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Sustainable Frameworks and Life Cycle Assessment for Reinforced Concrete Bridges for Sustainability in Transportation

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CSUTC California State University Transportation Consortium

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16. Abstract

Bridge structures are critical components of California's transportation network, with reinforced concrete (RC) bridges being among the most widely used. Extending the lifespan of these structures can lead to significant reductions in environmental impacts. However, California's frequent seismic activity has repeatedly exposed the vulnerability of existing RC bridges, highlighting the urgent need for seismic retrofitting and maintenance to improve infrastructure resilience against earthquakes and to increase sustainability. This research used detailed computer simulations known as nonlinear finite element models, which are highly detailed computer models, incorporating section damage indices to predict damage and assess structural deficiencies in RC bridges during earthquake events. The proposed modeling framework enables accurate evaluation of seismic performance and damage states, supporting informed recommendations for retrofitting. By extending the service life of existing bridges, the approach contributes to lower environmental impacts compared to complete replacement. Additionally, a life-cycle assessment (LCA) is used to compare the environmental impacts of retrofitting versus rebuilding an RC bridge, considering the full process from construction to demolition. Since new bridge construction demands substantial resources and energy, retrofitting is shown to be a more sustainable solution for minimizing environmental damage following seismic events.

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Executive Summary

California is prone to earthquakes due to its location on the San Andreas Fault and other active fault systems. California is located where the Pacific and North American tectonic plates meet, resulting in frequent seismic activity. California accounts for two-thirds of the nation's earthquake risk. There is a greater than 99% probability of an earthquake of magnitude 6.7 or larger occurring in California.

Reinforced concrete (RC) bridge structures are essential to transportation networks in California, where earthquakes have repeatedly demonstrated the seismic vulnerability of existing RC bridge structures. RC bridge structures with longer life spans can significantly reduce environmental impacts. There are urgent needs for seismic retrofitting and bridge maintenance to extend the life span of RC bridges. Therefore, sustainability in the transportation system could be improved.

In this research, two studies were performed. The Canyon Road Overcrossing RC highway bridge in California was selected for the studies. In study 1, fiber-based nonlinear finite element models with section damage indices are used for damage predictions and bridge deficiency assessment under earthquake motions. The proposed frameworks could accurately assess, predict the seismic performance and damage state of RC bridge structures, and make recommendations for retrofit to extend the life span of bridges. Therefore, significant reduction in environmental impacts can be accomplished. In study 2, the proposed Life Cycle Assessment (LCA) method of the selected RC bridge was performed to demonstrate that retrofitting existing RC bridge structures to extend their life span would be better than rebuilding new bridges to reduce the environmental impact to improve sustainable bridge structures under seismic hazards.

Fiber-based nonlinear finite element damage models were used to assess the seismic performance of RC bridges. The cross section of the RC bridge columns was divided into fiber cells, which were assigned uniaxial constitutive modeling with nonlinear material properties and could record the stress-strains history of concrete and steel under earthquake motions. The RC cross section was made up of cover concrete, core concrete, and reinforcing steel bars. Continuous recording of the progression of cover concrete and longitudinal reinforcing steel bars damages could be obtained. In addition, the RC bridge columns were discretized with finite element nodes. Nonlinear fiber-based and displacement-based beam-column elements were placed between the nodes. The nonlinear fiber-based and displacement-based beam-column elements could distribute plasticity which allows for the growth of nonlinearities along the members. Additionally, a low-cycle fatigue damage mechanism was also considered. Furthermore, the low-cycle fatigue effect with buckling was correlated by fatigue life coefficients as a function of the buckling parameter. Bond-slip effect was also considered by adding a zero-length section element at the intersection between the flexural member and an adjoining member to capture the strain penetration effects at the bridge column-to-footing intersection.

Life Cycle Assessment (LCA) is a comprehensive method for evaluating the environmental impacts of a product, process, or service throughout its entire life cycle. This includes all stages from raw material extraction to production, use, and disposal, which help identify and quantify the environmental burdens associated with each stage.

The proposed LCA method was performed on the selected RC highway bridge. The proposed LCA method includes the following stages: Product, Construction Process, Use, End-of-Life, and Beyond Building Life. The environmental footprint of the bridge due to global warming potential are recorded under each of the stages. The results indicated that Stage 1 (Product, A1 to A3) and Stage 5 (Beyond Building Life, D) were the prominent causes of environmental impact in the selected RC highway bridge. Although bridges are a crucial transportation medium where vehicles emit considerable amounts of CO_2, Stage 3 (Use, B2, B4, and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO_2. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO_2. The proposed LCA method shows that retrofitting existing RC bridge structures to extend their life span would be better than rebuilding new bridges to reduce the environmental impact to improve sustainable bridge structures under seismic hazards.

1. Introduction

Bridge structures are essential to transportation networks in California. Bridge structures with extended lifespans significantly contribute to a reduction in environmental impacts. This is because the environmental impact of bridge construction is significant, encompassing the entire life cycle from raw material extraction to end-of-life disposal. In California, earthquakes have repeatedly demonstrated the seismic vulnerability of existing bridge structures. There are urgent needs for seismic retrofitting and bridge maintenance to extend the life span of bridges. Therefore, sustainability in the transportation system could be improved.

The construction of new reinforced concrete (RC) bridges consumes a great number of resources and energy and generates significant environmental impact. Bridge construction uses a considerable amount of energy and raw materials, but considerations of their environmental performance are rarely integrated into the decision-making process (Du, 2015). The majority of bridges in California are made of reinforced concrete materials, but concrete releases a large amount of carbon dioxide during construction as demonstrated in various studies (Tait & Cheung, 2016; Chen et al., 2021; Mostafaei et al., 2023). Concrete is one of the most used construction materials. Consequently, concrete production is responsible for up to 8% of carbon dioxide emissions worldwide (Tait & Cheung, 2016). Producing the cement ingredient for concrete is a very carbon-intensive step of the concrete production process due to the extraction of materials such as limestone and heating in kilns. The limestone undergoes a calcination process to remove impurities and break down into calcium oxide, which is a process that releases large amounts of CO_2 from the chemical reaction. Additionally, the kilns require large amounts of energy to heat, mix, and cool the materials. This emission of CO_2 has led to the rapid acceleration of global warming.

Life cycle assessment (LCA) is an effective method for evaluating the environmental impact of a structure throughout its service life. When RC bridges undergo extensive damage from seismic ground motion, they need to be either repaired or rebuilt. However, rebuilding new RC bridge structures would negatively impact the environment.

The most widely used LCA analysis is based on International Standards ISO 14040 (Zimoch, 2012). LCA has a few different methods to carry out the assessment: cradle-to-gate, gate-to-gate, and cradle-to-grave. Cradle-to-gate is a method that starts the study from acquiring the resources (cradle) to the processing plant (gate). The use and disposal phases are not included. Gate-to-gate is an LCA analysis that only reviews one stage of production. Cradle-to-grave is an LCA analysis that includes the study from the extraction of resources (cradle) to their disposal (grave). This method is the most extensive as it looks at all phases of a structure's life and includes all inputs and outputs.

LCA is used in various industries. However, its applications on bridges are still limited and require further research. Bouhaya et al. (2009) conducted an LCA on a bridge structure made of wood and high-performance concrete, but the analysis did not consider the bridge's foundation. Additionally, the LCA was restricted to energy consumption and greenhouse gas emissions. They found that the production phase required the most energy which represented 73.4% of the total amount. Penadés-Plà et al. (2020) evaluated three alternative concrete bridge designs environmentally and socially. They found that the manufacturing phase had the highest impact on every alternative bridge design. Itoh and Kitagawa (2003) compared the CO_2 emission of three bridges: a PC pre-tensioned T-girder bridge, a PC box girder bridge, and a steel box girder bridge. However, their LCA excluded the end-of-life phase (EOL), the disposal of the bridge at the last life cycle. Du (2015) performed LCA analysis on various bridge types: a railway bridge with ballast or fix-slab track, a steel box-girder composite bridge, a steel I-girder composite bridge, a post tensioned concrete box-girder bridge, a balanced cantilever concrete box-girder bridge, a steel-soil composite bridge, and a concrete slab-frame bridge.

Research on sustainability is highly focused on buildings, while research for other structures such as RC bridges is still limited. Furthermore, most of the existing studies mentioned earlier were limited to a few environmental indicators or life stages.

Our research goal is to accurately predict the damage state after an earthquake, to determine bridge deficiencies, and to make recommendations for seismic retrofit and bridge maintenance to extend the life span of bridges as well as to improve sustainability in the transportation system in California.

In this research, two studies were performed. In study 1, nonlinear finite element models with section damage indices are used for damage predictions and bridge deficiency assessment under earthquake motions. The proposed frameworks could accurately assess and predict the seismic performance and damage states of RC bridge structures and can make recommendations for retrofitting to extend the life span of bridges. Therefore, significant reduction in environmental impacts can be improved. In addition, in study 2, the proposed LCA method will be used to demonstrate the environmental impact of rebuilding a new RC bridge from construction to demolition after earthquake damage. Therefore, retrofitting existing RC bridge structures to extend their life span would be better than rebuilding new bridges to reduce the environmental impact under seismic damage.

This research aims to provide a comprehensive seismic assessment of the sustainability of the reinforced concrete bridges. The case study used herein is a reinforced concrete highway bridge in California which is modeled using validated nonlinear finite element fiber-based numerical damage models (Ko, 2022; Ko & Gonzalez, 2023, 2024; Su et al., 2017). The selected reinforced concrete highway bridge underwent nonlinear dynamic analysis subjected to ten different earthquakes within the vicinity of the bridge. Section damage indices were determined for each earthquake motion. The seismic performance of the selected reinforced concrete highway bridge was obtained. The need for retrofitting was recommended to extend the life span of this existing bridge structure. In addition, the proposed LCA method was conducted for this selected reinforced concrete highway bridge as if it needs to be rebuilt. LCA results demonstrated that retrofitting existing RC bridge structures to extend their life span would be better than re-building new bridges to reduce the environmental impact to achieve sustainable bridge structures.

2. Descriptions of the Reinforced Concrete Bridge Selected for Assessment

2.1 The Canyon Road Overcrossing Reinforced Concrete Bridge

To investigate the seismic performance and LCA of the RC bridges, the Canyon Road Overcrossing RC highway bridge was selected for this study. The Canyon Road Overcrossing RC highway bridge is located about 5.5 miles south of Los Banos in California. This bridge is over Interstate 5 (I-5) and serves to connect transportation and promote mobility between Los Banos City and the Los Banos Reservoir.

2.2 Structural Descriptions of the Reinforced Concrete Bridge

The Canyon Road Overcrossing RC highway bridge is in a highly seismic area of California. As shown in Figure 1, this bridge consists of two spans at a total of 259 ft long, and the height of the circular column is 22 ft. Three box-girders make up its superstructure. As shown in Figure 2, the section of the box-girder is 5 feet and 6 inches tall and 34 feet wide.

In Figure 3, the cross section of the column is 6 feet in diameter with 3 inches of cover thickness and consists of forty-five #11 steel bars with 1.41 inches in diameter as longitudinal reinforcements as well as #4 steel bars with 0.50 inches in diameter and 12 inches in spacing as the transverse reinforcements. The yielding and ultimate strength of the steel reinforcements was 165 MPa and 196 MPa, respectively. The concrete strength was 8.96 MPa. The total axial load applied to the column was 432 kips. When determining the axial force on the bridge column, the distributed dead load from the superstructure and the live load from moving highway loads were accounted for. The bridge quantities included 155 cubic yards of structural bridge concrete, 585 cubic yards of cast-in-place prestressed concrete, and 137,000 lbs. of reinforcing steel bars.

Figure 1. Reinforced Concrete Bridge Elevation

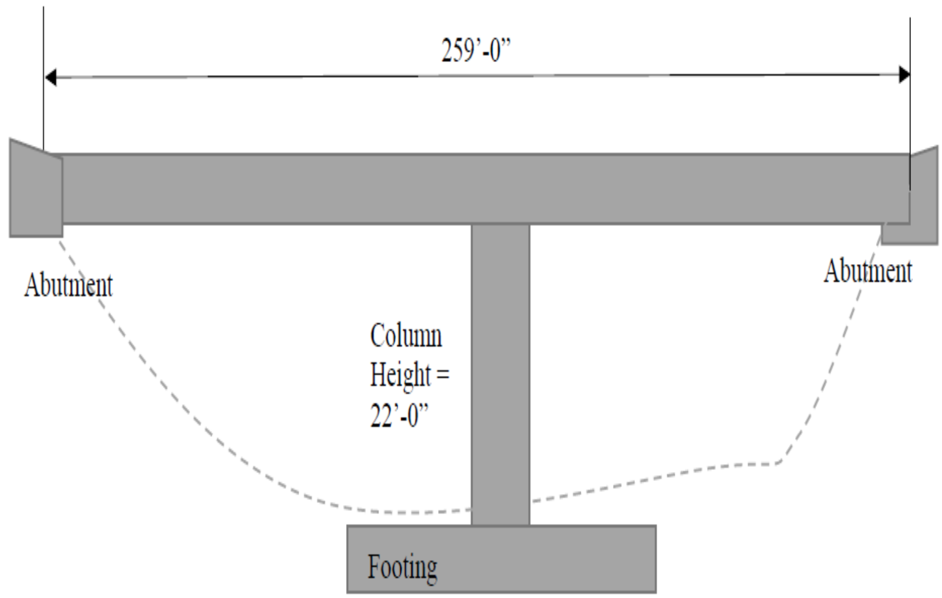


Figure 2. Reinforced Concrete Bridge Section

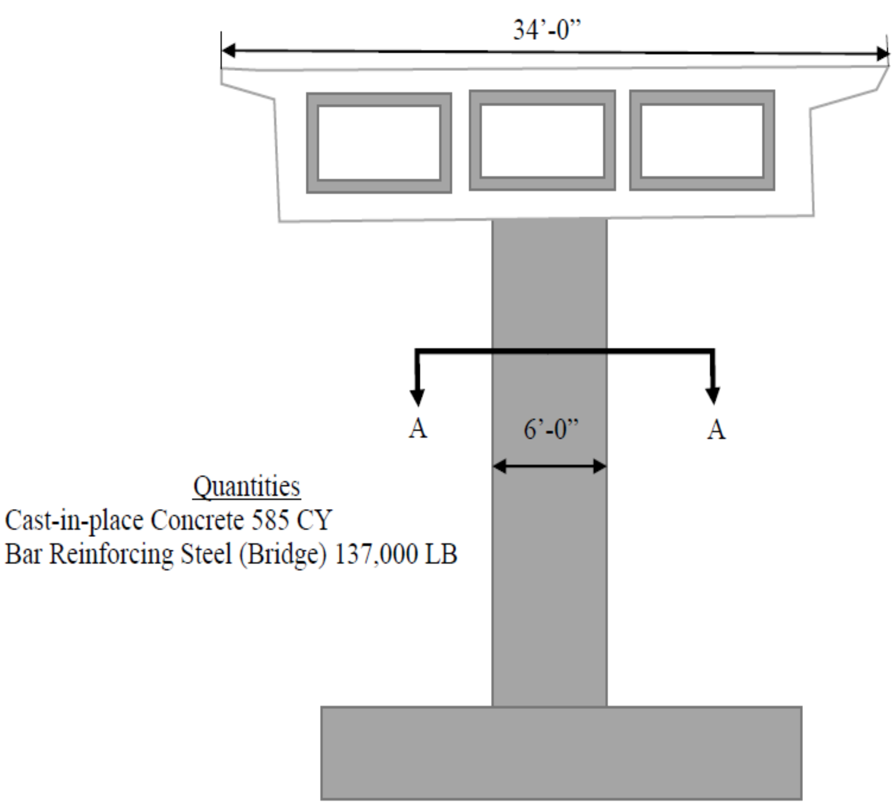
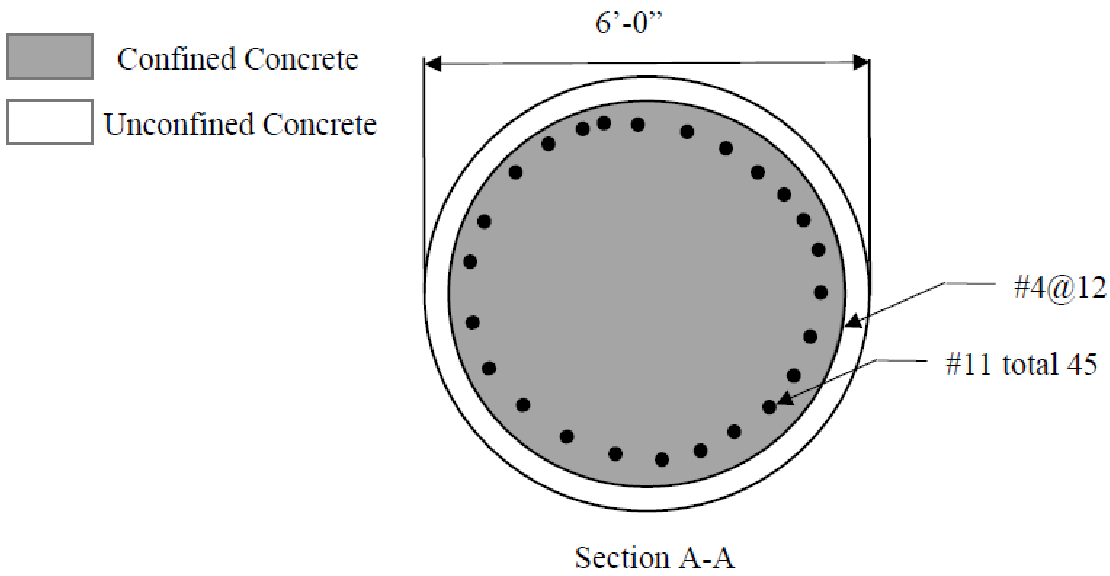


Figure 3. Reinforced Concrete Bridge Cross Section

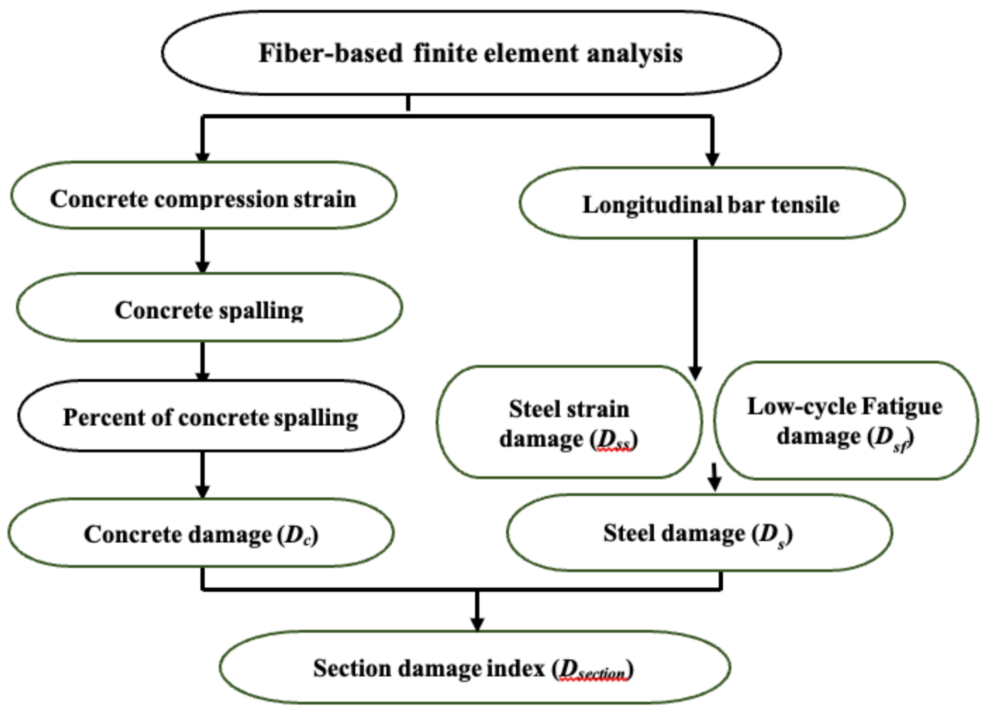


3. Study 1: Seismic Performance Assessment of the Selected Reinforced Concrete Bridge

3.1 Damage Indices and Seismic Performance Assessment

The seismic performance of the RC bridges was assessed using damage indices (Ko, 2022; Ko & Gonzalez, 2023, 2024; Su et al., 2017) as shown in Figure 4.

Figure 4. Section Damage Index



The section damage indices can be correlated with seismic performance assessments as shown in Table 1 (Stone & Taylor, 1993, 1999) and Table 2 (TRB, 2013). Table 1 (Stone & Taylor, 1993, 1999) classifies bridge performance assessment. There are five levels of performance characterizations used to measure the RC bridge performance which include Level I (Cracking), Level II (Yielding), Level III (Initiation of local mechanism), Level IV (Full development of local mechanism), and Level V (Strength degradation). Table 2 (TRB, 2013) defines the damage index levels of RC bridges from 0.0 to 1.0. This range corresponds to the structure damage.

Table 1. Bridge Performance Assessment (Stone & Taylor, 1993, 1999)

Level	Performance level	Qualitative performance characterization	Quantitative performance characterization
I	Cracking	Onset of hairline cracks	Cracks hardly visible
II	Yielding	Theoretical first yielding of longitudinal reinforcement	Crack widths <1 mm
III	Initiation of local mechanism	Initiation of inelastic deformation, onset of concrete spalling, development of diagonal cracks	Crack widths of 1–2 mm, length of spalled region >1/10 of the cross-section's depth
IV	Full development of local mechanism	Wide and extended cracks, significant spalling over local mechanism region	Crack widths >2 mm, diagonal cracks extend over 2/3 of the cross-section's depth, Length of spalled region >1/2 of the cross-section's depth
V	Strength degradation	Buckling of main reinforcement, Rupture of transverse reinforcement, Crushing of core concrete	Crack widths >2 mm in core concrete

Table 2. Definitions of Damage Index Levels (TRB, 2013)

Level	Damage Classification	Damage Value	Description	Performance Condition
I	None	$D < 0.1$	Onset of hairline cracks	Fully operational
II	Minor	$0.1 \le D < 0.2$	Crack widening, first yielding of reinforcement	Operational
III	Moderate	$0.2 \le D < 0.4$	Onset of cover concrete spalling	Limited damage
IV	Major	$0.4 \le D < 0.6$	Significant spalling	Life safety
V	Local Failure/Collapse	$0.6 \le D < 1.0$	Buckling of reinforcement, crushing of core concrete	Collapse

3.2. Fiber-Based Material Damage Models

The selected RC highway bridge was simulated using fiber-based nonlinear finite element damage models (Ko, 2022; Ko & Gonzalez, 2023, 2024; Su et al., 2017) with nonlinear analysis using the Open System for Earthquake Engineering Simulation (OpenSees) program (McKenna et al., 2000). The RC bridge column circular cross section is divided into fiber cells which are assigned uniaxial constitutive modeling with nonlinear material properties and can record the stress-strains history of concrete and steel under earthquake motions. The RC cross section is made up of the cover concrete, core concrete, and reinforcing steel bars as shown in Figure 3. The cover and core concrete are represented by the OpenSees Concrete02, a uniaxial material model that represents concrete with linear tension softening and a specified compressive behavior, and the longitudinal reinforcing bars are represented by the OpenSees Hysteretic material which considers the mechanical effects of strain softening, compression buckling, and tensile fracture, as well as low-cycle fatigue of the reinforcement bars. Benefits of the fiber-based nonlinear finite element are that continuous recording of the progression of cover concrete and longitudinal reinforcing steel bars damages could be obtained.

3.3 Nonlinear Finite Element Modeling Formulations

The RC bridge column was discretized with finite element nodes. Six nonlinear fiber-based and displacement-based beam-column elements are placed between the nodes. The nonlinear fiber-based and displacement-based beam-column elements can distribute plasticity which allows growth of nonlinearities along the members (Ko, 2022; Ko & Gonzalez, 2023, 2024; Su et al., 2017).

The circular cross section was comprised of confined core concrete fibers, unconfined cover concrete fibers, and longitudinal reinforcing steel fibers. The cross section was made up of uniaxial nonlinear fibers labeled as "UniaxialMaterial" to capture the stress-strain hysteresis behaviors of concrete and reinforcing steel bars. The uniaxial concrete material Concrete02 in OpenSees was used to represent the confined and unconfined concrete. The longitudinal reinforcing steel bars were modeled using uniaxial bilinear Hysteretic material.

Additionally, low-cycle fatigue was another damage mechanism that was considered and recorded in OpenSees by wrapping fatigue material to the Hysteretic material. The fatigue material model applied to the Coffin and Manson fatigue life relationship. Furthermore, the low-cycle fatigue effect with buckling was correlated by fatigue life coefficients as a function of buckling parameters (Tripathi et al., 2019a, 2019b; Dhakal & Maekawa, 2002; Goodnight, 2015, Goodnight et al., 2016; Feng et al., 2014; Bakkar et al., 2021; Brown & Kunnath, 2004).

Specifically, bond-slip effects (Ko, 2022) were also considered by adding a zero-length section element at the intersection between the flexural member and an adjoining member to capture the strain penetration effects at the bridge column-to-footing intersection. The concrete material within the zero-length section uses the same Concrete02 material as the fiber-based beam-column elements, but the reinforcing steel rebars adopted the Bond_SP01 uniaxial material, a uniaxial material model used to simulate the behavior of bond slip between steel reinforcing bars and concrete.

3.4 Seismic Performance Assessment Results of the Selected Reinforced Concrete Bridge

The numerical simulation methods and damage models described in Sections 3.1, 3.2, and 3.3 were used to conduct seismic performance assessments of the selected RC highway bridge under ten selected earthquakes. Ten ground motion records were selected from the Pacific Earthquake Engineering Research Center (PEER) Strong Motion Database (https://ngawest2.berkeley.edu/) in this study. The magnitude of the selected ground motions ranged from 4.9 to 6.9. Ten earthquake ground motion records were selected within the vicinity of the bridge's location. The selected ground motions are listed in Table 3. Peak Ground Acceleration (PGA) is a measure of the maximum acceleration of the ground during an earthquake. It is expressed in terms of a percentage of the Earth's gravitational acceleration (g). It is a key parameter adopted in seismic hazard assessment as well as structural analysis and structural design.

Table 3. Selected Ground Motion Records

No.	Event	Year	Station	Magnitude	PGA (g)
1	Gilroy	2002	Gilroy-Gavillan Coll.	4.9	0.2100
2	Gilroy	2002	Gilroy Array #6	4.9	0.0952
3	Gilroy	2002	Gilroy Array #3	4.9	0.2168
4	Coalinga-05	1983	Oil Fields Fire Station - FF	5.77	0.2175
5	Coalinga-04	1983	Transmitter Hil	5.77	0.7798
6	Coalinga-05	1983	Oil City	5.77	0.8412
7	Loma Prieta	1989	Corralitos	6.93	0.6447
8	Loma Prieta	1989	Hollister City Hall	6.93	0.2463
9	Coalinga-05	1983	Coalinga-14th & Elm (Old CHP)	5.77	0.3415
10	Hollister-03	1974	Gilroy Array #1	5.14	0.1003

There are two different levels of ground shaking used for structural design: Design Basis Earthquake (DBE) and Maximum Considered Earthquake (MCE). DBE has a lower magnitude of earthquakes with a higher probability of exceedance 10% in 50 years. MCE is the most severe earthquake with 2% in 50 years. For the site location of the selected RC highway bridge, DBE had a PGA value of 0.41 g, and MCE had a PGA value of 0.77 g.

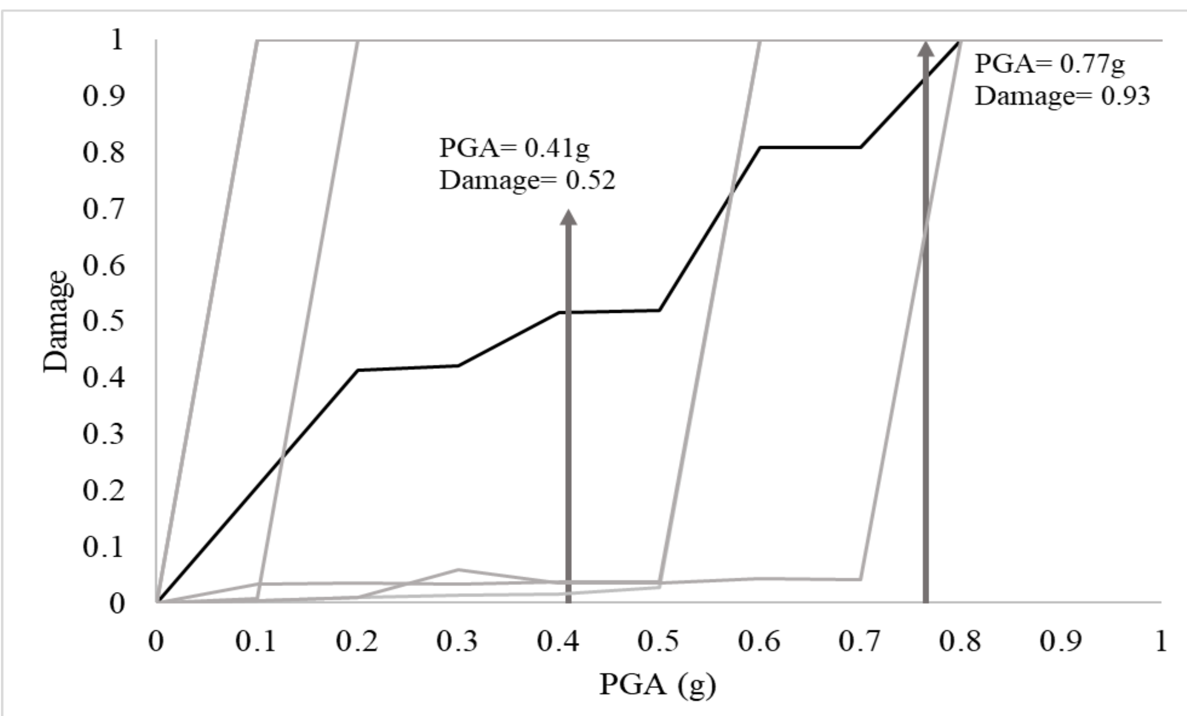
The PGAs of the ten selected earthquake ground motions were scaled from 0.1 g to 1.0 g in 0.1 g increments. Nonlinear time history analysis was conducted for each of these scaled ground motions using the proposed damage models and damage indices as described in Section 3 for the selected RC highway bridge under different ground motions (see Figure 5).

In Figure 5, the section damage indices for the scaled PGAs of each earthquake ground motion are indicated as gray lines. The average section damage indices of the ten earthquake ground motions are shown as the black line.

The results show that damage values increased with the increase of the PGA. The average section damage value of the selected RC highway bridge column under the DBE was 0.52, which signifies a major damage level, including significant concrete cover spalling. The average damage value of the selected RC highway bridge column was 0.93 under the MCE, which indicates failure or collapse of the RC bridge column, including buckling of reinforcement and crushing of the core concrete.

By considering the potential for different earthquake intensities and ground motion scenarios, this approach will achieve specific performance goals, such as preventing collapse or ensuring minimal damage. The results in Figure 5 also show that the selected RC highway bridge needs to be repaired and retrofitted prior to a DBE and an MCE. Otherwise, in the event of an MCE, this RC bridge would collapse and need to be rebuilt, which would negatively impact the environment.

Figure 5. Results of Damage Analysis



4. Study 2: Life Cycle Assessment of the Reinforced Concrete Bridge

4.1 Concept of Life Cycle Assessment

Life Cycle Assessment (LCA) is a method for evaluating the environmental impacts of a product or process throughout its entire lifespan, from raw material extraction to disposal. LCAs not only focus on the outcome but also focus on the impact of the process on the environment.

Therefore, LCAs can evaluate a product's impact on the environment during its entire life cycle. The environmental impact assessment can be conducted both for production and for its function during the lifespan of whole bridge structures. LCAs can include identification and quantitative assessment of environmental effects, including the materials used and the energy consumed during production and use.

4.2 Concept of Life Cycle Assessment of Reinforced Concrete Structures

LCAs of RC structures quantify the lifetime environmental impacts of RC structures. They are used to measure and reduce the embodied, operational, and whole-life carbon emissions of RC structures.

The infrastructure sector produces a large amount of greenhouse gas emissions, in particular carbon dioxide, which is emitted during all its phases: production, transportation, and construction (Mostafaei et al., 2023). Over time, structures deteriorate and need repair or rebuilding, which involves undergoing all the phases again. However, civil infrastructure is necessary for economic and social development. Therefore, it is crucial for structures to be designed to have a long service life to reduce their environmental impact.

One of the most used building materials is concrete due to its durability and strength. It is a versatile material that is often used in roads, overpasses, walls, and other structures. As such, concrete is a core building foundation of modern society. However, the use of concrete has significant environmental repercussions (Manjunatha et al., 2021), starting with the quarrying and manufacturing process, which includes acquiring natural resources such as limestone and produces greenhouse gas emissions. The production process has a large environmental impact; for example, transporting raw materials uses a lot of energy and emits CO_2 into the atmosphere. Construction also inevitably means the destruction of natural environments during quarrying. If a structure fails and is no longer serviceable, then demolishing the structure also adds to construction waste. Therefore, it is imperative that reinforced concrete structures be designed optimally.

Researchers have adopted LCAs to determine the ecological repercussions of various concrete mix designs. For instance, Mostafaei et al. (2023) investigated the effects of different concrete mix designs on the environmental impacts of RC structures within the system boundaries, which are the analysis limits of the LCA. Three different concrete mixing designs of strengths 20, 30, and 40 MPA were compared with regards to their effects on human health, ecosystem quality, climate change, resources, and acidification. The ingredients of the RC structures, including cement, sand, gravel, and water, were compared to determine which had the greatest impact. Although engineers prefer the higher compressive strength of concrete to reduce the cross-sectional areas of structures and thus reduce their weight, this increase in concrete mixes with higher compressive strength leads to an increase in energy-intensive constituents. They found that when the compressive strength of concrete increased from 20 to 40 MPa, the LCA indicators for human health, climate change, and human toxicity also increased by 12.58%, 19.49%, and 20.38%, respectively.

Additionally, Van den Heede and De Belie (2012) studied the environmental impacts of green concrete versus traditional concrete. They found that green concrete made from furnace slag created less contamination than Portland cement-based concrete. Black and Purnell (2016) also noted that the cost of the greener ingredients of concrete provides weak financial incentives and may easily be outweighed by other factors such as transportation and labor. The cost of developing greener concrete deters industries from exploring these alternative more sustainable options.

4.3 Life Cycle Assessment of the Selected Reinforced Concrete Bridge

4.3.1 The Proposed LCA Method

An LCA for reinforced concrete (RC) bridges follows a systematic process that includes defining the goal and scope, conducting an inventory analysis, performing an impact assessment, and interpreting the results, considering all stages of the bridge's life cycle from material extraction to demolition and recycling, including construction, maintenance, and end-of-life phases.

The proposed LCA method included the following stages: Stage 1 (Product) was labeled as A1 to A3 and included material productions as well as transportation of raw materials and manufacturing; Stage 2 (Construction Process) was labeled as A4 and A5 and included transportation of equipment to the construction site, installation, and construction; Stage 3 (Use) was labeled as B2, B4, and B6 and included maintenance and repair; Stage 4 (End-of-Life) was labeled as C1–C4 and included demolition and waste disposal; and Stage 5 (Beyond Building Life) was labeled D and included the reuse and recycling of material beyond the bridge's life cycle.

4.3.2 The LCA Results of the Selected RC Bridge

The bridge included 155 cubic yards of structural bridge concrete, 585 cubic yards of cast-in-place prestressed concrete, and 137,000 lbs. of reinforcing steel bars. The environmental footprint of the selected RC highway bridge due to global warming potential was recorded for each stage. The environmental impacts are summarized in Tables 4–8 and shown in Figure 6. The results show that Stage 1 (Product, A1toA3) and Stage 5 (Beyond Building Life, D) were the prominent causes of environmental impact in the selected RC highway bridge. Although bridges are a crucial transportation medium where vehicles emit considerable amounts of CO_2, Stage 3 (Use, B2, B4, and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO_2. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO_2.

The LCA's results highlight the need to retrofit, rather than rebuild, to reduce environmental impacts. The LCA demonstrates that retrofitting existing RC bridge structures to extend their life span would be better than rebuilding new bridges to reduce the environmental impact and improve sustainable bridge structures under seismic attacks.

Table 4. LCA Measure by Life Cycle Stages: Stage 1 (Product)

		PRODUCT (A1 to A3)		
LCA Measures	**Unit**	Manufacturing	Transport	**Total**
Global Warming Potential	kg CO2 eq	2.22E+05	3.48E+03	**2.26E+05**

Table 5. LCA Measure by Life Cycle Stages: Stage 2 (Construction Process)

		CONSTRUCTION PROCESS (A4 and A5)		
LCA Measures	**Unit**	Construction-Installation Process	Transport	**Total**
Global Warming Potential	kg CO2 eq	1.44E+04	1.09E+04	**2.53E+04**

Table 6. LCA Measure by Life Cycle Stages: Stage 3 (Use)

		USE (B2, B4, and B6)			
LCA Measures	**Unit**	Replacement Manufacturing	Replacement Transport	Operational Energy Use Total	**Total**
Global Warming Potential	kg CO2 eq	0.00E+00	0.00E+00	0.00E+00	**0.00E+00**

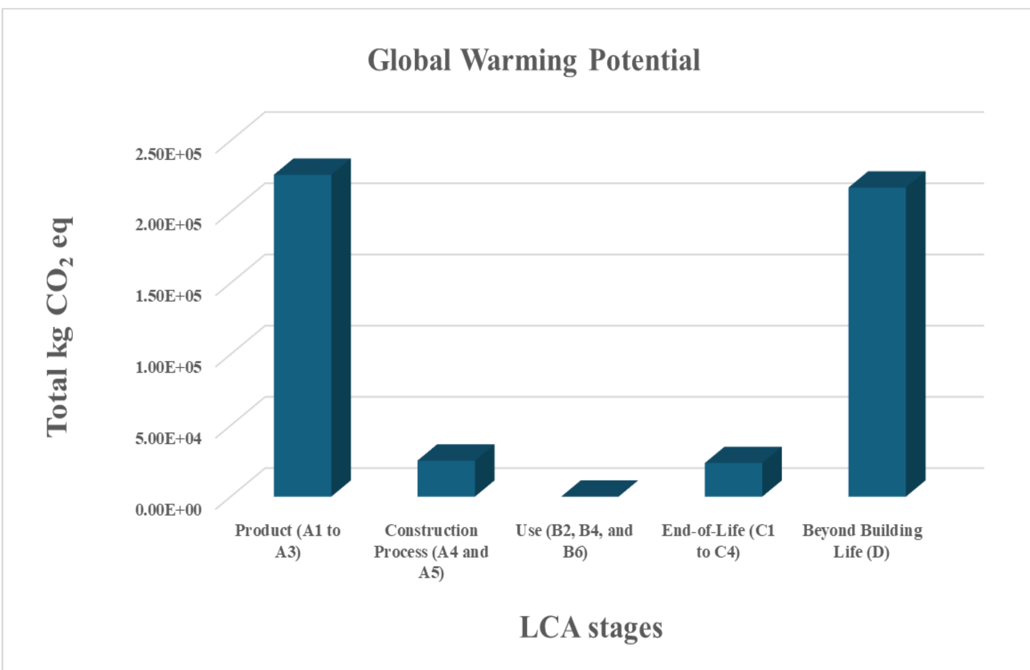
Table 7. LCA Measure by Life Cycle Stages: Stage 4 (End-of-Life)

		END-of-LIFE (C1 to C4)		
LCA Measures	**Unit**	De-construction, Demolition, Disposal & Waste Processing	Transport	**Total**
Global Warming Potential	kg CO2 eq	1.92E+04	4.40E+03	**2.36E+04**

Table 8. LCA Measure by Life Cycle Stages: Stage 5 (Beyond Building Life)

		BEYOND BUILDING LIFE (D)		
LCA Measures	**Unit**	BBL Material	BBL Transport	**Total**
Global Warming Potential	kg CO2 eq	2.17E+05	0.00E+00	**2.17E+05**

Figure 6. Global Warming Potential for Each LCA Stage



5. Summary & Conclusions

In this research, two studies were conducted. The Canyon Road Overcrossing RC highway bridge in California was selected for the studies. In study 1, fiber-based nonlinear finite elements were used to simulate the nonlinear seismic responses of the selected RC bridge, considering buckling and low-cycle fatigue of steel rebars as well as cover concrete damage. Damage indices based on fiber models were used to evaluate the damage states of the selected RC bridge. The selected RC bridge deficiency under earthquake motions was assessed. The proposed frameworks could accurately assess and predict the seismic performance and damage states of RC bridge structures and can make recommendations for retrofitting to extend the life span of bridges. Therefore, significant reduction in environmental impacts can be improved. In addition, in study 2, the proposed LCA methods were used to demonstrate the environmental impact of rebuilding a new RC bridge from construction to demolish after earthquake damages. LCA results show the need to retrofit rather than to rebuild the selected RC highway bridge to mitigate environmental impacts under seismic damage.

The selected RC highway bridge was simulated using fiber-based nonlinear finite element damage models with nonlinear analysis using OpenSees program to assess the seismic performance of the RC highway bridge. In addition, low-cycle fatigue effect with buckling was correlated with fatigue life coefficients as a function of buckling parameter. Moreover, bond-slip effects were also considered by adding a zero-length section element at the intersection between the flexural member and an adjoining member to capture the strain penetration effects at the bridge column-to-footing intersection. The selected RC highway bridge underwent ten selected earthquakes by nonlinear time-history analysis selected from the Pacific Earthquake Engineering Research Center (PEER) Strong Motion Database.

The simulation results demonstrate that section damage values increase with the increase of the PGA. In addition, the results reveal a major damage level to the selected RC highway bridge, including significant concrete cover spalling under the DBE as well as failure or collapse of the RC bridge column, including buckling of reinforcement and crushing of the core concrete, under the MCE. As a result, it is recommended that the selected RC highway bridge should be repaired and retrofitted prior to DBE and MCE. Collapse in the event of MCE can be prevented to avoid the needs to be rebuilt and result in negative impact to the environment.

The proposed LCA method considered various stages during the entire life cycle of the selected RC highway bridge. The environmental footprints of the RC bridge due to global warming potential are recorded under each of the stages: Stage 1 (Product), Stage 2 (Construction Process), Stage 3 (Use), Stage 4 (End-of-Life), and Stage 5 (Beyond Building Life). The results indicated that Stage 1 (Product, A1 to A3) and Stage 5 (Beyond Building Life, D) were the prominent causes of environmental impact in the selected RC highway bridge. Although bridges are a crucial transportation medium where vehicles emit considerable amounts of CO_2, Stage 3 (Use, B2, B4, and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO_2. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO_2. The results of the LCA emphasize the need to retrofit rather than to rebuild the selected RC highway bridge to mitigate environmental impacts. The LCA also demonstrated that retrofitting existing RC bridge structures to extend their life span would be better than rebuilding new bridges to reduce environmental impact and improve sustainable bridge structures under seismic risks. This research focused on global warming potential for LCA studies. However, LCA research, while valuable for evaluating the environmental impact of products and processes, faces several limitations. These include challenges related to the complexity of modeling various life cycle stages, the subjectivity in choosing methodologies and system boundaries, etc. Future LCA studies could be improved to address these challenges.

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