

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

Yu-Fu Ko, PhD, PE Jessica Gonzalez., EIT



MINETA TRANSPORTATION INSTITUTE

Founded in 1991, the Mineta Transportation Institute (MTI), an organized research and training unit in partnership with the Lucas College and Graduate School of Business at San José State University (SJSU), increases mobility for all by improving the safety, efficiency, accessibility, and convenience of our nation's transportation system. Through research, education, workforce development, and technology transfer, we help create a connected world. MTI leads the [California State University Transportation Consortium \(CSUTC\)](#) funded by the State of California through Senate Bill 1 and the Climate Change and Extreme Events Training and Research (CCEETR) Program funded by the Federal Railroad Administration. MTI focuses on three primary responsibilities:

Research

MTI conducts multi-disciplinary research focused on surface transportation that contributes to effective decision making. Research areas include: active transportation; planning and policy; security and counterterrorism; sustainable transportation and land use; transit and passenger rail; transportation engineering; transportation finance; transportation technology; and workforce and labor. MTI research publications undergo expert peer review to ensure the quality of the research.

Education and Workforce Development

To ensure the efficient movement of people and goods, we must prepare the next generation of skilled transportation professionals who can lead a thriving, forward-thinking transportation industry for a more connected world. To help achieve this, MTI sponsors a suite of workforce development and education opportunities. The Institute supports educational programs offered by the Lucas Graduate School of Business: a Master of Science in Transportation Management, plus graduate certificates that include High-Speed and Intercity Rail Management and Transportation Security Management. These flexible programs offer live online classes so that working transportation professionals can pursue an advanced degree regardless of their location.

Information and Technology Transfer

MTI utilizes a diverse array of dissemination methods and media to ensure research results reach those responsible for managing change. These methods include publication, seminars, workshops, websites, social media, webinars, and other technology transfer mechanisms. Additionally, MTI promotes the availability of completed research to professional organizations and works to integrate the research findings into the graduate education program. MTI's extensive collection of transportation-related publications is integrated into San José State University's world-class Martin Luther King, Jr. Library.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and accuracy of the information presented herein. This document is disseminated in the interest of information exchange. MTI's research is funded, partially or entirely, by grants from the U.S. Department of Transportation, the California Department of Transportation, and the California State University Office of the Chancellor, whom assume no liability for the contents or use thereof. This report does not constitute a standard specification, design standard, or regulation.

Report 25-21

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

Yu-Fu Ko, PhD, PE

Jessica Gonzalez., EIT

October 2025

A publication of the
Mineta Transportation Institute
Created by Congress in 1991

College of Business
San José State University
San José, CA 95192-0219

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. 25-21	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle Sustainable Frameworks and Life Cycle Assessment for Reinforced Concrete Bridges for Sustainability in Transportation		5. Report Date October 2025	
		6. Performing Organization Code	
7. Authors Yu-Fu Ko, PhD, PE Jessica Gonzalez., EIT		8. Performing Organization Report CA-MTI-2440	
9. Performing Organization Name and Address Mineta Transportation Institute College of Business San José State University San José, CA 95192-0219		10. Work Unit No.	
		11. Contract or Grant No. SB1-SJAUX_2023-26	
12. Sponsoring Agency Name and Address State of California SB1 2017/2018 Trustees of the California State University Sponsored Programs Administration 401 Golden Shore, 5th Floor Long Beach, CA 90802		13. Type of Report and Period Covered	
		14. Sponsoring Agency Code	
15. Supplemental Notes 10.31979/mti.2025.2440			
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.			
17. Key Words Sustainable transportation, life cycle analysis, earthquake engineering, earthquake resistant structures, reinforced concrete bridges.		18. Distribution Statement No restrictions. This document is available to the public through The National Technical Information Service, Springfield, VA 22161.	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 33	22. Price

Copyright © 2025

by **Mineta Transportation Institute**

All rights reserved.

DOI: 10.31979/mti.2025.2440

Mineta Transportation Institute
College of Business
San José State University
San José, CA 95192-0219

Tel: (408) 924-7560
Fax: (408) 924-7565
Email: mineta-institute@sjsu.edu

transweb.sjsu.edu/research/2440

Acknowledgments

This research work was financially supported by the Mineta Transportation Institute (MTI) for Transport Year 7, 2024. The research team would like to sincerely thank MTI for the support received to accomplish this study.

Contents

Acknowledgments	vi
List of Figures	viii
List of Tables	ix
Executive Summary.....	1
1. Introduction	3
2. Descriptions of the Reinforced Concrete Bridge Selected for Assessment.....	6
2.1 The Canyon Road Overcrossing Reinforced Concrete Bridge	6
2.2 Structural Descriptions of the Reinforced Concrete Bridge.....	6
3. Study 1: Seismic Performance Assessment of the Selected Reinforced Concrete Bridge.....	9
3.1 Damage Indices and Seismic Performance Assessment.....	9
3.2 Fiber Based Material Damage Models	11
3.3 Nonlinear Finite Element Modeling Formulations.....	11
3.4 Seismic Performance Assessment Results of the Selected Reinforced Concrete Bridge.....	12
4. Study 2: Life Cycle Assessment of the Reinforced Concrete Bridge	14
4.1 Concept of Life Cycle Assessment	14
4.2 Concept of Life Cycle Assessment of Reinforced Concrete Structures.....	14
4.3 Life Cycle Assessment of the Selected Reinforced Concrete Bridge.....	15
Summary & Conclusions	18
Bibliography	20
About the Authors	23

LIST OF FIGURES

Figure 1. Reinforced Concrete Bridge Elevation 7

Figure 2. Reinforced Concrete Bridge Section..... 7

Figure 3. Reinforced Concrete Bridge Cross Section..... 8

Figure 4. Section Damage Index 9

Figure 5. Results of Damage Analysis 13

Figure 6. Global Warming Potential for Each LCA Stage..... 17

LIST OF TABLES

Table 1. Bridge Performance Assessment (Stone & Taylor, 1993, 1999)	10
Table 2. Definitions of Damage Index Levels (TRB, 2013)	10
Table 3. Selected Ground Motion Records.....	12
Table 4. LCA Measure by Life Cycle Stages: Stage 1 (Product)	16
Table 5. LCA Measure by Life Cycle Stages: Stage 2 (Construction Process)	16
Table 6. LCA Measure by Life Cycle Stages: Stage 3 (Use)	16
Table 7. LCA Measure by Life Cycle Stages: Stage 4 (End-of-Life)	17
Table 8. LCA Measure by Life Cycle Stages: Stage 5 (Beyond Building Life).....	17

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 CO₂, Stage 3 (Use, B2, B4, and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO₂. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO₂. 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 CO₂ from the chemical reaction. Additionally, the kilns require large amounts of energy to heat, mix, and cool the materials. This emission of CO₂ 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 CO₂ 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

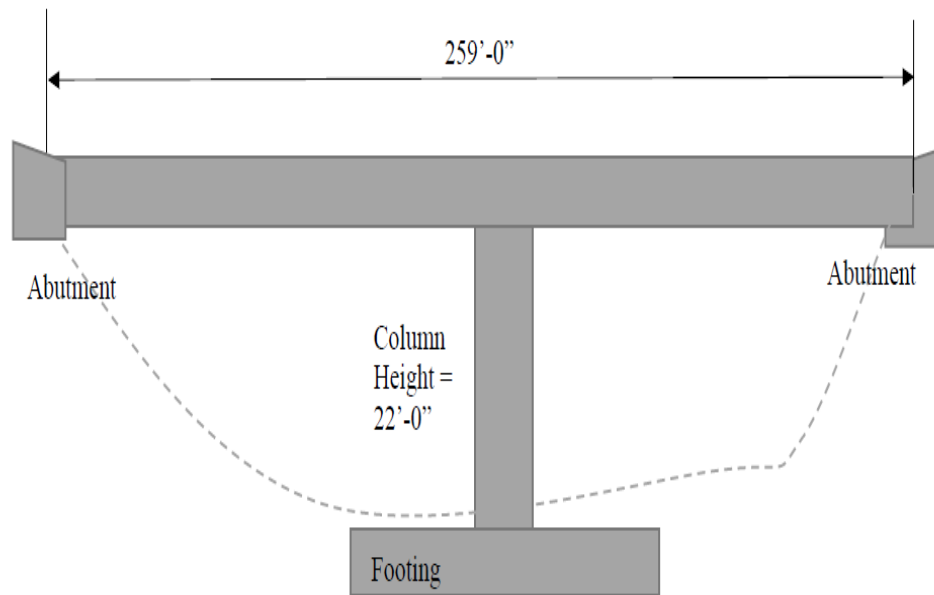


Figure 2. Reinforced Concrete Bridge Section

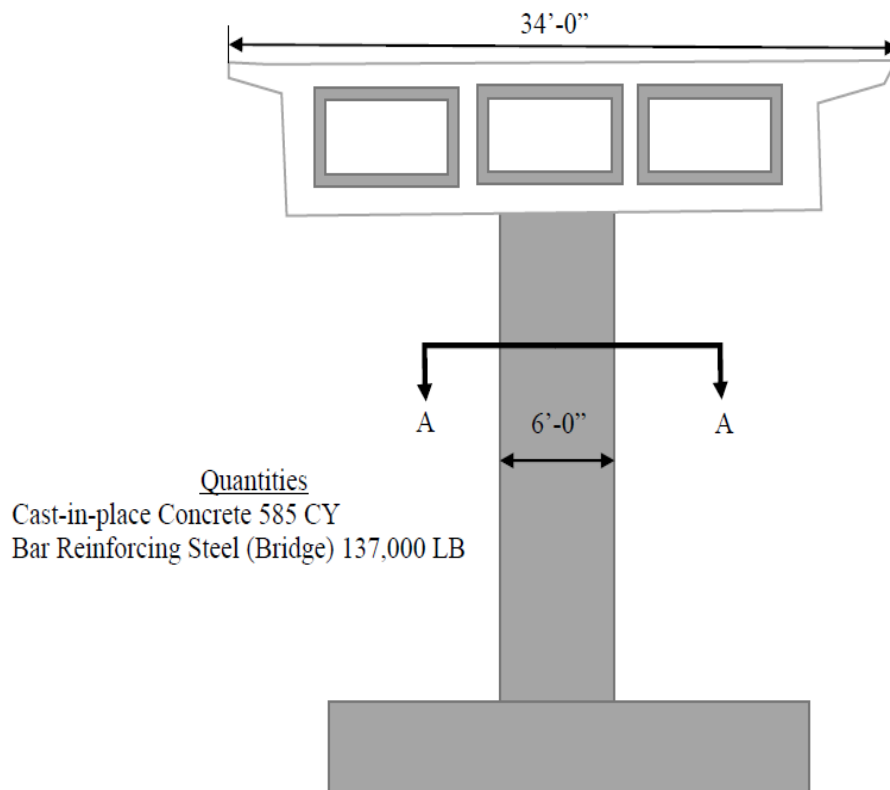
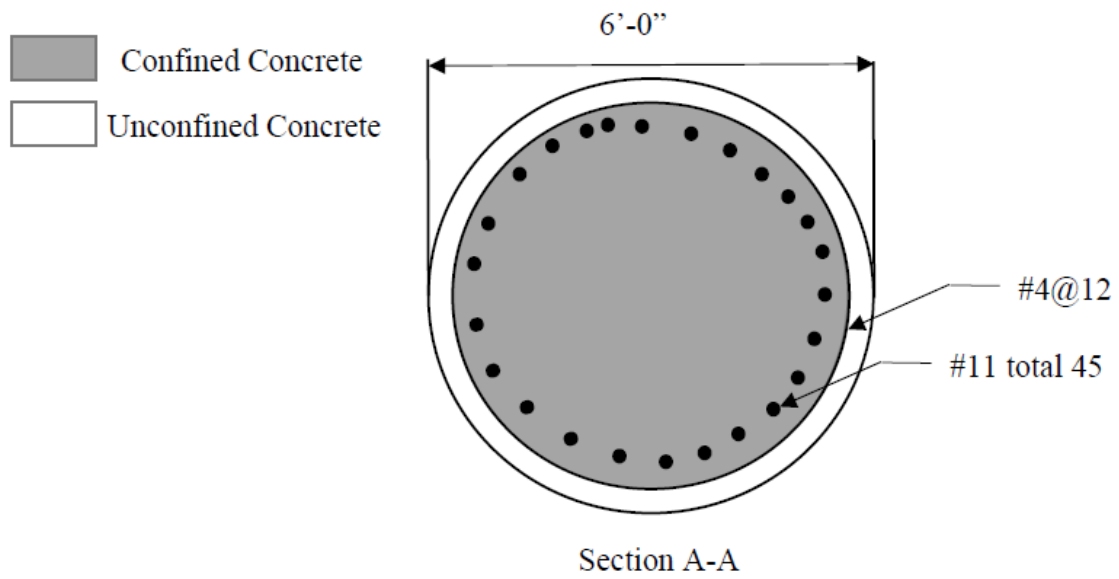


Figure 3. Reinforced Concrete Bridge Cross Section

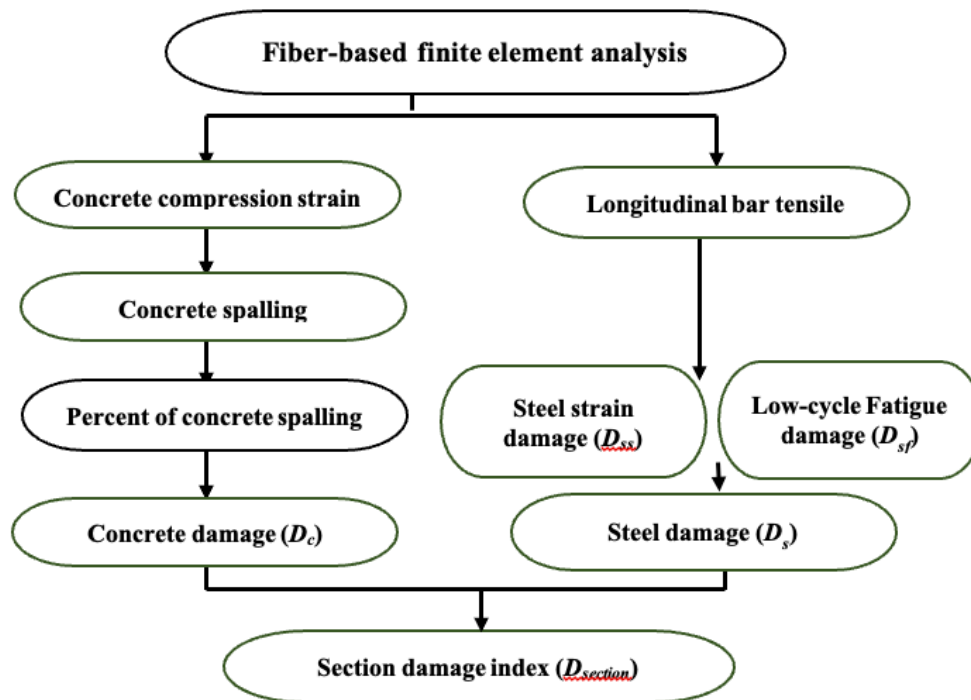


3. Study 1: Seismic Performance Assessment of the Selected Reinforced Concrete Bridge

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	$0.1 \leq D < 0.2$	Crack widening, first yielding of reinforcement	Operational
III	Moderate	$0.2 \leq D < 0.4$	Onset of cover concrete spalling	Limited damage
IV	Major	$0.4 \leq D < 0.6$	Significant spalling	Life safety
V	Local Failure/Collapse	$0.6 \leq D < 1.0$	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.

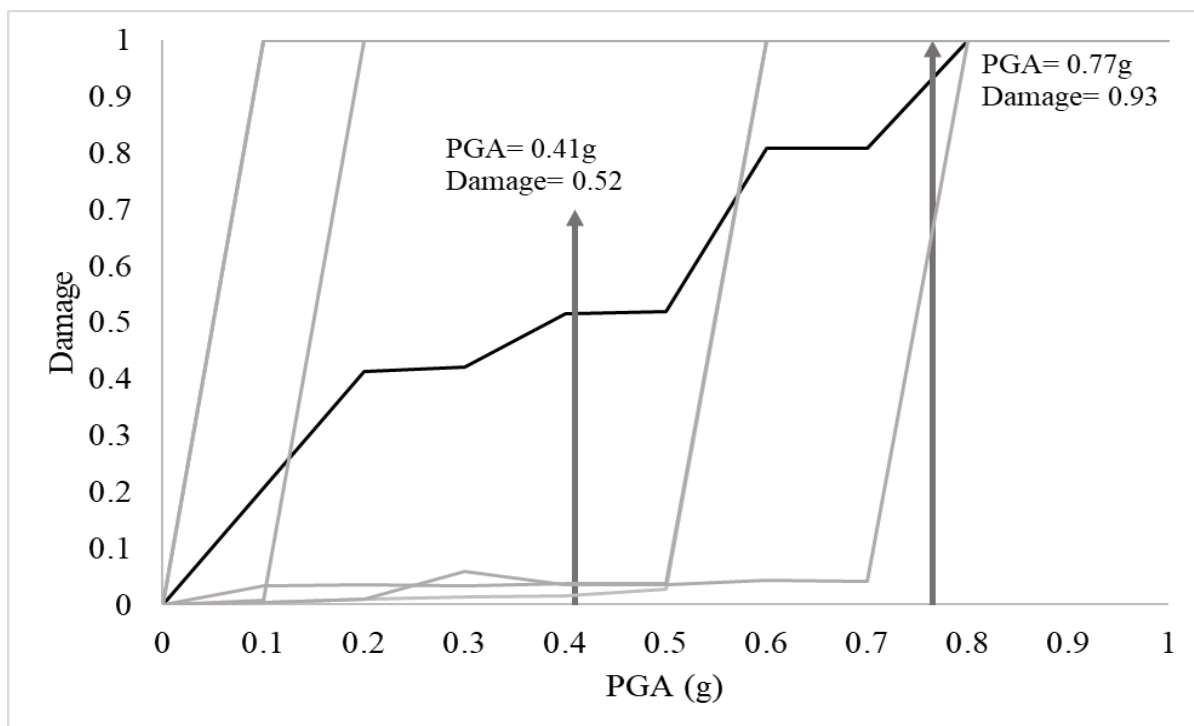
The PGAs of the ten selected earthquake ground motions were scaled from 0.1 g to 1.0 g in 0.1 g increments. Nonlinear time history analysis was conducted for each of these scaled ground motions using the proposed damage models and damage indices as described in Section 3 for the selected RC highway bridge 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 CO₂ 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 CO₂, Stage 3 (Use, B2, B4, and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO₂. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO₂.

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

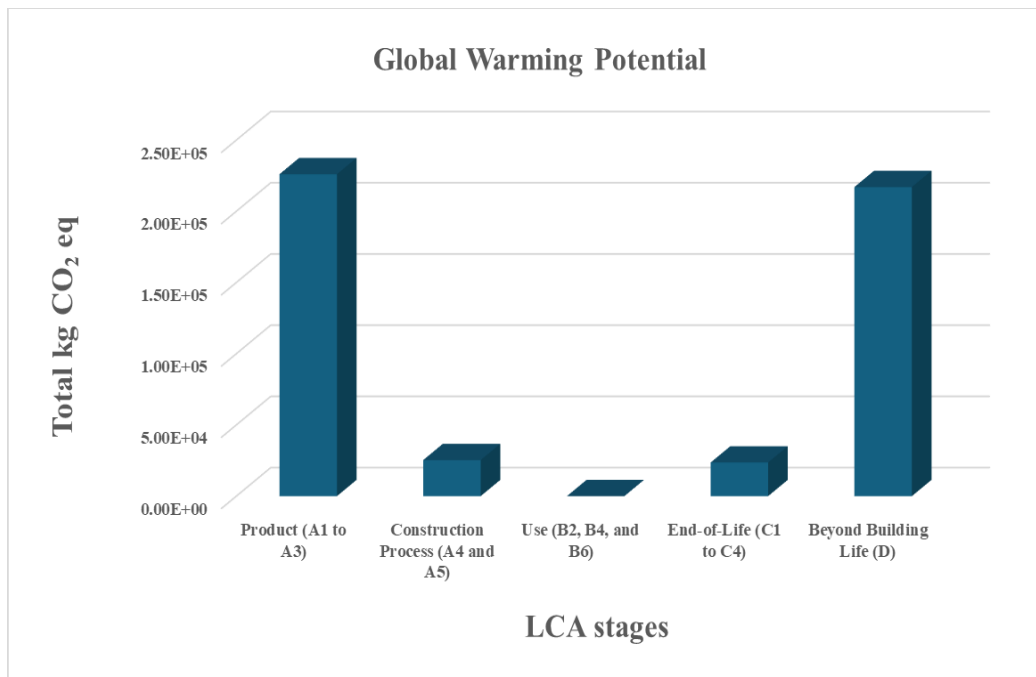
Table 7. LCA Measure by Life Cycle Stages: Stage 4 (End-of-Life)

		END-of-LIFE (C1 to C4)		
LCA Measures	Unit	De-construction, Demolition, Disposal & Waste Processing	Transport	Total
Global Warming Potential	kg CO ₂ 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 CO ₂ 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 CO₂, Stage 3 (Use, B2, B4,

and B6) had zero contribution in all stages of all areas as the structure itself does not emit any CO₂. Stage 2 (Construction Process, A4 and A5) and Stage 4 (End-of-Life, C1 to C4) contributed similar amounts of CO₂. 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.

Bibliography

- Bakkar M. A., Saha, R., & Das, D. (2021). Low cycle fatigue performance and failure analysis of reinforcing bar. *Metals and Materials International*, 27(12), 4952–4966.
- Black, L., & Purnell, P. (2016). Is carbon dioxide pricing a driver in concrete mix design? *Magazine of Concrete Research*, 68(11), 561–567.
- Bouhaya, L., Le Roy, R., & Feraille-Fresnet, A. (2009). Simplified environmental study on innovative bridge structure. *Environmental Science & Technology*, 43(6), 2066–2071.
- Brown, J., & Kunnath, S. K. (2004). Low-cycle fatigue failure of reinforcing steel bars. *ACI Materials Journal*, 101(6), 457–466.
- Chen, E., Berrocal, C. G., Löfgren, I., & Lundgren, K. (2021). Comparison of the service life, life-cycle costs and assessment of hybrid and traditional reinforced concrete through a case study of bridge edge beams in Sweden. *Structure and Infrastructure Engineering*, 19(1), 39–57. <https://doi.org/10.1080/15732479.2021.1919720>
- Dhakar, R. P., & Maekawa, K. (2002). Modeling for postyield buckling of reinforcement. *Journal of Structural Engineering*, 128(9), 1139–1147.
- Du, G. (2015). *Life cycle assessment of bridges, model development and case studies* [Doctoral dissertation, KTH Royal Institute of Technology].
- Feng, Y., Kowalsky, M. J., & Nau, J. M. (2014). Effect of seismic load history on deformation limit states for longitudinal bar buckling in RC circular columns. *Journal of Structural Engineering*, 141(8), 04014187.
- Goodnight, J. C. (2015). *The effects of load history and design variables on performance limit states of circular bridge columns* (Vol. 1). Alaska DOT & PF.
- Goodnight, J. C., Kowalsky, M. J., & Nau, J. M. (2016). Strain limit states for circular RC bridge columns. *Earthquake Spectra*, 32(3), 1627–1652.
- Itoh, Y., & Kitagawa, T. (2003). Using CO₂ emission quantities in bridge lifecycle analysis. *Engineering Structures*, 25(5), 565–577.
- Ko, Y.-F. (2022). Finite element analysis of reinforced concrete single-column bridge bent with flexural failure under near-fault ground motion. *International Journal of Civil Engineering*, 20(3), 237–256.

- Ko, Y.-F., & Gonzalez, J. (2023). *Fiber-based seismic damage and collapse assessment of reinforced concrete single-column pier-supported bridges using damage indices*. Mineta Transportation Institute. <https://doi.org/10.31979/mti.2023.2241>
- Ko, Y.-F., & Gonzalez, J. (2024). *Effects of low-cycle fatigue fracture of longitudinal reinforcing steel bars on the seismic performance of reinforced concrete bridge piers*. Mineta Transportation Institute. <https://doi.org/10.31979/mti.2024.2328>
- Manjunatha, M., Preethi, S., Mounika, H. G., & Niveditha, K. N. (2021). Life cycle assessment (LCA) of concrete prepared with sustainable cement-based materials. *Materials Today: Proceedings*, 47, 3637–3644.
- McKenna, F., Fenves, G. L., & Scott, M. H. (2000). Open system for earthquake engineering simulation [Computer software].
- Mostafaei, H., Badarloo, B., Chamasemani, N. F., Rostampour, M. A., & Lehner, P. (2023). Investigating the effects of concrete mix design on the environmental impacts of reinforced concrete structures. *Buildings*, 13(5), 1313.
- Peer Ground Motion Database. (n.d.). Retrieved from <https://ngawest2.berkeley.edu/>
- Penadés-Plà, V., Martínez-Muñoz, D., García-Segura, T., Navarro, I. J., & Yepes, V. (2020). Environmental and social impact assessment of optimized post-tensioned concrete road bridges. *Sustainability*, 12(10), 4265–4283.
- Stone, W. C., & Taylor, A. W. (1993). *Seismic performance of circular bridge columns designed in accordance with aashto/caltrans standards*. National Institute of Standards and Technology.
- Stone, W. C., & Taylor, A. W. (1999). *Performance evaluation database for concrete bridge components and systems under simulated seismic loads*. Pacific Earthquake Engineering Research Center.
- Su, J., Dhakal, R. P., & Wang, J. (2017). Fiber-based damage analysis of reinforced concrete bridge piers. *Soil Dynamics and Earthquake Engineering*, 96, 13–34.
- Tait, M. W., & Cheung, W. M. (2016). Comparative cradle-to-gate life cycle assessment of three concrete mix designs. *The International Journal of Life Cycle Assessment*, 21(6), 847–860.
- TRB (2013). *Performance-based seismic bridge design*. National Cooperative Highway Research Program.

- Tripathi, M., Dhakal, R. P., & Dashti, F. (2019a). Bar buckling in ductile RC walls with different boundary zone detailing: Experimental investigation. *Engineering Structures*, 198, 109544.
- Tripathi, M., Dhakal, R. P., & Dashti, F. (2019b). Low-cycle fatigue damage of buckling prone reinforcing bars. *New Zealand Society for Earthquake Engineering*, 1–9.
- Van den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment (LCA) of traditional and “green” concretes: Literature review and theoretical calculations. *Cement & Concrete Composites*, 34(4), 431–442.
- Zimoch, E. (2012). *Life-cycle assessment (LCA) of existing bridges and other structures*. Universitat Politècnica de Catalunya.

About the Authors

Yu-Fu Ko, PhD, PE

Dr. Ko joined the California State University, Long Beach (CSULB) Civil Engineering and Construction Engineering Management Department in Fall 2009. He received his B.S. in Structural Engineering from National Taiwan University of Science and Technology and his M.S. and Ph.D. (as an outstanding Ph.D. award recipient) in Civil Engineering, focusing on Structural Mechanics and Structural Engineering/Dynamics, from the University of California, Los Angeles (UCLA). Prior to joining CSULB, Dr. Ko was a postdoctoral researcher and lecturer at UCLA and a senior structural design engineer at Englekirk and Sabol Consulting Structural Engineers, Inc. He is a registered Professional Civil Engineer in the state of California. Dr. Ko's areas of research include micro/nano-mechanics modeling of heterogeneous composite materials, micromechanical damage mechanics modeling and associated applications, damage assessment and experimental mechanics of structural materials, nonlinear/linear structural dynamic analysis of structures subjected to earthquake motions, finite element method code-based and performance-based structural design of structures, and seismic retrofitting of existing structures. He has presented at national and international conferences and published research papers in national and international peer-reviewed journals. He actively participates in ASCE, ASME, AISC, ACI, SEAOSC, IACM, USACM, and other national and international societies. He is also a peer reviewer for numerous technical journals.

Jessica Gonzalez, EIT

Jessica Gonzalez is a research graduate assistant working with Dr. Ko at CSULB. She received her B.S. in Civil Engineering from CSULB with cum laude degree honors and is currently enrolled as a graduate student working towards her master's degree. She is certified as an Engineer-in-Training (EIT) and is currently employed as a structural designer at RailPros, Inc. Her research interests include finite element modeling of bridges and seismic analyses of bridge components. Additionally, her software skills include AutoCAD and OpenSees.

MTI FOUNDER

Hon. Norman Y. Mineta

MTI BOARD OF TRUSTEES

Founder, Honorable Norman Mineta***
Secretary (ret.),
US Department of Transportation

Chair, Donna DeMartino
Retired Managing Director
LOSSAN Rail Corridor Agency

Vice Chair, Davey S. Kim
Senior Vice President & Principal,
National Transportation Policy &
Multimodal Strategy
WSP

Executive Director, Karen Philbrick, PhD*
Mineta Transportation Institute
San José State University

Rashidi Barnes
CEO
Tri Delta Transit

David Castagnetti
Partner
Dentons Global Advisors

Kristin Decas
CEO & Port Director
Port of Hueneme

Dina El-Tawansy*
Director
California Department of
Transportation (Caltrans)

Anna Harvey
Deputy Project Director –
Engineering
Transbay Joint Powers Authority
(TJPA)

Kimberly Haynes-Slaughter
North America Transportation
Leader,
TYLin

Ian Jefferies
President and CEO
Association of American Railroads
(AAR)

Priya Kannan, PhD*
Dean
Lucas College and
Graduate School of Business
San José State University

Therese McMillan
Retired Executive Director
Metropolitan Transportation
Commission (MTC)

Abbas Mohaddes
Chairman of the Board
Umovity Policy and Multimodal

Jeff Morales**
Managing Principal
InfraStrategies, LLC

Steve Morrissey
Vice President – Regulatory and
Policy
United Airlines

Toks Omishakin*
Secretary
California State Transportation
Agency (CALSTA)

Sachie Oshima, MD
Chair & CEO
Allied Telesis

April Rai
President & CEO
COMTO

Greg Regan*
President
Transportation Trades Department,
AFL-CIO

Paul Skoutelas*
President & CEO
American Public Transportation
Association (APTA)

Rodney Slater
Partner
Squire Patton Boggs

Lynda Tran
CEO
Lincoln Room Strategies

Matthew Tucker
Global Transit Market Sector
Director
HDR

Jim Tymon*
Executive Director
American Association of
State Highway and Transportation
Officials (AASHTO)

K. Jane Williams
Senior Vice President & National
Practice Consultant
HNTB

* = Ex-Officio
** = Past Chair, Board of Trustees
*** = Deceased

Directors

Karen Philbrick, PhD
Executive Director

Hilary Nixon, PhD
Deputy Executive Director

Asha Weinstein Agrawal, PhD
Education Director
National Transportation Finance Center Director

Brian Michael Jenkins
Allied Telesis National Transportation Security Center

