in accordance with the current design code, the contribution of further damage states to the overall loss is minimal. Design R4, which has a higher resistance capacity, presents a lower potential environmental impact in relation to seismic events. On the other hand when the total environmental impact of building -including building components and seismic damage- is considered, it is seen that despite its higher resistance, Design R4 causes more carbon emissions than Design R7a. Therefore, it can be concluded that reducing emissions related solely to seismic repairs will not compensate for the increased resources required to build a stronger structure. When comparing high ductility class Design R7a and R7b, it is observed that while a slight increase in reinforcement ratio only reduces environmental impacts caused by seismic events, it ultimately leads to an increase in the overall environmental impact. Additionally, the structural elements of the building were found to have the most significant impact on emissions among all building components (i.e. including non-structural ones). As a result of only seismic repairs, it has been observed that the building component that caused the most emissions was the non-structural elements.

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