A Comparison of LCA Approaches for Existing Buildings Subjected to Earthquake Considering Environmental and Structural Performance

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June 22, 2023

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Abstract. Natural disasters such as recent earthquakes have highlighted the importance of resilience against natural hazards as a key component of sustainability. Evaluating existing buildings under sustainable perspective requires the understanding of building's life-cycle stages exposed to these disasters. In comprehensive life-cycle-analysis (LCA) of a building, damage repair costs and downtime (economy component), environmental emissions and waste generation (environmental impact component), and deaths (society component) should be quantified and evaluated [1].

After any earthquake, Damage repair costs and downtime causing harmful impacts due to additional material and energy consumption, and also generating additional waste production, despite of consideration other important impacts such as Deaths and injuries. Therefore to minimize these impacts, Researchers have taken different approaches, they assessed the impacts of a single building in different form and details focused on whole building or individual building systems. Or in some cases they performed a comparative study, focused on comparing the different impacts between two or more buildings, aiming to optimize a comprehensive model that has a more sustainable structure.

Most of the previous comparative LCA studies have been, however, applied to evaluate the environmental impact between two or more buildings without considering structural performance of the buildings. Recently, in addition to the environmental impact of the aforementioned conventional activities, Researchers have attempted to incorporate seismic risks into traditional building LCA models and developed appropriate methods for comparing different design alternatives with respect to the impact of seismic damages and their recovery activities.

The evaluation of five LCA studies, which took into account both the environmental and structural performance of earthquake-affected structural systems, will be the primary focus of this paper. The paper will also examine the main factors that influenced the assessment's findings and provide a summary of the most significant findings of them.

Keywords: Life cycle assessment, environmental impacts, structural performance

1 INTRODUCTION

Nowadays, one of the main contributors to the climate crisis is the construction industry. As it generates 36% of EU greenhouse gas (GHG) emissions and uses 40% of EU energy [2]. Based on these statistics, building sector turns out to be a great market that can help to satisfy sustainable goals. The Bekker study at the beginning of the 1980 can be introduced as a first life cycle thinking to the construction sector [3], He highlighted that a life cycle approach is an appropriate method for analyzing the use of energy and other natural resources, as well as the impact on the environment in the building sector. The process of designing and constructing buildings considering ecological, economic and socio-cultural aspects is called “sustainable construction” [4].
During its life cycle, buildings may face any kind of natural hazards such as earthquake which could lead to collapse or severe damage. A structure located in the hazard-zone and does not show adequate resilience to natural hazards, it will sustained significant damages, and the cost of repairing, retrofitting or rebuilding the damaged infrastructure will be significantly high. These activities will directly affect the environment by consuming energy and natural resources, and by generating waste and air emissions, despite of other important considerations such as deaths and injuries. According to the Federal Emergency Management Agency (FEMA), earthquakes caused the United States cost over $5 billion (U.S. dollars) annually [5]. Moreover the 1994 Northridge earthquake caused direct losses from $25.5 to $53.3 billion (U.S. dollars) which included the loss in infrastructures (highways, buildings, and residences) [6]. Due to these reasons, the goals of sustainability cannot be achieved without resilience, because seismic performance of a structure and Resilience to natural hazards is directly related to sustainability. Consequently, sustainable construction should satisfy not only the requirements of the three dimensions of sustainability but also requirements related to the structural design in accordance to the principles of Sustainable Development.

Design for the whole life cycle of a building turned out to be a key point toward sustainable structures. Researchers always seek comprehensive life cycle assessments of buildings in order to model structures considering appropriate system. On the other hand, buildings are complex systems that make it nearly impossible to conduct a holistic analysis. The form and detail of a building life cycle assessment will depend on the overall goal of the study. Based on this goal there could be two types of models of the LCA studies [7]:

1. The first model is assessing the impacts of a single building, it can be comprehensive assessment when applied to whole building. Or it could concentrate on evaluating distinct building systems.
2. The second model, called a comparative LCA study, focuses on comparing the different impacts between two buildings that provide the same function (i.e. same boundary conditions, same space and use-type assessed over the same time period).

In the light of previous research findings, this review paper contribute to a better understanding of use of seismic loss estimation methods and their application in comparative LCA studies. The integration of seismic loss assessment and life cycle assessment in the light of five comparative LCA studies are discussed in detail in section 4.

2 OBJECTIVE.

Various approaches integrating life cycle assessment with seismic loss assessment have been conducted over the past few years, but a consensus on the best approach has not yet emerged. This research will focus on reviewing five comparative LCA studies that investigated both environmental and structural performance of different building. The main points of each study are summarized with emphasis on the main findings.

3 LIFE CYCLE ASSESSMENT METHODOLOGY

Regarding to the environmental performance of the building industry, one of the methodology or a functional tool for evaluating the environmental impacts of a product or a process that has become popular in the world today is Life Cycle Assessment (LCA). The technique investigate the product or a process ranging from the extraction of raw materials from the earth to manufacturing, product use, and recycling/disposal at the end and mainly defined in four phases (goal and scope, inventory analysis, impact assessment and interpretation) [8].

As the concept of sustainable construction became more and more prominent, simultaneously lead to an increase of academic interest in LCA in building sector, and make it unique in comparison to other complex products. This is not only due to the complexity of buildings but also because of the following main factors [9]:

1. Difficult in predicting the whole life-cycle due to longer life time
2. Undergoing many changes in its form and function during its life span, make an opportunity to minimize the environmental impacts of changes.
3. During its use phase, building will face many environmental impacts (i.e. natural hazards), it can be minimized by Proper design and material selection.

In interest to LCA significantly increased and played a crucial role to facilitate decision-making options by evaluating the cost and environmental impact components of sustainability. LCA has several applications in the construction sector, Comparative LCA studies are the most effective method, usually dealing with the comparison of alternative systems that have a similar function. They are done to take decisions regarding the best-performing (minimum-impact) aiming to identify the most environmentally friendly scenario. For instance, one of the first LCA studies was developed by Jonsson et al [10], in regard to the application of LCA as a method for comparing the environmental impacts of seven concrete and steel building frames. They discovered that the environmental impact of building production from cradle to gate approximately equal to same amount that produced by maintenance and replacement of heat losses through external walls.

When the Most comparative LCA studies are revised, here one can already see that how the comparative LCA used for finding the best alternative among the other scenarios from environmental point of view. Also how the typology of the buildings has significant effect on energy demands and environmental emissions of buildings. On the other hand, due to the scope of the study, the boundaries of the system are usually clearly described. Some papers consider only desired phases of buildings. But either most of them consider wider boundaries or all phases of life cycle of building.

4 PREVIOUS COMPARATIVE LCA STUDIES CONSIDER BOTH STRUCTURAL AND ENVIROMENTAL PERFORMANCE

Under normal condition, the life cycle impacts related to structures are usually predictable and regular. However, its magnitude and unpredictability may be significantly greater during extraordinary events. LCA studies considered the impacts of all stages of the building life cycle, including material production, construction, use, and end-of-life, but those impacts caused by natural hazards events were rarely considered by the researchers. While considering these events, will lead researchers to develop the concept of building's seismic risk and propose the most realistic impact assessment.

The total life cycle impact assessment of a structure can be defined as the integration of all impacts due to material production, construction, and end of life as well as damage repair from expected seismic events, in addition to use/operation phase. The first three can be predicted and reduced through improving initial structural design. While the last one is a probabilistic damage that depends on the lifetime performance of the structure, by optimizing the structure performance, this damage can be reduced and, consequently, a reduction in overall environmental impacts. Bocchini et al. [11] Drew attention to the idea that resilience, which is the ability of withstanding extraordinary events and recovering quickly from them, should be integrated with sustainability. A novel approach developed by Menna et al. [12], revealed that the LCA results will be affected by the expected seismic events during various building life cycle phases. They calculated that seismic damages, In terms of four impact indicators, contributed around 6% of total environmental impacts over the building's lifetime, and also, they demonstrated that in comparison to the initial environmental impacts during the construction phase, the impacts caused by seismic damage were around 25% .

Estimating the expected earthquake damage that a building may experience during its lifetime has been challenging until now. In many studies, researchers have used two different models, HAZUS and The performance-based earthquake engineering (PBEE), to estimate the expected seismic damage to buildings [13], [14]. The PBEE method's significance in seismic probabilistic assessment was discussed in some of the studies such as [1], [15] [16]. Feese et al. [5] and Wei et al. [17] used HAZUS a as software program that estimates potential losses from earthquake.

Most of the comparative LCA studies, comparing between various structural systems but they did not take into consideration the damage caused by earthquake events, which could have a significant effect on the total lifetime environmental impact (i.e., cost, environment or society), whereas only a limited number of comparative LCA studies accounted the performance of structures subjected to earthquakes. In this regard, the following five comparative LCA studies, which consider environmental and structural performance and applied to different scenarios, will be the focus of this study.

4.1 STUDY NO.1

Discussion: Feese et al. [5] evaluated the Life cycle assessments of two deferent buildings i.e. steel and concrete, subjected to an earthquake event, to compare their environmental and structural performance, through upgrading the building structural performance by considering different seismic design code levels. They modeled two low-rise, four-story commercial buildings (concrete and steel) in Los Angeles, California. A comprehensive LCA was carried out for each case using the Athena LCA software. Because both buildings have the same internal building materials and only had different structural frames, they assumed that their annual energy consumption was the same.

HAZUS-MH software as a comprehensive tool was used to estimate multi-hazard loss with taken into consideration three seismic design code levels—high, moderate, and low—as well as the pre-code for buildings. Two earthquake events were selected for the study and an annualized damage analysis for a building in Los Angeles, California. HAZUS calculated the total probability of damage to the general population of steel and concrete buildings, after that, the probability of damage for each of the four damage states, each kind of building, and each design code was calculated, then, for each damage state and building type, structural repair cost ratios in percent of building replacement costs were provided. To incorporating Seismic Damage in a Life-Cycle Assessment, they determined the cost and environmental impacts for seismic damage repairs by using a relationship between the cost of the building and its embodied energy. HAZUS-MH software also used to obtain the total probability of damage for each building, and then by multiplying to the total cost of the building, the total cost of damage was obtained. Finally, they determine the amount of energy required to repair the damage to each building.

Important findings:

1. It was determined that the general population of concrete buildings had a lower damage cost than the general population of steel buildings. In contrast, the steel buildings had a lower potential for global warming and a lower consumption of fossil fuels than the concrete buildings.
2. Upgrading a building's design to a higher code standard can help to reduce the energy consumption and repair costs attributable caused by future earthquakes. For instance, as shown in the **Fig. 1. (A)** , in one year, a steel building with moderate code design will experience $4,673 of damage repair costs and will consume 4,103 MJ of energy, by upgrading this building to high code design the number reduced to $1,894 of annual damage repair costs and 1,663 annual energy consumption due to damage repair. This creates savings of approximately $2,779 from damage repair costs and reduces annual energy consumption by 2,440 MJ. The same calculation will also be practicable for the concrete building as shown in the **Fig. 1. (B)**.

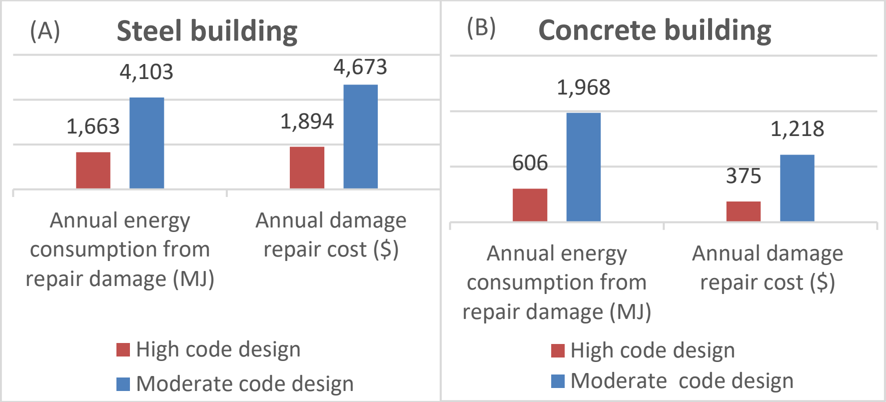


Fig. 1. The annual cost and amount of energy consumption due to repair damage are both reduced by upgrading buildings from a moderate code design to a high code design level.

4.2 STUDY NO.2

Discussion: Gencturk et al. [1] carried out life-cycle sustainability assessment (LCSA) framework on a hypothetical four-story, three-bay RC moment resisting frame located in San Francisco, California. Cradle-to-grave as a system boundary was adopted in the study with the exclusion of operation, maintenance and non-seismic repair, which were completely unrelated to structural performance. In order to investigate the impact of structural design on life-cycle sustainability performance, five variations of the RC frame (distinct in structural capacity) were developed (Design No. 1 to 5). After being subjected to the same load—dead, live, and earthquake, the PBEE method used to convert the probabilistic condition of a structure's damage throughout its life cycle. Static pushover analysis was used to determine the capacity for collapse. The pushover curves for the RC frames were shown and collapse capacities were summarized.
They also realized that although the direct economic impacts of material production, construction, repair, and demolition/recycling can be measured in monetary value, downtime as indirect economic impact is measured in units of time, it cannot be converted into monetary values. So, they converted these metrics into an indicator of environmental impacts known as environmental performance score (EPS).

Important findings:

1. The design alternative with poorest structural performance was found to have the lowest lifecycle cost and environmental impact, but it also caused more fatalities and downtime when exposed to a seismic hazard. To lessen these, the design needed to be upgraded to be more resilient. For example by upgrading buildings from design 1 to design 4, fatalities can be reduced to zero , but in order to achieve this, the life-cycle cost increases by 97% (from 99.4 * 103 $ to 195.5 * 103 $) and also life-cycle environmental impact increases by 192% (from 111.9 EPS to 326.3 EPS) as shown in **Fig. 2 (A, C, E, F).**

2. A more robust design can reduce the use phase's cost and impact on the environment. As shown in **Fig. 2 (B, D)**.

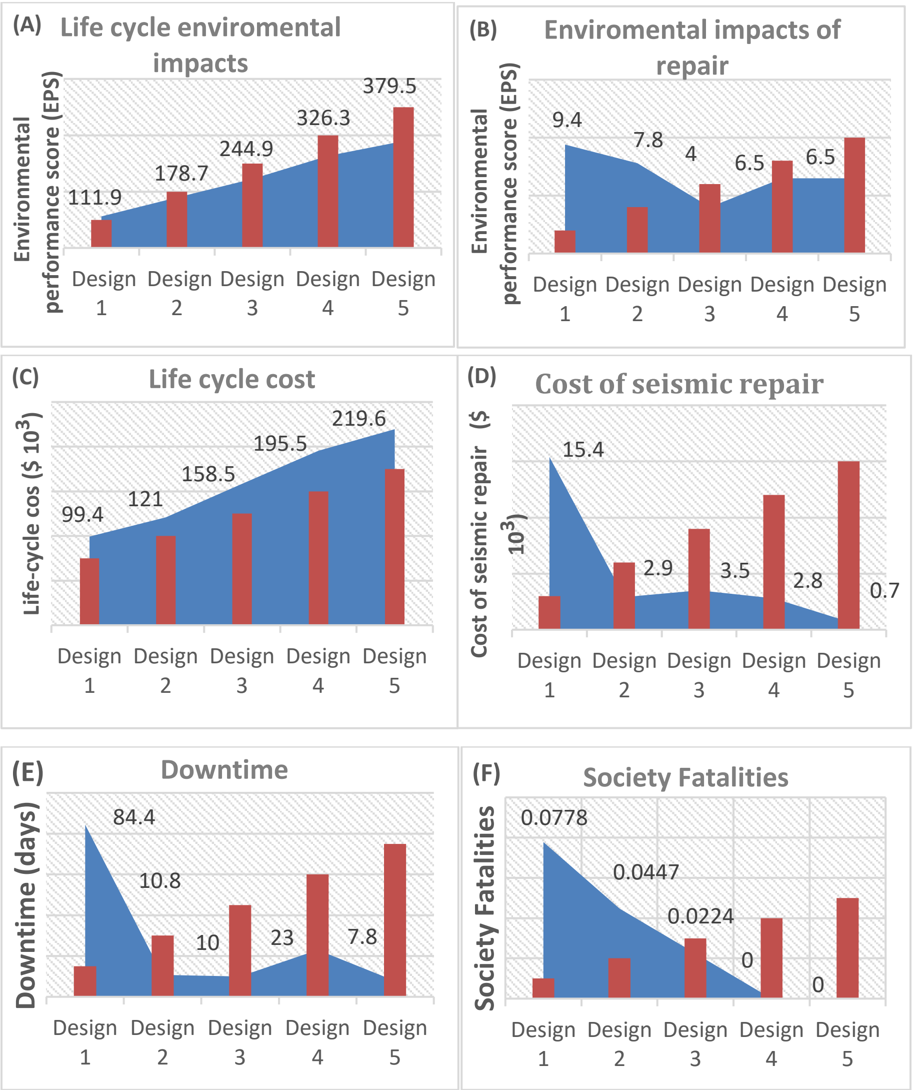


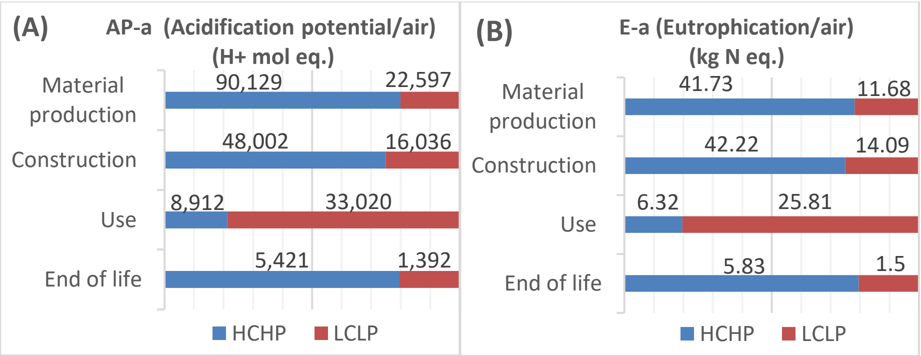
Fig. 2. Comparison of (A) life-cycle environmental impact, (B) environmental impacts of repair, (C) life-cycle cost, (D) Cost of seismic repair, (E) downtime, and (F) fatalities for the five RC frame designs that differ in structural capacity.

4.3 STUDY NO.3

Discussion: Hossain et al. [15] developed a detailed framework for assessing the lifecycle environmental impacts of two RC buildings, and accounting the emissions produced for repairing RC members after damaging earthquakes. A 4-story 3-bay special moment-resisting RC frame is used as the case study building. These two designs were selected for their distinctly different characteristics: one having a high initial cost and high performance (HCHP; i.e., low maximum interstory drift) and the other having a low initial cost and low performance (LCLP; i.e., high maximum interstory drift). They preferred the PBEE methodology for seismic analysis structural response evaluation, damage assessment, and loss analysis to incorporate environmental impact assessment. The system boundaries were defined as cradle to grave, excluding operation and maintenance, which were not directly affected from the structural performance of a building under an earthquake. In the framework, they took into account (resources and energy) as environmental inputs and (emissions and waste) as environmental outputs. As an indicator, the EPS was used for comparison of the lifetime environmental impacts. A LCA framework proposed for a seismic sustainability assessment of typical RC buildings, merged all three sustainability factors by adopting three interactive functions: life-cycle cost assessment (LCCA), life-cycle structural performance assessment (LCSPA), and LCEIA. Each of these components comprises various subcomponents.

Important findings:

1. The LCLP and HCHP designs appear to have significantly different results. The LCLP design requires fewer materials in construction phase; therefore, the initial and end of life phases of the design have fewer environment impacts if compared to the HCHP design.
2. As shown in the **Fig.3. (A, B, C, D)**, The HCHP design has a greater environmental impacts in various categories than the LCLP design. This is because the HCHP design have the greater material usage and increased construction effort, and the consequent increase in initial and end of life environmental impacts. In contrast, the environmental impacts of LCLP design in the use phase are significantly higher for certain categories, such as photochemical smog, global warming, acidification, and eutrophication, when compared to HCHP. As a result, the LCLP design offers more sustainable solution in terms of environmental impact.



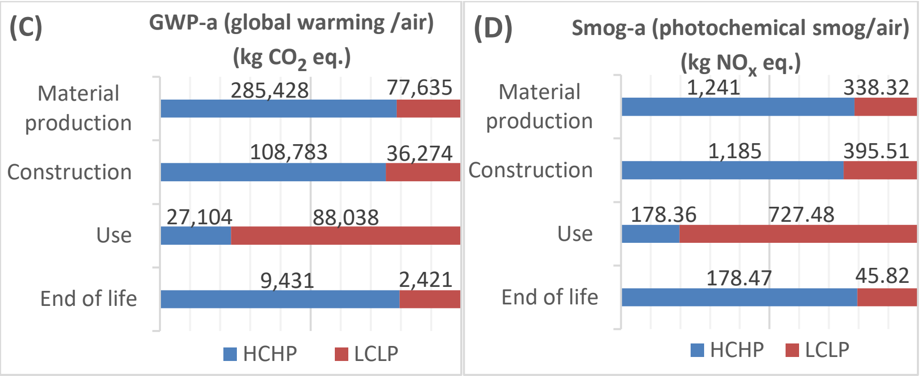


Fig. 3. The environmental impacts of certain categories i.e. (**A**) acidification, (**B**)eutrophication, (**C**) global warming, and (**D**)photochemical smog, respectively, caused by different life-cycle phases of the LCLP and HCHP designs.

4.4 STUDY NO.4

Discussion: Wei et al. [17] designed an innovative LCA framework, which included risk analysis, and showed how the expected environmental loss caused by natural hazards can be effectively reduced by pre-event mitigation through structural retrofit on buildings, they also developed methods to convert seismic risk into measurable CO_2 emissions during pre-seismic structure retrofitting and post-seismic reconstruction. In such manner, they chosen CO_2 emissions as the impact indicator due to their widespread adoption as a standard metric in public regulations. The construction, retrofit and rehabilitation phases were taken into consideration as the system boundaries, and also they considered material, equipment, and transportation as the three basic emission sources. It should also be noted that both the operation and end-of-life phases were not considered in this study because their environmental impacts were not directly influenced by their structural vulnerability to hazards.

For the case study, they chose a pre-1980 RC building with three-story. To demonstrate their proposed approach, they conducted two case studies. In the first case, by using the LCA framework, they evaluated the environmental impacts caused by the construction, retrofitting and renovation of an individual RC building ،and also, the environmental emissions of rehabilitation phase were examined in light of the four damage states. In the second case study, HAZUS catastrophe risk modeling was used to determine the anticipated number of old RC buildings in each damage state following the 12 seismic events in the city of Tiberias (Israel). Combined with the seismic emissions impact of a single building, got from the first case study. The anticipated emissions resulting from the rehabilitation of damaged buildings were calculated, for both as-built and retrofitted building inventories over their service life.

Important findings:

1. As shown in **Fig. 4.** With respect to the four damage states, they investigated the CO2 emissions of a single reinforced concrete building due to rehabilitation and

compared them with CO2 emissions from the building's initial construction. They observed that, in a state of slight damage, the rehabilitation emissions (Er) from the building were estimated to be 4,890 kg of CO2, which is equal to only (1.1%) of emissions from initial construction (Ec), But this ratio gradually increases when the building is in a higher state of severe damage. In a state of complete damage, the total emission of reconstruction from a building in a state of complete damage is estimated to be 536,443 kg of CO2, which is equal to 117.8% of Ec.

2. They also compared the expected CO2 emissions due to rehabilitation over 40 years between as built and retrofitted cases in various damage states. As shown in **Fig. 5**, they demonstrated that, structural retrofitting caused significant changes in their emissions. Although the expected emission from slightly damaged buildings is increased, whereas the expected emission from extensively, moderately and completely damaged buildings are decreased in great portion respectively.

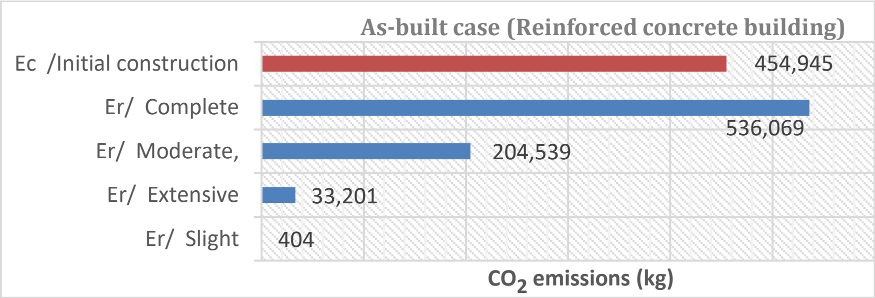


Fig. 4. Investigation of CO_2 emissions of a single reinforced concrete building due to rehabilitation with respect to the four damage states and compared them with CO_2 emissions from the building's initial construction.

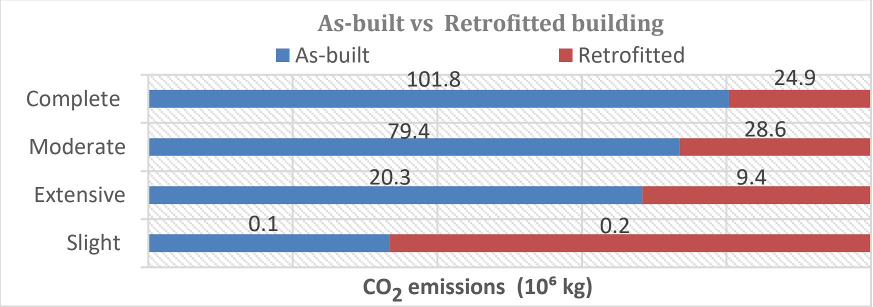


Fig. 5. The expected CO_2 emissions due to rehabilitation for both as-built and retrofitted building inventories over a 40-year period by different building damage states.

4.5 STUDY NO.5

Discussion: Lamperti et al. [16] implemented Sustainable Structural Design method (SSD) with two case-studies of office buildings (precast and cast-in-situ structural systems The SSD framework consisted of three evaluation phases: Energy performance Assessment. Life cycle assessment; and structural performance Assessment.

The first phase consisted solely of calculating the operational energy only for electricity and gas. In the second phase of the SSD, They carried out the Life Cycle Assessment of the two building solutions with the help of SimaPro [18] in a cradle-to-grave approach. They considered only the structural and walling system components in the analyses that were different in both configurations. Elements that were the same in both buildings were omitted. The environmental impacts for both structures were expressed in terms of greenhouse gas emissions (tons of CO2), but they converted it into monetary Units. They used the simplified Performance-Based Assessment (sPBA) method as the third phase of the SSD for calculating the total expected losses for each design. After calculating the initial construction cost for each solution, based on four different limit states—light damage, heavy damage, severe structural damage, and loss or collapse—they determined the total expected losses for each design solution.

The outputs of the phases were expressed in different measurement units, so they converted outputs of the energy and environmental impact into monetary units (costs), and then they used Global Assessment Parameter (RSSD), which is the sum of energy, environmental and structural costs, as the basis for the comparison of various solutions.

Important findings:

1. The solution with the lowest Global Assessment Parameter value is the most sustainable solution, because it may have a higher initial cost, but it also has better environmental performance and/or requires less damage cost in the event of an earthquake during its lifespan.
2. During the construction phase, the greenhouse gas emissions of a cast-in-situ building are higher than those of a precast building.

   The environmental and structural performance of a precast building is superior to that of a cast-in-situ building as shown in **Fig. 6.**

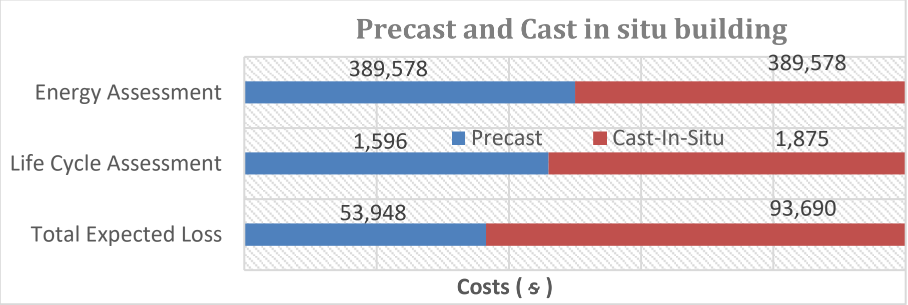


Fig. 6. Comparison of precast and cast in situ building.

5 CONCLUSION

The purpose of this paper was to provide a well-organized, succinct review and analysis the findings of previous research on the environmental and structural performances of earthquake-affected structural systems. It focused on reviewing five comparative LCA studies that looked in depth at both environmental and structural performance of various building scenarios. All the five studies tried to develop methodology, or a model relates to the concept of building's seismic risk and mitigation strategies that minimize a building's life cycle impacts with respect to these risks. The most important of the summarized findings of the study are as follows:

1. By upgrading building design to higher code design caused reducing the amount of annual damage repair costs and annual energy consumption due to damage repair. This creates savings from damage repair costs and reduces annual energy consumption by significant portion.
2. By robusting a structural design, downtime could be significantly reduced, while the number of collapse and partial collapse cases could be reduced to zero (hence resulting in near zero fatalities). However, the life-cycle cost and life-cycle environmental impact increases by 97% and 192%, respectively.
3. When compared to the (HCHP), the environmental impacts of the (LCLP) design in use phase are higher for certain categories, such as global warming, acidification, eutrophication, and photochemical smog. In contrast, in the phases of material production, construction and end-of-life, The (HCHP) design has a greater environmental impact for those categories.
4. In a state of slight damage, the rehabilitation emissions (Er) from a reinforced concrete building equal to only (1.1%) of emissions from initial construction (Ec), but this ratio gradually increases when the building is in a higher state of severe damage.
5. Structural retrofitting caused significant changes in their emissions. Although the expected emission from slightly damaged buildings is increased, whereas the expected emission from extensively, moderately and completely damaged buildings are decreased in great portion respectively.
6. A precast building has superior environmental and structural performance to a cast-in-situ building. While a building with the lowest Global Assessment Parameter value may have a higher initial cost, it also has better environmental performance and/or requires less damage during its lifespan in the event of an earthquake.

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