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Abstract

Assessing embodied carbon can drive innovation in materials, structural systems, and design practices that strengthen both disaster resilience and resource efficiency. This project aims to enhance the industry's capacity to assess the embodied carbon of resilient buildings by delivering a new method and tool. This can improve the competitiveness of U.S. industry in the global market. Pelicun is an open-source software package developed by the Natural Hazards Engineering Research Infrastructure's (NHERI) Computational Modeling and Simulation Center (SimCenter) to evaluate building damage and losses resulting from natural hazard events. Based on the Pelicun framework, we develop a Python library, Pelicun-LCA, which utilizes a hybrid method to probabilistically quantify the embodied carbon associated with post-disaster building repairs. This method considers the direct impact of repair materials and the indirect impact of repair processes, including construction equipment, labor travel, debris disposal, and occupant displacement. This method combines detailed process analysis with comprehensive input-output analysis to improve the accuracy and completeness of carbon assessments. However, due to its added complexity and substantial computational workload, automated calculation tools are essential for practical application. This report presents the technical details of Pelicun-LCA, a tool that streamlines the probabilistic assessment of embodied carbon in post-disaster building repairs. Pelicun-LCA has three key features: detailed embodied carbon breakdowns, built-in design databases for various building archetypes, and parallel processing for cross-building comparisons. Eighteen design variants targeting different seismic performances are examined to demonstrate the capabilities of Pelicun-LCA. Finally, this report discusses the potential applications and limitations of Pelicun-LCA to help users develop effective case studies.

Keywords

Building repairs, embodied carbon, hybrid method, functional recovery, seismic resilience, repair materials, construction equipment, labor travel, debris disposal, occupant displacement

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1. Introduction

This report presents a tool, along with the underlying method, for quantifying the embodied carbon impact of post-disaster building repairs. Repair-related embodied carbon has long been overlooked due to the difficulty in predicting the timing and location of hazard events and the limited methods and tools for quantifying these impacts [3]. Assessing the embodied carbon associated with post-disaster repairs is essential for a complete understanding of a building's life cycle performance [2, 4, 5]. Moreover, **such assessment can support the development of innovative materials and systems, as well as engineering practices that enhance both structural integrity and resource efficiency [2, 6], thereby strengthening the competitiveness of the U.S. building industry in the global market**.

The development of such a method and tool is a direct response to industry needs. By 2025, a total of 172 firms across North America and globally had committed to the Structural Engineers 2050 Commitment Program (SE2050). This US based program seeks to transform structural engineering practice toward net-zero embodied carbon[1] structural systems by 2050 [1]. To support this initiative, the Structural Engineering Institute of the American Society of Civil Engineers released a Prestandard for Assessing the Embodied Carbon of Structural Systems for Buildings, aiming to establish a consistent framework for evaluating and comparing the embodied carbon of structural systems [1, 46]. Compared with the Prestandard, our method places greater emphasis on resilient buildings by incorporating nonstructural components, accounting for natural hazard risks, and considering post-disaster repair impacts [12]. Recent studies have attempted to incorporate seismic risks into building life cycle assessments (LCAs). For example, Huang and Simonen [3] examined five types of structural systems with identical layouts and heights in Northern California and found that Risk Category (RC) IV buildings have lower embodied carbon than RC-II buildings due to more stringent seismic design requirements and less damage during seismic events. Welsh-Huggins and Liel [7] indicated that in highly seismic regions, enhancing lateral strength of reinforced concrete buildings can reduce the life-cycle embodied carbon losses, which is enough to offset the higher upfront embodied carbon from constructing larger structural members. Gonzalez et al. [8] analyzed a four-story steel moment frame building in New Zealand and suggested that designing stronger and stiffer buildings could reduce annual embodied carbon by 7.9 % compared to code-compliant buildings when seismic risk is considered. Aljawhari et al. [9] analyzed three reinforced concrete residential buildings of different heights in Italy and indicated that annual embodied carbon impacts due to earthquakes could be 57 % lower for modern buildings than those constructed before the 1970s.

Some studies have applied LCA results to improve design schemes. For example, Horiuchi and Wang [10] compared eight lateral force-resisting systems of constructed buildings with similar height and seismic exposure, and suggested that for concrete structures, shear wall buildings tend to have higher embodied carbon compared to moment frame buildings. Even though

[1] Embodied carbon refers to the CO_2 equivalent emissions resulting from the manufacturing, transportation, installation, maintenance, replacement, and disposal of construction materials used in buildings [1, 2].

moment frame buildings might be less effective in resisting lateral loads, shear walls may introduce underutilized concrete materials. For steel structures, braced frames tend to have less embodied carbon when compared to similar structures using moment frames [10]. Moreover, Comber et al. [11] indicated that the annualized embodied carbon impact of the standard shear wall system is 22 % less than that of the concrete moment frame system, and the annualized impact of the isolated shear wall system is 94 % less than that of the standard shear wall system. These findings are not always consistent due to the many factors in play, such as LCA methods and tools [4], underscoring the need to standardize embodied carbon assessment for buildings.

The tool presented in this report aims to improve the accuracy, transparency, efficiency, and standardization of building performance assessments. The input–output method[2] adopted by exiting tools provides an industry-average estimate of carbon emissions, which cannot fully reflect the characteristics and performance of individual buildings [2, 3, 12, 13]. To address this limitation, we proposed using a hybrid method to assess the embodied carbon impact of post-disaster building repairs and functional losses [12]. This method considers the direct impact of repair materials and the indirect impact of repair processes, which is often overlooked. However, the indirect impact, such as transporting materials and debris, using construction equipment, traveling to damaged buildings for labor, and displacing occupants due to the temporary loss of building functions, can account for a significant proportion of the total embodied carbon impact resulting from building repairs [12, 14].

Moreover, the hybrid method incorporates component-level estimates of damage probabilities and repair consequences generated using the Federal Emergency Management Agency (FEMA) P-58 methodology [13], enabling a detailed, probabilistic carbon assessment. The method then combines process analysis[3] with input-output analysis to quantify the embodied carbon associated with repair materials, material transport, construction equipment, labor travel, debris disposal, and occupant displacement. Although a hybrid method is more complex and computationally intensive than an input–output method, it provides a more accurate and complete assessment of the embodied carbon impacts of post-disaster repairs [12, 13].

To streamline hybrid analysis, we developed Pelicun-LCA, an automated tool that couples FEMA P-58 outputs with carbon calculations through the Pelicun framework [15]. Pelicun-LCA provides a detailed breakdown of the embodied carbon associated with building repairs, as well as embedded design databases for concrete moment frame, concrete shear wall, and steel moment frame buildings. It also offers the option of parallel computing for cross-building comparisons. The tool is freely accessible from the National Institute of Standards and Technology (NIST) GitLab[4] and includes installation, use, and troubleshooting instructions.

This report is organized as follows: Section 2 introduces the Pelicun-LCA library. Section 3 provides use cases for Pelicun-LCA. Three building types with improved earthquake resilience

[2] Input-output analysis converts repair cost estimates to carbon emission results. It does not require detailed repair assumptions or an in-depth understanding of manufacturing and construction processes.
[3] Process analysis quantifies the material quantities necessary to repair or replace damaged components based on detailed accounting of the repair actions needed for each component and each damage state.
[4] https://gitlab.nist.gov/ynz23/pelicun-lca

are examined to demonstrate the capability of the tool. Section 4 discusses the applications and limitations of Pelicun-LCA. It also summarizes and concludes this report.

2. Pelicun-LCA

Pelicun-LCA is a standalone Python library that leverages the Pelicun framework [15] to assess potential impacts of building damage and repair due to earthquakes. The next section reviews commonly used tools for building damage and loss assessment. The sections that follow introduce the Pelicun library and the Pelicun-LCA library, respectively.

2.1. Tools for building damage and loss assessment

Table 1 outlines five tools for assessing building damage and losses due to natural hazards. Hazus is a Geographic Information System (GIS) based risk assessment tool. It can be applied to assess potential disaster losses, identify effective mitigation strategies, develop response and preparedness plans, and support real-time emergency response efforts [16]. The Hazus database provides an inventory of structures, buildings, and facilities for any location in the United States, as well as hazard information, such as the extent and severity of earthquakes. It also offers a collection of damage functions for estimating the potential impact of hazards. Several computational tools have been developed based on the Hazus framework to quantify the embodied carbon associated with seismic damage, such as the Environmental Analysis Tool [6, 17, 18].

The Performance Assessment Calculation Tool (PACT) and the Seismic Performance Prediction Platform (SP3) both implement the FEMA P-58 performance-based assessment methodology to evaluate damage and losses for individual buildings. PACT adopts the second edition of the methodology, while SP3 uses its own unpublished version. The performance-based assessment can help researchers and practitioners to identify the vulnerability of building components and to prioritize design or retrofit of building systems for risk reduction. In addition, SP3 incorporates a state-of-the-art methodology for downtime estimation, accounting for both repair time and time delays due to impeding factors, as well as repair pathways tailored to the specific needs of tenants [19, 20]. However, SP3 currently does not account for carbon effects in its risk assessment, and PACT employs an input-output method from FEMA P-58.

The Interdependent Networked Community Resilience Modeling Environment (IN-CORE) is a web-based software platform that helps decisionmakers to assess and enhance community resilience. IN-CORE offers a suite of physical, social, and economic metrics that align with community-level resilience goals [21]. These metrics include damage and functionality of physical infrastructure, household and population characteristics at the Census block level, and establishments and jobs by industry and worker characteristics [22]. IN-CORE utilizes state-of-the-art models to simulate the performance and recovery of interdependent infrastructure under natural hazards and to assess the resulting social and economic impacts. The assessments can inform design, retrofitting, and recovery planning strategies. Currently, the platform does not assess the carbon emissions associated with post-disaster recovery.

Table 1. State-of-the-art tools for building damage and loss assessment.

Tool	**Hazus** [16]	**PACT** [13]	**SP3** [27]	**IN-CORE** [22]	**Pelicun** [15]
Year of release	1997	2012	2014	2018	2019
Publisher	FEMA	FEMA	Haselton Baker Risk Group	NIST CoE	NHERI SimCenter
Platform	Publicly available local GIS-based software package	Publicly available local software package	Proprietary web-based analysis platform	Publicly available web-based analysis platform	Open-source software package that can be run locally or in an HPC
Assessment method(s)	Hazus	FEMA P-58	FEMA P-58, ATC-138	Hazus and other custom models, CGE	Hazus, FEMA P-58, other models, and custom modeling options
Scale	Regional analysis	Individual buildings	Individual buildings	Regional analysis	Regional analysis or individual buildings
Hazard scenario	Earthquake, hurricane wind, flood, tsunami	Earthquake	Earthquake	Earthquake, flood, tornado, hurricane	Earthquake, flood, wind
Scope	Building damage, economic losses, displaced households, casualties, debris, and the loss of function for essential facilities	Repair costs, repair time, energy use, carbon emissions	Repair costs, recovery time (re-occupancy, functional recovery, full recovery)	Physical, social, and economic impacts	Repair costs, repair time, energy use, carbon emissions

Note: These tools are continuously maintained, updated, and improved. Therefore, the method, scale, scope, and platform summarized here can change over time.
FEMA = Federal Emergency Management Agency.
NIST = National Institute of Standards and Technology.

CoE = Center of Excellence for Risk-Based Community Resilience Planning.
NHERI = Natural Hazards Engineering Research Infrastructure.
GIS = Geographic Information System.
HPC = High Performance Computing.
ATC = Applied Technology Council.
CGE = Computable General Equilibrium.

The Probabilistic Estimation of Losses, Injuries, and Community Resilience under Natural Disasters (Pelicun) is part of computational tools developed by the Natural Hazards Engineering Research Infrastructure's (NHERI) Computational Modeling and Simulation Center (SimCenter) [15]. Pelicun has integrated various modeling approaches, from the detailed component-based FEMA P-58 methodology to the more approximate building-level Hazus approach [23]. Users can customize fragility and consequence functions and integrate Pelicun with other SimCenter workflows to simulate earthquake and hurricane effects on communities. However, Pelicun also employs an input-output method to quantify carbon emissions associated with building repairs.

2.2. Pelicun library

Pelicun is available as a free and open-source Python library, ready to be integrated into custom applications (e.g. SimCenter PBE [44]) using a well-defined Application Programming Interface [23]. The version used in this report (v.3.5.1) is composed of four primary models, which represent various steps of the generic Pelicun workflow [15]:

- `asset_model.py`, which reads a CSV file that contains component information, such as quantity, location, and direction.
- `demand_model.py`, which defines the marginal distribution and covariance of each demand variable (e.g., peak floor acceleration, inter-story drift ratio) either by calibrating raw demand data from a CSV file or by loading distribution parameters (e.g., mean, standard deviation) as inputs. It can generate a demand sample from these distributions and estimate residual inter-story drifts (an indicator for irreparable damage) based on peak inter-story drift values.
- `damage_model.py`, which loads damage model parameters, such as fragility curves that describe limit state exceedance probabilities, and one or more damage states assigned to each limit state exceedance. It organizes the demand data and calculates damage to each component.
- `loss_model.py`, which imports parameters for the consequence models of various decision variables (i.e., repair cost, repair time, energy consumption, carbon emission) and calculates the consequences of each component damage in the asset. After component-specific calculations, it aggregates repair consequences across components considering economies of scale.

Damage and loss assessment is conducted through classes and methods defined inside `assessment.py`, which integrates the four primary models into a single assessment module.

In addition, Pelicun integrates model parameters for various methodologies using data from two pairs of method-specific database files to facilitate performance-based assessment [45]. The following files were used for FEMA P-58 implementation in this report:

- `fragility.csv`, which is the FEMA P-58 fragility database. It lists the capacity of components for each limit state exceedance as a function of engineering demand variables (median and coefficient of variance) for each component.
- `consequence_repair.csv`, which is the FEMA P-58 repair consequence model database. It provides estimates for the median and coefficient of variance of repair costs, repair times, energy consumption, and carbon emissions corresponding to the repair of each component and damage state. By default, carbon emissions are calculated directly from the repair cost estimates using the input-output method. The method maps building components to their respective industry sectors and converts repair costs to carbon emissions via an input-output table. The table describes the relationship between the production input and output of various industrial sectors.
- `consequence_repair.json`, which is a supplemental metadata file for the FEMA P-58 consequence models. It provides damage descriptions and repair action assumptions for each component.

The inputs of Pelicun include three data files:

- `config.json`, which defines the models, units, and sample sizes for the assessment.
- `CMP_QNT.csv`, which defines the component type, quantity, and location for the building components to be assessed.
- `response.csv`, which contains response information for the building and is used as inputs for the demand model.

The outputs of Pelicun are as follows:

- `CMP*.csv`, which provides asset/component quantities.
- `DEM*.csv`, which provides demand/response information.
- `DMG*.csv`, which provides the quantity of damaged components at the component, group, or building level.
- `DV_repair*.csv`, which describes repair costs, repair time, energy use, and carbon emissions at the component, group, or building level.
- `DL_summary*.csv`, which provides a summary of damage and loss assessment results.

The asterisk (*) represents any sequence of characters, including an empty string. It should be noted that how economies of scale is considered can affect the damage and loss assessment results. The quantity of damaged components can be aggregated across floors of the building and/or across damage states. Four aggregation options are available in Pelicun:

- All floors and all damage states (adopted by PACT)

- All floors but only the given damage state (adopted by SP3)
- All damage states but only the given floor
- Only the given floor and only the given damage state (adopted by Pelicun-LCA)

The FEMA P-58 methodology considers economies of scale by applying a reduction to repair consequences when the quantity of damage exceeds a threshold.

2.3. Pelicun-LCA library

Figure 1 presents the workflow for Pelicun-LCA (or `LCA.py`). We created two databases to implement this workflow. The archetype building data (or `examples`) provides component information and response information for 18 design variants, including 3 structural types, 3 building heights, and 2 seismic design levels. Users can customize these archetype buildings for their specific research needs.

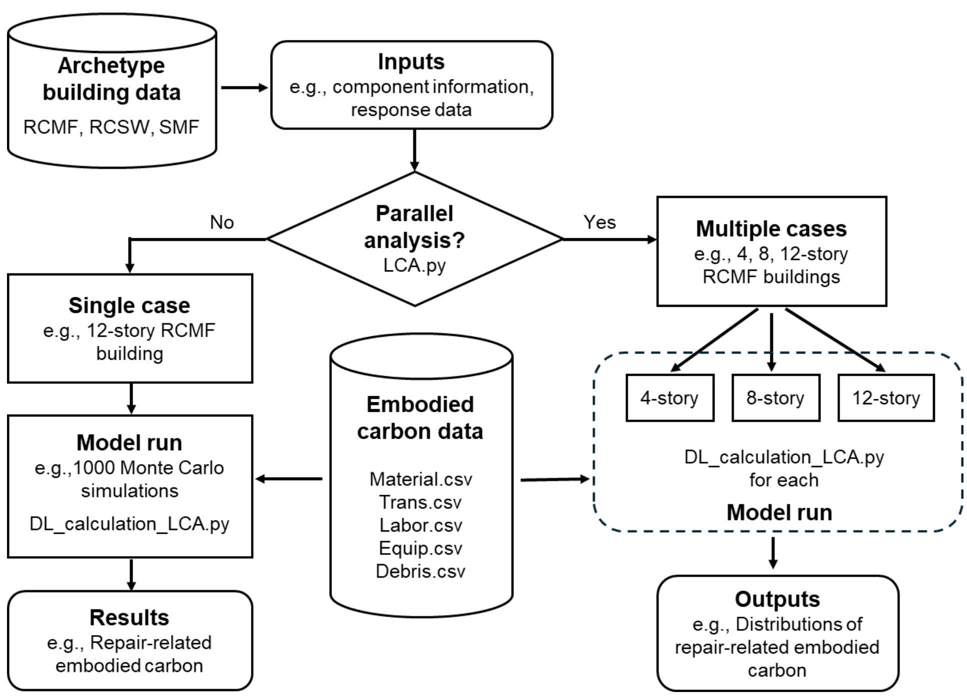

Figure 1. Workflow for Pelicun-LCA.

The embodied carbon data (or `database`) was collected from multiple sources (see Appendix A) and developed based on a set of repair assumptions (see Appendix B). The methodology is described in the following section. The data is structured as component ID by damage state, in accordance with the FEMA P-58 database, as illustrated in Figure 2. Five datafiles were created to describe the contribution of repair materials, material transport, construction equipment, labor travel, and debris disposal to the total embodied carbon impacts, respectively:

- `Material.csv`, which contains embodied carbon data for repair materials. The data is organized by component category and damage state, consistent with the FEMA P-58 consequence database.
- `Trans.csv`, which contains embodied carbon data for material transport from the manufacture to the site. The median distance from the manufacturer to the construction site (one-way) is assumed to be 155 miles (250 km) by default. Users can customize this value either by applying a scaling factor to the embodied carbon results for transportation, which scale linearly with distance, or by directly revising the CSV file for specific components.
- `Labor.csv`, which contains embodied carbon data for labor travel. The median travel distance to the damaged building (one-way) is assumed to be 12.4 miles (20 km) by default. The distance is double counted as employee commuting is a two-way travel, equal in distance. Users can customize this value either by applying a scaling factor to the embodied carbon results for labor, which scale linearly with distance, or by directly revising the CSV file for specific components. Note that we complied two files `Labor_max.csv` and `Labor_min.csv` to account for economies of scale. `Max` and `Min` correspond to the maximum and minimum labor travel per component damage state, respectively.
- `Equip.csv`, which contains embodied carbon data for construction equipment. Users can customize this value by directly revising the CSV file for specific components. Similarly, we complied two files `Equip_max.csv` and `Equip_min.csv` to account for economies of scale. `Max` and `Min` correspond to the maximum and minimum equipment use per component damage state, respectively.
- `Debris.csv`, which contains embodied carbon data for debris disposal. The median distance from the construction site to the landfill (one-way) is 30 miles (50 km) by default. Users can customize this value either by applying a scaling factor to the embodied carbon results for debris, which scale linearly with distance, or by directly revising the CSV file for specific components.

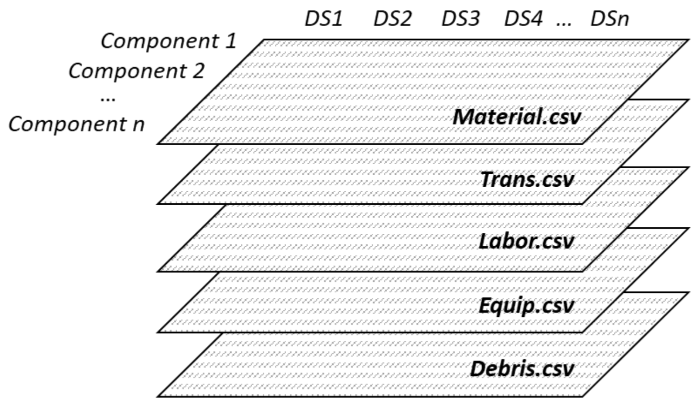

Figure 2. Data layers for hybrid analysis. *DS* refers to damage state.

The FEMA P-58 database contains more than 700 distinct building components [10], but a typical building consists of about 30 types of components. To improve computational efficiency, the five data files only contain the components relevant to the analysis, as specified in `CMP_QNT.csv`. Users can update embodied carbon data for specific components or damage states by modifying the five files directly.

In addition, Pelicun simulates a single return period of seismic hazards at a time. We developed a parallel analysis capability that allows multiple return periods to be evaluated simultaneously, thereby reducing total computation time. Users can enable parallel analysis in `LCA.py` on their personal computers or a high-performance computing environment.

The inputs for Pelicun-LCA are the same as Pelicun:

- `config.json`, in which we defined the model (FEMA P-58 earthquake), units, and sample sizes (2 500 Monte Carlo simulation runs) for our case study buildings.
- `CMP_QNT.csv`, in which we specified the category, number, and location of structural and nonstructural components for our case study buildings. Although user-input component units can be automatically converted to the default units, we chose to use the default units (FEMA P-58 repair database) when preparing this CSV file.
- `response.csv`, in which we specified peak floor accelerations and interstory drift ratios for each return period.

The outputs include default Pelicun outputs and two additional files:

- `embodied_carbon.csv`, which provides results for repair-related carbon emissions across different return periods and contributors.
- `building_embodied_carbon.csv`, which provides results for annual expected repair-related carbon emissions for the entire building.

2.3.1. Methodology

According to FEMA P-58, the annual carbon emission (EI) due to earthquakes can be calculated as follows [14]:

$$EI = \sum_{ds}\sum_{edp}\sum_{im} ei \times p(ds|edp)p(edp|im)p(im) \tag{1}$$

where ei is the embodied carbon impact associated with the damage state ds. Each damage state represents a severity level of damage to a building component, which requires a particular type and amount of repair effort. edp is the engineering demand parameter, used to quantify the damage to structural and nonstructural components. im is the intensity measure for seismic ground shaking. $p(x|y)$ is the exceedance probability of x given y.

The sources of uncertainty include seismic intensity, engineering demand parameters, damage states, and embodied carbon associated with a damage state. To quantify the uncertainty in annual embodied carbon, Monte Carlo simulation is employed in Pelicun-LCA to propagate uncertainties from building performance models to embodied carbon results.

The hybrid method [13] can be applied to quantify embodied carbon associated with damage states. Specifically, embodied carbon associated with building repairs (ei_{repair}) is calculated as the sum of embodied carbon resulting from materials ($ei_{material}$), associated with material transport from manufacture to site ($ei_{distribution}$), resulting from construction equipment ($ei_{equipment}$), resulting from labor travel (ei_{labor}), resulting from debris disposal (ei_{debris}), and resulting from occupant displacement ($ei_{displacement}$).

$$ei_{repair} = ei_{material} + ei_{distribution} + ei_{equipment} + ei_{labor} + ei_{debris} + ei_{displacement} \tag{2}$$

Equations 3 through 8 demonstrate how the mean of the distribution of each contributor is calculated. Embodied carbon resulting from materials is estimated by combining process analysis with input-output analysis. Table A1 in Appendix A summarizes the data sources for building materials and components employed in Pelicun-LCA. Input-output data [24, 25] is only used when process data is not available, such as seismic bracing, anchorages, and joints.

$$ei_{material} = q_m f_m \quad or \quad c_m f_c \tag{3}$$

where q_m is the quantity of material. f_m describes the carbon emission per quantity of material. c_m is material cost estimate. f_c translates costs to carbon emissions through input-output analysis.

$$ei_{distribution} = d_m f_t \tag{4}$$

where d_m is the distance of the manufacturer to the construction site. f_t is the carbon emission per transportation mode (e.g., trucks) and transportation distance.

$$ei_{equipment} = t_e f_e \tag{5}$$

where t_e is repair time. f_e is the carbon emission per energy type and energy use. Table A2 in the Appendix A summarizes the energy type and emission factor for typical construction equipment considered in Pelicun-LCA.

$$ei_{labor} = d_l\, f_t \tag{6}$$

where d_l is the travel distance from home to the damaged building. Assumptions for worker days vary by component type and damage state [24].

$$ei_{debris} = q_w d_w f_t \tag{7}$$

where q_w is the quantity of waste to be transported to the landfill. d_w is the distance of the construction site to the landfill.

Repair materials, material transport, construction equipment, labor travel, and debris disposal are evaluated at the component level based on a statistic of thousands of Monte Carlo model runs. Occupant displacement is evaluated at the building level and dependent on the probability of functional loss (repair time greater than zero) [34]. However, Pelicun currently does not have an embedded model for functional recovery assessment [19, 20, 26]. Therefore, we exclude occupant displacement in this analysis, as developing such a model is beyond the scope of this study.

The uncertainty of hybrid analysis stems from the process and input-output data sources. For process data, we assume that ei follows a normal distribution. The coefficient of variation is set to 0.2, corresponding to a $\pm$10 % deviation [12]. Negative values are truncated as embodied carbon cannot be negative. For input-output data, the uncertainty in ei is estimated to match the uncertainty in the repair cost, which follows a normal or a lognormal distribution. The coefficient of variation is directly related to that for repair cost and is computed by increasing it from the repair cost by 0.25 using the Square Root of the Sum of Squares (SRSS) approach [13].

The sources of uncertainty in the FEMA P-58 methodology, such as seismic intensities, demand parameters, damage states, and repair costs, are discussed in [13]. Pelicun currently does not support other types of uncertainty analysis, and therefore only Monte Carlo simulations are available in Pelicun-LCA.

3. Case study

To demonstrate the use of Pelicun-LCA, we examined eighteen building design variants. The next sections provide design information and response analyses for these buildings, as well as repair assumptions employed in Pelicun-LCA. The section following presents assessment results for embodied carbon associated with building repairs.

3.1. Building information

A set of archetype buildings were designed for downtown Los Angeles with a Seismic Design Category D and Site Class C. Table 2 summarizes the design parameters for these buildings. All buildings have a footprint of 120 ft × 120 ft (36.6 m × 36.6 m), first floor height of 15 ft (4.6 m), and 13 ft (4.0 m) height for floors above.

Reinforced Concrete Moment Frame (RCMF) buildings: The lateral system encompasses exterior frame lines in a perimeter frame configuration with five bays per side. The gravity system consists of 8 in (0.2 m) thick post-tensioned slabs and 20 gravity columns per story. Concrete compressive strength is 5 ksi (34.5 MPa) for beams and 7 ksi (48.3 MPa) for columns.

Reinforced Concrete Shear Wall (RCSW) buildings: Reinforced concrete shear walls are arranged around the perimeter of the building, spanning the entire height of the structure without significant punchouts, but reduced in length in the upper floors due to decreased loading conditions. The gravity system consists of 12 in (0.3 m) thick reinforced concrete slabs, supported by 25 gravity columns per story. Concrete compressive strength is 6 ksi (41.4 MPa) for shear walls and 7 ksi (48.3 MPa) for columns.

Steel Moment Frame (SMF) buildings: The steel moment frame is arranged equally around the perimeter of the building, spanning two or three bays per side, depending on the loading conditions. The gravity system consists of a composite floor slab system that distributes vertical loads into 25 wide flange gravity columns on each story. The floor slab is made of a 3.5 in (0.09 m) steel deck and a 2 in (0.05 m) concrete topping supported by purlins and girders.

Nonstructural systems are determined using the FEMA P-58 Normative Quantity Estimation Tool via SP3 [27], which provides quantity estimates based on building occupancy and square footage. It represents the type and quantity of nonstructural components typically present in office buildings in the United States. Please refer to [28] for more details about structural and nonstructural designs.

Table 2. Design variants for archetype RCMF, RCSW, and SMF buildings.

Story	Height (ft)	Floor area (ft^2)	Design criteria*	Importance factor	Drift ratio
4	54	57,600	RC II	1	2 %
			RC IV	1.5	1 %
8	106	115,200	RC II	1	2 %
			RC IV	1.5	1 %
12	158	172,800	RC II	1	2 %
			RC IV	1.5	1 %

Note: 1 ft = 0.3048 m. 1 ft^2 = 0.0929 m^2.

* Risk category II and Risk category IV buildings are designed per American Society of Civil Engineers (ASCE) 7-16 requirements [36].

3.2. Response analysis

The structural evaluation was carried out using OpenSees [29] for a suite of eight ground motions, representing hazard levels with 43, 72, 108, 224, 475, 975, 2475 and 4975-year return periods. The response models and simulation results have been archived in the NIST Building Archetype Model Database (BAM-DB)[5].The data are reformatted for use in Pelicun-LCA as follows:

- `pfa_summary.csv`, which provides peak floor accelerations (g) for up to 44 simulations per return period.
- `idr_summary.csv`, which provides inter-story drift ratios (no unit).

3.3. Assumptions

Repair assumptions are summarized in Appendix B for RCMF, RCSW, SMF, and nonstructural components. These assumptions are developed based on damage state description and repair action/activities defined in the FEMA P-58 database [24, 27], professional estimates of type and quantity [28], and published peer-review articles [30]. As noted earlier, we assume that median travel distance for labor to the damaged building in Los Angeles is 12.4 miles (20 km) [31],

[5] https://github.com/usnistgov/BAM-DB/tree/main

median distance from the manufacturer to the construction site is 155 miles (250 km) [32], and median distance from the construction site to the landfill is 30 miles (50 km) [33].

3.4. Results

The assessment results for annual embodied carbon associated with building repairs are presented in Figure 3. Two scenarios are evaluated to illustrate the uncertainty resulting from the hybrid method, as shown in Tables 3 and 4. Scenario 1 assumes that ei follows a normal distribution with a coefficient of variation of 0.2. Scenario 2 assumes a deterministic ei (i.e., a normal distribution with a coefficient of variation of 0.00001). For each case study building, the statistics are based on 2 500 Monte Carlo simulations. A comparison of the standard deviations in Tables 3 and 4 reveals that the uncertainty is primarily attributed to the FEMA P-58 methodology used to estimate the damage states.

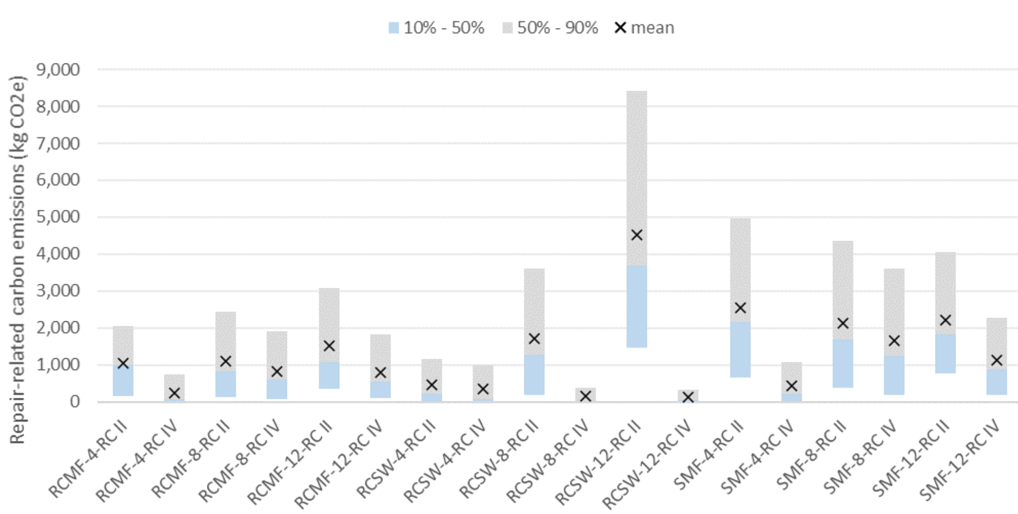

Figure 3. Annual embodied carbon associated with building repairs, mean and the 10th, 50th, and 90th percentiles.

Table 3. Annual embodied carbon associated with building repairs (Scenario 1).

Type	Story	Design	Embodied carbon (kg CO_2e)				
			Mean	**SD**	**10 %**	**50 %**	**90 %**
RCMF	4	RC II	1 039.7	10 005.6	157.8	990.7	2 038.7
		RC IV	235.8	5 817.2	1.4	71.2	750.8
	8	RC II	1 091.1	12 719.5	124.2	821.1	2 438.0
		RC IV	821.3	12 657.1	65.2	601.8	1 906.5
	12	RC II	1 506.1	21 611.0	347.8	1 071.7	3 078.0
		RC IV	786.8	11 715.8	85.2	553.7	1 826.4
RCSW	4	RC II	465.6	9 048.5	8.4	202.1	1 148.9
		RC IV	353.5	8 196.1	0.5	62.8	989.3
	8	RC II	1 709.7	19 093.9	184.8	1 265.2	3 600.0
		RC IV	156.4	6 957.1	0.4	24.3	366.9
	12	RC II	4 524.3	32 848.0	1 449.3	3 686.3	8 413.3
		RC IV	129.5	6 104.1	0.8	39.3	320.4
SMF	4	RC II	2 536.1	13 747.8	655.8	2 161.5	4 958.9
		RC IV	420.6	6 225.2	15.9	208.9	1 083.0
	8	RC II	2 129.5	17 870.6	367.3	1 675.2	4 355.7
		RC IV	1 643.4	16 163.2	186.6	1 226.5	3 603.6
	12	RC II	2 202.8	17 211.9	779.8	1 820.5	4 043.4
		RC IV	1 114.3	13 207.5	191.0	872.0	2 264.7

SD = standard deviation.

Table 4. Annual embodied carbon associated with building repairs (Scenario 2).

Type	Story	Design	Embodied carbon (kg CO_2e)				
			Mean	**SD**	**10 %**	**50 %**	**90 %**
RCMF	4	RC II	1 039.2	9 940.7	161.0	999.3	2 020.6
		RC IV	235.1	5 771.6	1.4	71.5	749.1
	8	RC II	1 090.4	12 676.7	126.4	829.2	2 414.3
		RC IV	821.1	12 640.8	65.5	598.3	1 905.1
	12	RC II	1 505.4	21 506.5	347.3	1 076.1	3 077.9
		RC IV	786.6	11 643.1	85.3	560.0	1 816.5
RCSW	4	RC II	468.2	8 847.9	9.5	209.3	1 174.0
		RC IV	351.4	8 036.6	0.6	64.0	1 019.4
	8	RC II	1 709.6	19 093.9	184.8	1 265.2	3 600.0
		RC IV	156.4	6 644.9	0.4	25.0	382.3
	12	RC II	4 721.1	33 993.3	1 528.5	3 860.2	8 870.4
		RC IV	120.1	5 405.1	0.8	36.2	285.3
SMF	4	RC II	2 529.8	13 546.1	666.1	2 169.7	4 873.5
		RC IV	419.9	6 205.6	15.7	210.3	1 091.0
	8	RC II	2 127.5	17 860.8	373.7	1 667.8	4 321.0
		RC IV	1 642.7	16 164.1	187.3	1 225.3	3 555.9
	12	RC II	2 220.3	17 053.4	786.0	1 826.3	4 055.8
		RC IV	1 112.9	13 172.2	192.6	873.7	2 252.4

SD = standard deviation.

Table 5 and Figure 4 present the breakdown results for annual embodied carbon associated with building repairs. Repair materials account for a large proportion of the total emissions, followed by construction equipment, material transport, labor travel, and debris disposal. Occupant displacement is not included in the assessment because Pelicun currently does not have an embedded model for assessing functional recovery of buildings. In addition, RC IV buildings consistently lead to lower embodied carbons than RC II counterparts.

Table 5. Breakdown results for annual embodied carbon associated with building repairs, the 50th percentile of each contributor.

Type	Story	Design	Embodied carbon (kg CO_2e)				
			Repair materials	Material transport	Construction equipment	Labor travel	Debris disposal
RCMF	4	RC II	875.1	42.0	86.2	61.6	8.4
		RC IV	200.4	10.0	17.8	13.6	2.0
	8	RC II	926.4	41.5	69.0	79.0	8.3
		RC IV	701.0	31.5	49.4	58.4	6.3
	12	RC II	1 338.2	49.0	66.8	81.5	9.8
		RC IV	665.8	33.0	49.9	57.9	6.6
RCSW	4	RC II	404.0	15.4	17.5	37.9	3.1
		RC IV	307.7	12.3	12.5	28.3	2.5
	8	RC II	1 483.1	50.6	66.7	139.5	10.1
		RC IV	132.9	5.4	5.0	16.5	1.1
	12	RC II	3 997.8	109.0	162.7	320.2	21.8
		RC IV	111.8	5.0	4.3	11.3	1.0
SMF	4	RC II	2 395.4	52.0	30.7	89.3	10.4
		RC IV	395.0	14.0	5.8	14.2	2.8
	8	RC II	1 967.4	52.0	22.1	119.2	10.4
		RC IV	1 518.2	43.0	17.2	90.7	8.6
	12	RC II	2 029.2	58.5	25.5	124.8	11.7
		RC IV	1 034.5	30.5	12.5	55.3	6.1

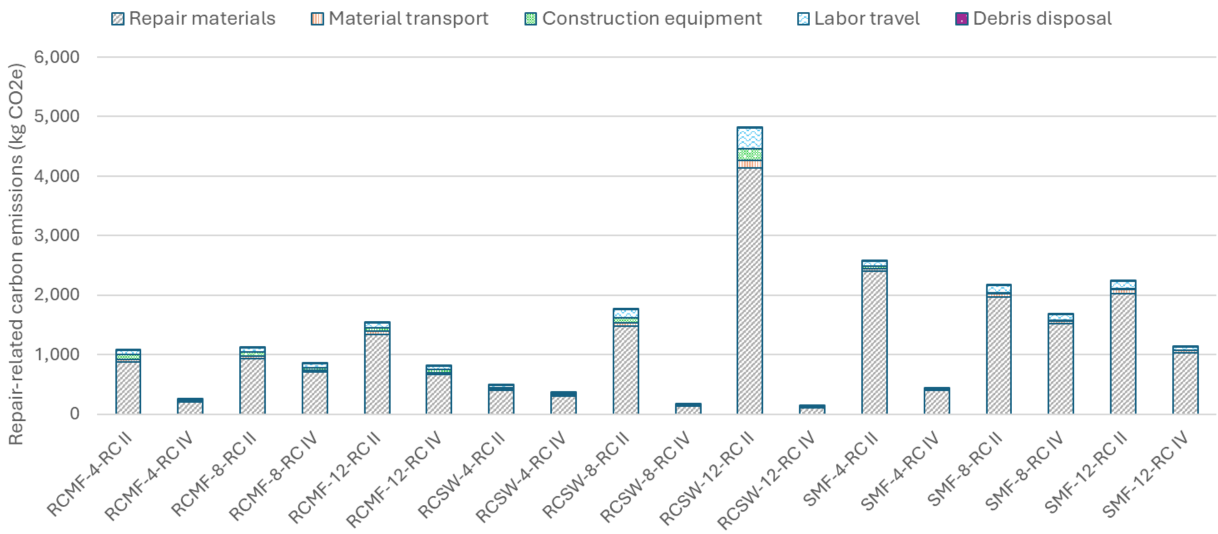

Figure 4. Annual average embodied carbon associated with building repairs.

Figures 5 and 6 compare embodied carbon impacts to repair costs (building-level impacts) and total economic losses (building and community-scale impacts) [34], respectively. The comparison reveals that high repair costs or economic losses may not correspond to high embodied carbon impacts, and vice versa.

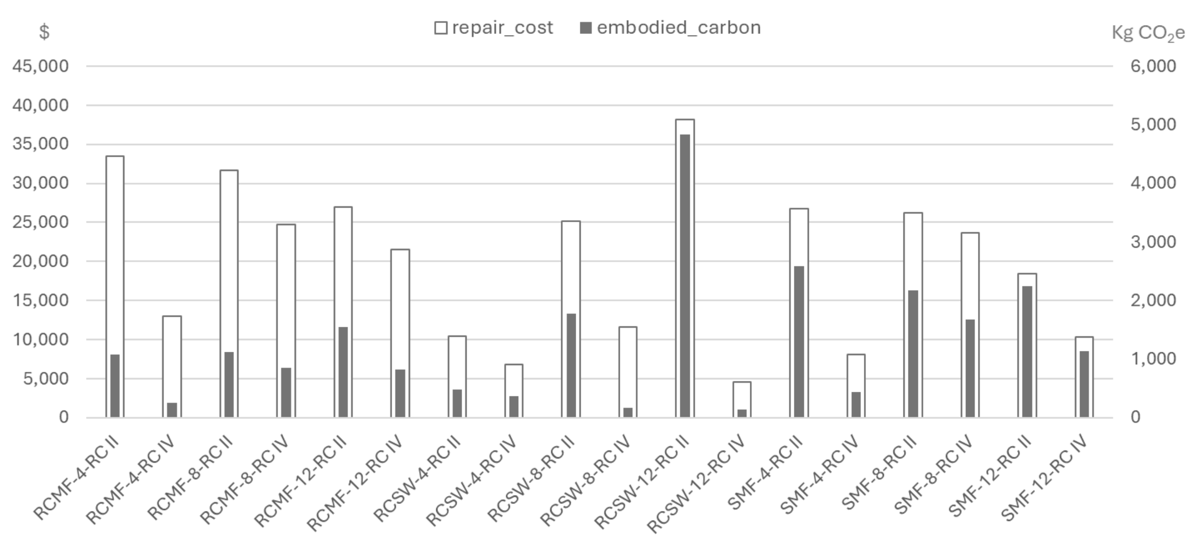

Figure 5. Annual average embodied carbon and repair costs.

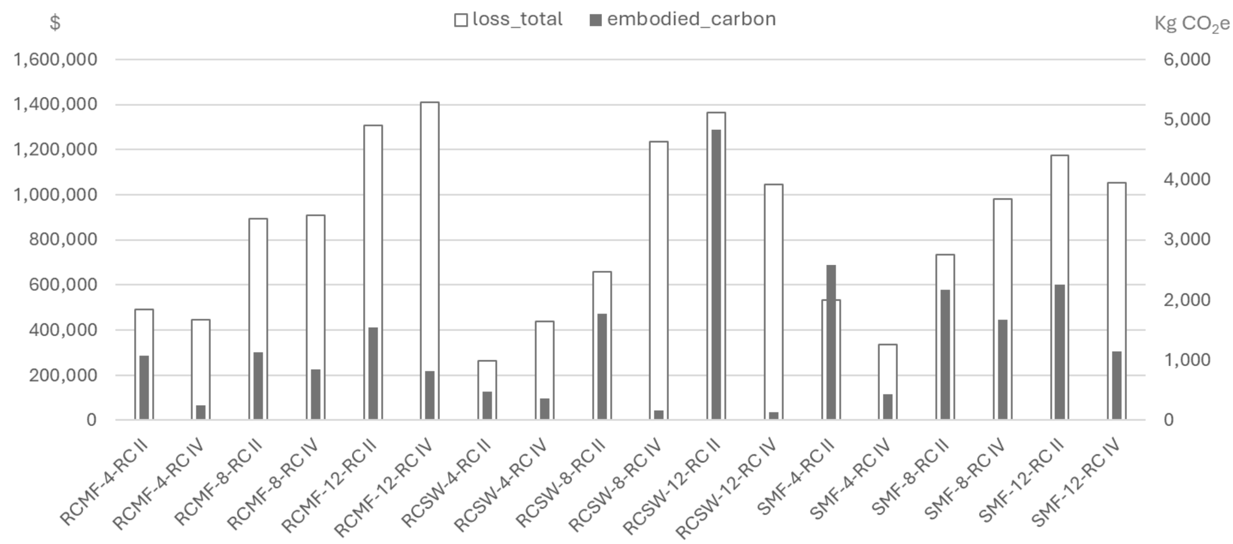

Figure 6. Annual average embodied carbon and total losses.

4. Conclusions

The tool presented in this report aims to improve the accuracy, transparency, efficiency, and standardization of assessing the embodied carbon impact of building repairs. Compared to existing tools (e.g., Environmental Analysis Tool [17, 18], PACT [13]), Pelicun-LCA has three advantages:

- **Detailed breakdowns of annual embodied carbon associated with building repairs**. The hybrid method implemented in Pelicun-LCA accounts for embodied carbon resulting from various sources, including repair materials, material transportation, construction equipment, labor travel, debris disposal, and occupant displacement due to loss of building functions. In addition, the FEMA P-58 methodology focuses on component-level details, reveals the vulnerability of building components, and underscores the need for nonstructural improvement. These collectively can improve the decisions for material use and component design for a building.
- **Built-in design databases for various building archetypes**. The databases are structured in accordance with FEMA P-58 and are developed based on a set of repair assumptions. Eighteen archetype buildings are provided, including three structural types (RCMF, RCSW, SMF), three building heights (4, 8, 12 stories), and two seismic design levels (RC II, RC IV). These archetype buildings can be customized by users for their specific research needs. The repair assumptions (Appendix B) can be modified to compare the impact of different repair strategies on building carbon footprints.
- **Parallel processing for cross-building comparisons**. Pelicun-LCA standardizes output formats to enable easier interpretation and comparison of results, and leverages parallel processing where applicable to accelerate computations and enhance efficiency. This allows users to compare a range of buildings simultaneously. In addition, the results are presented at multiple levels, including component, floor, and building levels.

However, the current version of Pelicun-LCA has several limitations. First, it does not account for certain nonstructural components, including precast concrete panels, heating, ventilation, and air condition (HVAC) fans, chillers, cooling towers, air handling units, and electrical systems. It cannot evaluate the impact of nonstructural improvements, such as the use of seismically certified equipment and the increase of bracing and anchorage, due to data scarcity. Second, the absence of functional recovery models in Pelicun restricts the ability of Pelicun-LCA to quantify embodied carbon associated with the loss of building functions.

Furthermore, the current version of Pelicun-LCA does not account for long-term effects (e.g., permanent relocation, land use change), other life cycle metrics (e.g., energy use, ozone depletion potential, acidification potential, eutrophication potential, photochemical smog potential), and life cycle stages beyond repair (e.g., reconstruction). Incorporating these components into the design database and analysis framework would enhance the accuracy of carbon assessment. Future work can also expand the design database to include other structural types (e.g., steel braced frame, wood frame, dual frame), and extend this methodology to evaluate the performance of existing buildings and the impacts of other natural hazards (e.g., floods and hurricanes).

Despite these limitations, Pelicun-LCA is a valuable tool for comparing embodied carbon impacts of different building designs and supporting design decisions for functional recovery. The embodied carbon associated with building repairs has long been overlooked; however, studies have shown that post-disaster reconstruction efforts can generate large carbon footprints [35, 36]. The case study presented in this report further demonstrates that repairing RC-II buildings in highly seismic regions can result in substantial carbon impact. Moreover, building repair and reconstruction are expected to increase as the intensity and frequency of some natural hazard events increase, and land covers and soil characteristics change in the future [37, 38]. Evaluating building performance at the early design stage can help to mitigate embodied carbon impacts in the long run.

Finally, functional recovery design represents a new design paradigm for improving building recovery performance following natural hazard events [39]. Compared to conventional code minimum design, which protects life safety, functional recovery design offers additional benefits such as reduced building damage, reduced downtime and repair effort, and reduced economic and social losses during large earthquakes [34, 40, 41]. More importantly, achieving functional recovery goals for individual buildings is a critical step toward community resilience [39, 42]. However, many challenges exist for adopting functional recovery design, such as the tradeoff between resilience and sustainability [7, 8, 43]. Understanding its embodied carbon impact can help to develop design strategies that provide long-term benefits to the community.

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Appendix A. Data sources

Table A1. Process data for building materials and components.

Category	Component	Region	LCA method	Life cycle stages[b]	Data source
Super structure	Ready-mix concrete	North America	SimaPro 8.5, plant survey	A1-A3	NRMCA (National Ready Mixed Concrete Association). (2022). National and regional LCA benchmark (industry average) report - v3.2. https://www.nrmca.org/wp-content/uploads/2022/02/NRMCA_LCAReportV3-2_20220224.pdf
	Steel reinforcement bar	North America	GaBi 2021, plant survey	A1-A3	CRSI (Concrete Reinforcing Steel Institute). (2022). Environmental product declaration - Steel reinforcement bar. https://www.crsi.org/wp-content/uploads/CRSI_Industry-Wide_EPD_Sep2022.pdf
	Precast concrete panel	North America	Average[a]	A1-A3	EC3 (2024). Embodied Carbon in Construction Calculator. https://buildingtransparency.org/ec3
Exterior enclosure	Curtain wall	North America	GaBi 2019, plant survey	A1-A3	NGA (National Glass Association). (2019). Environmental product declaration - Flat glass. https://www.glass.org/sites/default/files/2019-12/NGA_EPD_2019_12_16_signed.pdf
	Partition wall with metal studs	North America	SimaPro 9.0, US LCI database, Ecoinvent 3.5	A1-A3	ASMI (2020). An industry average cradle-to-gate life cycle assessment of 1/2 in lightweight and 5/8 in type X conventional gypsum board for the USA and Canadian markets. https://ecomedes.s3.us-west-2.amazonaws.com/client-data/certainteed/Easi-Lite+Industry+Wide+LCA_GA+Report+_FINAL_28042020_ATHENA.pdf

	Partition wall without metal studs	North America	SimaPro 9.0, US LCI database, Ecoinvent 3.5	A1-A3	GA (2020). Industry average EPD for 5/8 in type X conventional gypsum board. https://www.usg.com/content/dam/USG_Marketing_Communications/united_states/product_promotional_materials/finished_assets/2020-type-x-wallboard-epd-en.pdf
Stairs	Precast concrete staircase	Europe	SimaPro 9.4, Ecoinvent 3.8	A1-A3	HORMIPRESA (2023). Environmental Product Declaration, Precast concrete product – Staircases. https://api.environdec.com/api/v1/EPDLibrary/Files/39510a73-3862-44c0-4832-08db1f315c5e/Data
	Prefabricated steel staircase	Europe	SimaPro 9.5.2, Ecoinvent 3.9.1	A1-A3	TLC (2024). Environmental product declaration – Steel Stairs. https://api.environdec.com/api/v1/EPDLibrary/Files/11de4908-3dff-4224-60a9-08dc646df636/Data
Interior finishes	Raised access floor	North America	OpenLCA 1.11 software, Ecoinvent 3.10 database	A1-A3	RFCI. (2019). Environmental product declaration – Homogeneous vinyl flooring. https://rfci.com/wp-content/uploads/2024/05/SCS-EPD-10144_RFCI_Heterogeneous-Sheet_050924_compressed.pdf
	Suspended ceiling	North America	Average[a]	A1-A3	EC3 (2024). Embodied Carbon in Construction Calculator. https://buildingtransparency.org/ec3
	Pendant lightings	Europe	Simapro 9.2, Ecoinvent 3.6	A1-A3	LAMP (2022). KOMBIC100, KOMBIC150 and KOMBIC200 Luminaires. https://www.lamp.es
Conveying	Elevator	North America	GaBi 2022	A1-D	Otis (2022). Gen3 Peak™ Elevator. https://api.environdec.com/api/v1/EPDLibrary/Files/dc1b6664-5821-4fa2-5ec4-08dac61988c5/Data

Plumbing	Portable water pipe	Europe	GaBi 2016	A1-A3, C3-D	ERCIYAS (2020). Steel pipe. https://www.cloverpipe.com.au/wp-content/uploads/2023/06/CLO_Erciyas-Steel-Pipe-Environmental-Product-Declaration-EPD.pdf
	Sanitary pipe	Europe	GaBi 2016	A1-A3, C3-D	ERCIYAS (2020). Steel pipe. https://www.cloverpipe.com.au/wp-content/uploads/2023/06/CLO_Erciyas-Steel-Pipe-Environmental-Product-Declaration-EPD.pdf
HVAC	Water Cooled Chiller, 350 ton	North America	GaBi 2023	A1-C4	Carrier (2021). AquaEdge® 19MV Water-Cooled Centrifugal Chiller. https://www.shareddocs.com/hvac/docs/1005/Public/08/19MV-EPD-04.19.2024.pdf
	Cooling tower, 350 ton	Europe	EIME 6.0.5, CODE-2023-02 database	A1-D	Carrier (2023). 30KAV-ZE 350 - 1300, 30KAVPZE 350 - 800, 30KAVIZE 500 - 1250. https://register.pep-ecopassport.org/pep/consult/mbesqrsCBZbWbKJq6-kJ3gbzSXZd1DDtN3sZYEhUIg8/mbesqrsCBZbWbKJq6-kJ3lQmBuGvAHsLUfQU9idjOpk
	Fan coils	Europe	SimaPro 9.5, Ecoinvent 3.9.1	A1-D	Sabiana (2023). Fan Coils – SkyStar SK-ECM. https://kesko-onninen-pim-resources-production.s3-eu-west-1.amazonaws.com/pimdocuments/23165140.pdf
	HVAC ducting	Europe	Air.e LCA 3.14.0.15, Ecoinvent 3.9	A1-A3, C1-D	DANA (2023). Galvanized steel coil. https://api.environdec.com/api/v1/EPDLibrary/Files/7b0dc57f-fedc-4f9a-9aee-08db7e35bd3c/Data

	HVA drops/diffusers	Europe	GaBi 2021	A1-A5, C1-D	Swegon (2023). Swegon Ceiling Diffuser 600. https://ecowise.lv/wp-content/uploads/2023/08/epd_swegon-ceiling-diffuser-600.pdf
	Variable air volume box	Europe	Ecoinvent 3.6	A1-A4, C1-D	TROX (2023). TVE-D. https://cdn.trox.de/59b78693b2cc6b8a/900adf1ce6e5/EnvironmentalProductDeclarationTVE_D.pdf
	HVAC fan	Europe	Ecoinvent 3.9.1	A1-A5, B6, C1-D	NOVENCO (2024). ZerAx AZL 710/350. https://www.novenco-building.com/media/ykrlr2oj/md-23170-en.pdf
	Air handling unit	Europe	GaBi 2023	A1-D	Swegon (2024). GOLD RX 050/ 060 – SILVER C RX 050/ 060. https://www.swegon.com/siteassets/_product-documents/air-handling-units/gold-version-f/epd/epd-goldrx-050-060.pdf
	HVAC control panel	Europe	Ecoinvent 3.9.1	A1-C4	ABB (2024). Variable speed drive ACH580-01 Frame R6 37 to 75 kW. https://search.abb.com/library/Download.aspx?DocumentID=3AXD10002176537&LanguageCode=en&DocumentPartId=&Action=Launch
Fire protection	Fire sprinkler water pipe	North America	GaBi 2021	A1-A3	WHEATLAND (2022). Steel pipe and fire sprinkler pipe. https://www.wheatland.com/wp-content/uploads/2022/02/Environmental-Product-Declaration-Standard-Fire-Sprinkler.pdf

	Fire sprinkler drop	North America	SimaPro 9.3, Ecoinvent 3.8	A1-A3	Reliable (2023). A company-specific cradle-to-gate EPD for Reliable® Sprinkler Model P22 ESFR Sprinklers. https://pcr-epd.s3.us-east-2.amazonaws.com/888.Reliable_P22_EPD.pdf
electric	Transformer	Europe	SimaPro 9.3, Ecoinvent 3.8	A1-C4	TOSHIBA (2022). Aluminum wound, Mineral oil filled Transformer – 8177 Series. https://api.environdec.com/api/v1/EPDLibrary/Files/b0a2b349-dfc3-4e6a-153e-08daab5a6b31/Data
	Motor control center and low voltage switchgear	Europe	SimaPro 9.4, Ecoinvent 3.8	A1-C4	ABB (2023). MNS 3.0 switchgear. https://search.abb.com/library/Download.aspx?DocumentID=4TUA099010&LanguageCode=en&DocumentPartId=&Action=Launch
	Distribution panel	North America	SimaPro 9.5, Ecoinvent 3.9	A1-A3, A5, B1, C1-C4	ABB (2023). ABB ReliaGear Lighting Panelboards (Copper Bus). https://search.abb.com/library/Download.aspx?DocumentID=1SQC173004D0201&LanguageCode=en&DocumentPartId=&Action=Launch

Note: LCA = life cycle assessment.
[a] Averaged on a range of Environmental Product Descriptions (EPDs) that employ different LCA methods.
[b] Material production (A1–A3), construction and installation (A4–A5), maintenance and refurbishment (B1–B5), demolition and waste disposal (C1–C4), reuse and recycle (D).

Table A2. Process data for construction equipment and transportation.

Category	Machine	Activity	Capacity	Energy	Emission factor[*]
Earthwork machinery	Crawler dozer[a]	Pushes material like soil, sand, and rubble	105 kw	diesel	192.79 kg CO_2e/machine/day
	Crawler excavator with single bucket[a]	Digs sites, demolishes structures and surfaces, carries out trenching, and lifts heavy objects	1 m^3	diesel	199.76 kg CO_2e/machine/day
	Tyre loader bucket[a]	Digs into the ground to scoop up and transports materials like dirt, snow, feed, and more	1 m^3	diesel	167.20 kg CO_2e/machine/day
	Electric rammer[a]	Compacts soil and gravel to create a solid base for construction projects	250 Nm	electricity	2.85 kg CO_2e/machine/day
Transportation machinery	Medium and heavy-duty truck[b]	Transports manufactured products to site; transports demolished building components to landfills	Above 10,000 lbs	diesel	0.1714 kg CO_2e/ton/mile
	Passenger car[b]	Travels between home and workplace	4 people	diesel	0.3153 kg CO_2e/vehicle/mile
Lifting machinery	Electric single barrel slow speed winch[a]	Hoists, pulls or drags heavy objects	3 ton	electricity	17.55 kg CO_2e/machine/day
	Crawler crane[a]	Lifts, lowers, or moves heavy objects	15 ton	diesel	92.84 kg CO_2e/machine/day

	Jack-up tower crane[a]	Uses steel barrels to create lifting towers for multi-point lifts	2500 kNm	electricity	162.31 kg CO_2e/machine/day
	Truck crane[a]	Lifts, lowers, or transports materials	10 ton	diesel	92.53 kg CO_2e/machine/day
	Double cage construction elevator[a]	Transports workers and building materials	21 ton, 100 m	electricity	49.94 kg CO_2e/machine/day
Concrete machinery	Concrete pump truck[a]	Transfers liquid concrete by pumping	75 m^3/h	diesel	265.94 kg CO_2e/machine/day
	Mortar mixer[a]	Blends fine-grained materials like mortar, plaster, grout, cement, sand, and gravel into a consistent mixture	200 L	electricity	1.48 kg CO2e/machine/day
	Concrete mixer[a]	Combines cement, water, and other materials to create concrete	400 L	electricity	5.86 kg CO_2e/machine/day
	Concrete flattener[a]	Flattens concrete	5.5 kw	electricity	14.12 kg CO_2e/machine/day
	Concrete slitting machine[a]	Removes and reshapes concrete surfaces	7.5 kw	electricity	19.25 kg CO_2e/machine/day
Processing machinery	Steel bar straightener[a]	Removes bends, kinks, and curves from steel bars to achieve precise dimensional accuracy	14 mm	electricity	7.26 kg CO_2e/machine/day

	Steel bar cutter[a]	Cuts steel bars, rods, and wires into different lengths and gauges	40 mm	electricity	19.58 kg CO_2e/machine/day
	Steel bar bender[a]	Bends steel bars into different shapes	40 mm	electricity	7.81 kg CO_2e/machine/day

Note: 1 day = 8 hours
* Emission factors are adjusted to the current California policy scenario in 2024.
[a] Wu et al. (2019) The case study of carbon emission in building construction process. IOP Conf. Ser.: Earth Environ. Sci. 371, 022011. https://iopscience.iop.org/article/10.1088/1755-1315/371/2/022011/pdf
[b] EPA (2023) Emission Factors for Greenhouse Gas Inventories. https://www.epa.gov/system/files/documents/2023-03/ghg_emission_factors_hub.pdf

Appendix B. Repair assumptions

Table B1. Repair assumptions for RCMF.

Component	Damage state	Damage description	Repair action	Repair assumptions
Reinforced concrete beam, one end continuous beam	DS1	Beams or joints exhibit residual crack widths greater than 0.06 in. No significant spalling. No fracture or buckling of reinforcing.	Prepare work area; epoxy injection; patch concrete with grout; repair/replace finishes; 4 ft long repair zone (one side)	50 linear feet of epoxy injection, epoxy grout 0.15 gallon per linear foot (crack depth 24 in, crack width 1/8 in)
	DS2	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; 4 ft long repair zone (one side)	20 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
	DS3a	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes a significant length of beam longitudinal reinforcement. Crushing of core concrete may occur. Fracture or buckling of reinforcing requiring replacement may occur.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; remove damaged rebar and splice in new; 4 ft long repair zone (one side)	20 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; top 4 #10 bars, bottom 4 #8 bars; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
	DS3b	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; remove damaged rebar and splice in new; 4 ft long repair zone (one side)	20 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1

Reinforced concrete beam, both end continuous beam	DS1	Beams or joints exhibit residual crack widths greater than 0.06 in. No significant spalling. No fracture or buckling of reinforcing.	Prepare work area; epoxy injection; patch concrete with grout; repair/replace finishes; 4 ft long repair zone (per side)	50 linear feet of epoxy injection, epoxy grout 0.15 gallon per linear foot (crack depth 24 in, crack width 1/8 in)
	DS2	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; 4 ft long repair zone (per side)	40 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
	DS3a	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes a significant length of beam longitudinal reinforcement. Crushing of core concrete may occur. Fracture or buckling of reinforcing requiring replacement may occur.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; remove damaged rebar and splice in new; 4 ft long repair zone (per side)	40 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; top 4 #10 bars, bottom 4 #8 bars; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
	DS3b	Beams or joints exhibit residual crack widths greater than 0.06 in. Spalling of cover concrete exposes beam and joint transverse reinforcement but not longitudinal reinforcement. No fracture or buckling of reinforcing.	Prepare work area; remove loose concrete, clean rebar; epoxy injection; formwork; concrete; remove damaged rebar and splice in new; 4 ft long repair zone (per side)	40 % replacement, 24 in × 36 in × 20 ft concrete beam, 5000 psi; #7 stirrups @ 3.5 in; concrete pump truck; concrete flattener 1 machine/day; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
Prestressed concrete slab	DS1	Yield strain of the slab flexural reinforcement has been exceeded. Spalling of concrete may or may not occur. Slab exhibits large enough crack widths to allow epoxy injection.	Prepare work area; inject epoxy into cracks; the repair zone extends in a 10 ft radius from the center of the column.	100 % replacement, 20 ft × 20 ft × 8 in concrete slab, 5000 psi; concrete pump truck; concrete flattener 1 machine/day
	DS2	Punching occurs, causing significant spalling of concrete. Epoxy injection is no longer expected to be sufficient to restore the required strength and	Prepare work area; formwork; reinforcing steel; mechanical splice to reinforcing; concrete; the repair zone	100 % replacement, 20 ft × 20 ft × 8 in concrete slab, 5000 psi; prestressing strand @ 36 in OC; concrete pump truck; concrete flattener 1 machine/day;

		stiffness to the slab and the slab column connection.	extends in a 10 ft radius from the center of the column.	steel bar straightener 1; steel bar cutter 1; steel bar bender 1
Precast concrete panel	DS1a	In plane deformation. Cladding units damaged by impact at corners at column covers. Damage in the field is either attributed to natural edge chipping/damage or is deemed to not warrant full repair.	Cosmetic chip patching	20 % replacement, 13 ft × 30 ft × 4.5 in precast concrete panel; truck crane 0.2 machine/day
	DS1b	Cladding units damaged by impact at corners at column covers.	New cladding panel; new window; new gypsum board and insulation	100 % replacement, 13 ft × 30 ft × 4.5 in precast concrete panel; truck crane 0.2 machine/day
	DS1c	Cladding units damaged by out of plane anchorage failure. The unit requires replacement.	New cladding panel; new window; new gypsum board and insulation	100 % replacement, 13 ft × 30 ft × 4.5 in precast concrete panel; truck crane 0.2 machine/day

Note: 1 day = 8 hours.

Table B2. Repair assumptions for RCSW.

Component	Damage state	Damage description	Repair action	Repair assumptions
Slender concrete wall	DS1	Spalling of cover, vertical cracks greater than 1/16 inch.	Epoxy inject cracks and patch spalled concrete.	300 ft of epoxy injection per 100 ft2 of wall, epoxy grout 0.025 gallon per linear foot (crack depth 8 in, crack width 1/16 in)
	DS2	Exposed longitudinal reinforcing.	Shore wall, remove all concrete in damaged regions, replace concrete.	15 % replacement of concrete, 13 ft high, 312 in long, 6000 psi; 15% replacement of steel, 40 #9 boundary bars, 36 #5 web bars; concrete mixer 0.1 machine/day; concrete flattener 1; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
	DS3	Core concrete damage, buckled reinforcing, fractured reinforcing, shear failure, web failure, bond slip	Replace wall or reinforce with R/C jacket if possible. Shore floor and wall, remove damaged concrete and steel within one development length of damaged region, replace removed concrete and steel.	100 % replacement of concrete, 13 ft high, 312 in long, 6000 psi; 100% replacement of steel, 40 #9 boundary bars, 36 #5 web bars; concrete flattener 1; steel bar straightener 1; steel bar cutter 1; steel bar bender 1
Reinforced concrete flat slab	DS1	Yield strain of the slab flexural reinforcement has been exceeded. Spalling of concrete may or may not occur. Slab exhibits large enough crack widths to allow epoxy injection.	Remove furnishings, ceilings and mechanical, electrical and plumping systems (as necessary) 5 feet either side of the damaged area. Replace and repair finishes. Replace furnishings, ceilings and mechanical, electrical and plumping systems (as necessary).	160 linear feet of epoxy injection, epoxy grout 0.15 gallon per linear foot (crack depth 24 in, crack width 1/8 in)
	DS2	Punching occurs, causing significant spalling of concrete. Epoxy injection is no longer expected to be sufficient to restore the required strength and	Prepare a work area for epoxy injection, inject epoxy into 85 feet of crack (60 feet top, 25 feet bottom of slab) per 100 square feet of floor panel. Fabricate new	20 ft × 20 ft × 8 in concrete slab, 5000 psi; strand @ 36 in OC; concrete mixer 0.1 machine/day; concrete flattener 1; steel bar straightener 1; steel bar cutter

		stiffness to the slab and the slab column connection.	structural steel shear head (column capital) that attaches to the column beneath the slab.	1; steel bar bender 1

Table B3. Repair assumptions for SMF.

Component	Damage state	Damage description	Repair action	Repair assumptions
Shear tab	DS1a	Yielding of shear tab and elongation of bolt holes, possible crack initiation around bolt holes or at shear tab weld. Damage in the field is either obscured or deemed to not warrant repair. No repair conducted.	Careful inspection and welded repair to any cracks and possible replacement of shear tab if bolt hole deformations are excessive (possible for deeper 6-bolt or deeper shear tabs). Field condition is deemed to not warrant repair by field observation.	No repair
	DS1b	Yielding of shear tab and elongation of bolt holes, possible crack initiation around bolt holes or at shear tab weld.	Careful inspection and welded repair to any cracks and possible replacement of shear tab if bolt hole deformations are excessive (possible for deeper 6-bolt or deeper shear tabs).	Two 508 × 762 × 19 mm steel plates replacement (20 in × 30 in × 3/4 in)
	DS2	Partial tearing of shear tab and possibility of bolt shear failure (6-bolt or deeper connections).	Repairs will include either welded repair of shear tab or possible complete replacement of shear tab and installation of new bolts. Repairs may require shoring of the beam.	Two 508 × 762 × 19 mm steel plates replacement plus 6 bolts, 22 mm (7/8 in) diameter
	DS3	Complete separation of shear tab, close to complete loss of vertical load resistance.	Repair will include complete replacement of shear tab and installation of new bolts. Repairs will require shoring of the beam.	Two 508 × 762 × 19 mm steel plates replacement plus 6 bolts, 22 mm (7/8 in) diameter
Column base plate	DS1a	Initiation of crack at the fusion line between the column flange and the base plate weld. Damage in the field is either obscured or deemed to not warrant repair. No repair conducted.	The repair will involve removal of a portion of grade slab, gouging out material surrounding the fracture initiating and re-welding, then repair of slab. Field condition is deemed to not warrant repair by field observation.	No repair

	DS1b	Initiation of crack at the fusion line between the column flange and the base plate weld.	The repair will involve removal of a portion of grade slab, gouging out material surrounding the fracture initiating and re-welding, then repair of slab.	For Column 150 plf < W < 300 plf, 889 mm (35 in) weld. For Column W > 300 plf, 889 mm (35 in) weld.
	DS2	Propagation of brittle crack into column and/or base plate.	Depending on the crack trajectory, the repair will range from replacement of a portion of the column or base plate to full replacement of the column base. Replacement will require shoring of column, torch cutting to remove damaged material, and fabrication and field welding to install replacement material.	For Column 150 plf < W < 300 plf, 2.29 m (90 in) weld and 635 × 635 × 102 mm plate replacement (25 in × 25 in × 4 in). For Column W > 300 plf, 2.67 m (8.8 ft) weld, 889 × 889 × 152 mm plate replacement (35 in × 35 in × 6 in).
	DS3	Complete fracture of the column (or column weld) and dislocation of column relative to the base.	Repair would likely involve replacing the entire base plate assembly and most of the column in the story above the base plate.	For Column 150 plf < W < 300 plf, 2.29 m weld, 635 × 635 × 102 mm plate replacement, 3.96 m (13 ft) W14 × 257 section replacement. For Column W > 300 plf, 2.67 m weld, 889 × 889 ×152 mm plate replacement, 3.96 m (13 ft) W14 × 500 section replacement.
Welded column splice	DS1a	Ductile fracture of the groove weld flange splice. Damage in the field is either obscured or deemed to not warrant repair. No repair conducted.	Repair would involve gouging out the material adjacent to the fracture and repairing with a new groove weld. Field condition is deemed to not warrant repair by field observation.	For Column 150 plf < W < 300 plf, 2 × 381 × 381 × 25 mm plates (2 × 15 in × 15 in × 1 in), 2 × 1.52 m welds (2 × 60 in). For Column W > 300 plf, 2 × 305 × 305 × 25 mm plates (2 × 12 in × 12 in × 1 in), 2 × 1.27 m welds (2 × 50 in).
	DS1b	Ductile fracture of the groove weld flange splice.	Repair would involve gouging out the material adjacent to the fracture and repairing with a new groove weld.	For Column 150 plf < W < 300 plf, 4 × 381 × 381 × 25 mm plates (4 × 15

				in × 15 in × 1 in), 4 × 1.52 m welds (4 × 60 in). For Column W > 300 plf, 2 × 305 × 305 × 25 mm plates (2 × 12 in × 12 in × 1 in), 2 × 305 × 635 × 25 mm plates (2 × 12 in × 25 in × 1 in), 2 × 1.27 m welds (2 × 50 in), 2 × 1.78 m welds (2 × 70 in).
	DS2	DS1 followed by complete failure of the web splice plate and dislocation of the two column segments on either side of the splice.	Repair may not be practically feasible but would require either realignment or replacement of adjacent column segments and rewelding of splice.	For Column 150 plf < W < 300 plf, 4 × 381 × 381 × 25 mm plates, 4 × 1.52 m welds, 3.96 m (13 ft) W14 × 283 section. For Column W > 300 plf, 2 × 305 × 305 × 25 mm plates, 2 × 305 × 635 × 25 mm plates, 2 × 1.27 m welds, 2 × 1.78 m welds, 3.96 m W24 × 335 section.
Post-Northridge Reduced Beam Section (RBS) connection, beam one side of column only	DS1	Local beam flange and web buckling.	The likely repair state is heat straightening of the buckled flanges and web. Repair and replace partitions at connection.	Heat straightening
	DS2	DS1 plus lateral-torsional distortion of beam in hinge region.	Repair will necessitate removal and replacement of distorted and or fractured portions of beam. Repair and replace partitions at connection.	For beam depth <= W27, 4.57 m (15 ft) W27 × 84, 1 moment resisting connection For beam depth >= W35, 4.57 m W33 × 141, 1 moment resisting connection
	DS3	Low-cycle fatigue fracture in the buckled region of RBS.	Repair will necessitate removal and replacement of distorted and/or fractured portions of beam. Repair and replace partitions at connection.	For beam depth <= W27, 4.57 m (15 ft) W27 × 84, 1 moment resisting connection For beam depth >= W35, 4.57 m W33 × 141, 1 moment resisting connection

Post-Northridge Reduced Beam Section (RBS) connection, beam both sides of column	DS1	Local beam flange and web buckling.	The likely repair state is heat straightening of the buckled flanges and web. Repair and replace partitions at connection.	Heat straightening
	DS2	DS1 plus lateral-torsional distortion of beam in hinge region.	Repair will necessitate removal and replacement of distorted and or fractured portions of beam. Repair and replace partitions at connection.	For beam depth <= W27, 6 m (20 ft) W27 × 84, 2 moment resisting connections For beam depth >= W35, 6 m W33 × 141, 2 moment resisting connections
	DS3	Low-cycle fatigue fracture in the buckled region of RBS.	Repair will necessitate removal and replacement of distorted and/or fractured portions of beam. Repair and replace partitions at connection.	For beam depth <= W27, 6 m (20 ft) W27 × 84, 2 moment resisting connections For beam depth >= W35, 6 m W33 × 141, 2 moment resisting connections

Table B4. Repair assumptions for non-structural components.

Component	Damage state	Damage description	Repair action	Repair assumptions
Curtain wall	DS1	Glass cracking.	100% glass replacement	100 % replacement, 30 sf × 1/4 in glass; truck crane 0.1 machine/day
	DS2	Glass falls from frame	100% glass replacement	100 % replacement, 30 sf × 1/4 in glass; truck crane 0.1 machine/day
Partition wall with metal studs	DS1	Screw pop-out. Cracking of wall board. Warping or cracking of tape. Slight crushing of wall panel at corners.	5% new tape, paste, paint	5 % replacement, 13 ft × 100 ft metal panel cladding, 13 ft × 100 ft × 1/2 in gypsum board, low speed electric winch 0.1 machine/day
	DS2	Moderate cracking or crushing of gypsum wall boards (typically in corners). Moderate corner gap openings. Bending of boundary studs.	50% new tape, paste, paint; 25% new wallboard	25 % replacement, 13 ft × 100 ft metal panel cladding, 13 ft × 100 ft × 1/2 in gypsum board, low speed electric winch 0.1 machine/day
	DS3	Buckling of studs and tearing of tracks. Tearing or bending of the top track. Tearing at corners with transverse walls. Large gap openings. Walls displaced.	100% complete replacement	100 % replacement, 13 ft × 100 ft metal panel cladding, 13 ft × 100 ft × 1/2 in lightweight gypsum board, low speed electric winch 0.1 machine/day
Partition wall without metal studs	DS1	Wallpaper warped and torn.	Remove existing wallpaper (or wall) and install new wallpaper for the wall.	100 % replacement, 9 ft × 100 ft × 5/8 in wallpaper
Precast concrete staircase	DS1	Nonstructural damage. Local concrete cracking. Localized concrete spalling. Localized rebar yielding.	Minor repair of finishes, epoxy injection	Finishes repair and epoxy injection
	DS2	Structural damage. Live load capacity remains intact. Extensive concrete	Cut out damaged sections/patch; replace buckled rebar; patch/repair adjacent finishes	10 % replacement

		cracking. Concrete crushing. Buckling of rebar.		
	DS3	Loss of live load capacity. Extensive concrete crushing. Connection failure.	New stair & landing; new balustrade; new floor finishes; new soffits; patch/repair adjacent finishes	100 % replacement; truck crane 0.2 machine/day
Prefabricated steel staircase	DS1	Nonstructural damage, local steel yielding.	Patch, paint.	Finishes repair
	DS2	Buckling of steel, weld cracking.	Removal and replacement of damaged components. Field repair of damage (such as welding). Repair finishes.	10 % replacement
	DS3	Loss of live load capacity. Connection and or weld fracture.	Replace stair and handrail. Repair and replace affected soffits and floor finishes.	100 % replacement; truck crane 0.2 machine/day
Raised access floor	DS1	Minor damage to the flooring system. Damage to the equipment of the flooring system.	Repair the flooring system, assume cost equal to 5% of the replacement cost.	5 % replacement, resilient flooring, homogeneous vinyl
Suspended ceiling	DS1	5 % of ceiling grid and tile damage.	Reinstall, repair, or replace 5% of the ceiling area.	5 % replacement, acoustical ceiling, 250 sf
	DS2	30% of ceiling grid and tile damage.	Replace 30% of the ceiling area.	30 % replacement, acoustical ceiling, 250 sf
	DS3	50% of ceiling grid and tile damage.	Replace the entire ceiling	100 % replacement, acoustical ceiling, 250 sf
Pendant lightings	DS1	Disassembly of rod system at connections with horizontal light fixture. Low cycle fatigue failure of the threaded rod. Pullout of rods from ceiling assembly.	Replace damaged lighting components.	100 % replacement, lighting components

Elevator	DS1	Controller anchorage failure. Machine anchorage failure. Motor Generator anchorage failure. Governor anchorage failure. Rope guard/tail sheave anchorage failure.	Reinstall or replace the controller. Reinstall or replace the motor generator with appropriate anchors. Install a new governor. Reinstall or replace rope guards. Repair or replace tail sheave.	No replacement, repair only
		Car guide shoes damaged. Counterweight guide shoes damaged. Counterweight distorted frame. Cab ceiling damaged. Cab stabilizer brackets bent. Cab walls and/or cab doors damaged.	Replace car guide shoes. Replace counterweight guide shoe. Repair or replace counterweight frame. Repair or replace cab ceiling. Repair or replace cab walls.	100 % cab replacement
		Guide rail distortion	Replace rail	100 % guide rail replacement
		Intermediate guide rail brackets break or bend. Car guide rail brackets break or bend. Counterweight guide rail brackets break or bend.	Replace intermediate brackets. Replace brackets or tie rod. Replace counterweight brackets.	100 % guide rail brackets replacement
Portable water pipe, 2.5 inch in diameter	DS1	Minor leakage at flange connections. One leak per 1000 feet of pipe.	Retightening flange bolts at leaking joints. One joint per 1000 LF.	No replacement, repair only
	DS2	Pipe Break. One break per 1000 feet of pipe.	Replace 20 foot sections of pipe where breaks occur. One repair per 1000 LF.	2 % pipe replacement, 2.5 in diameter, steel pipe
	DS1	Lateral Brace Failure. One failure per 1000 feet of pipe.	Replace failed lateral braces. One repair per 1000 LF.	No replacement, repair only (brace replacement)
Portable water pipe, 4 inch in diameter	DS1	Minor leakage at flange connections. One leak per 1000 feet of pipe.	Retightening flange bolts at leaking joints. One joint per 1000 LF.	No replacement, repair only (brace replacement)
	DS2	Pipe Break. One break per 1000 feet of pipe.	Replace 20-foot sections of pipe where breaks occur. One repair per 1000 LF.	2 % pipe replacement, 4 in diameter, steel pipe

	DS1	Vertical Brace Failure. One failure per 1000 feet of pipe.	Replace failed vertical braces. One repair per 1000 LF.	No replacement, repair only (brace replacement)
	DS2	Vertical Brace Failure. One failure per 1000 feet of pipe.	Replace failed vertical braces. One repair per 1000 LF.	No replacement, repair only (brace replacement)
Sanitary pipe	DS1	Isolated support failure w/o leakage. An average 0.5 supports fail per 1000 feet of pipe (assuming supports every 20 feet).	Replace failed supports.	No replacement, repair only, pipe support. Pipe (24 in diameter, cast iron pipe)
Chiller, 350 ton (ground)	DS1a	Anchorage failure.	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad. Chiller removed, repaired offsite, and reinstalled.	100 % chiller replacement, 350 ton
	DS1c	Damaged. Inoperative but anchorage is OK.	Repair chiller and attached piping. Chiller removed, repaired offsite, and reinstalled.	100 % chiller replacement, 350 ton
Cooling tower, 350 ton (roof)	DS1a	Anchorage failure.	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad. Chiller removed, repaired offsite, and reinstalled.	100 % cooling tower replacement, 350 ton
	DS1c	Damaged. Inoperative but anchorage is OK.	Repair chiller and attached piping. Chiller removed, repaired offsite, and reinstalled.	100 % cooling tower replacement, 350 ton

HVAC ducting	DS1	Individual supports fail and duct sags. One failed support per 1000 feet of ducting.	Replace failed supports and repair ducting in vicinity of failed supports.	No replacement, repair only (support replacement)
	DS2	Several adjacent supports fail and sections of ducting fall. An average 60 feet of ducting fail and fall per 1000 feet of ducting.	Replace sections of failed ducting and supports.	6% HVAC ducting replacement
HVAC fan	DS1a	Anchorage failure.	Repair anchorage and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Repair anchorage and replace equipment.	100 % HVAC fan replacement
	DS1c	Damaged. Inoperative but anchorage is OK.	Repair equipment.	100 % HVAC fan replacement
Air handling unit	DS1a	Anchorage failure.	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad. Remove, repair offsite, and reinstall air handler.	100 % AHU replacement, 40000 CFM or 19.5 m3/s
	DS1c	Damage to attached ducting or piping but anchorage is OK.	Repair attached ducting or piping - equipment does not require replacement and anchorage does not require repair	No replacement, repair only (anchorage replacement)
	DS1d	Equipment damaged beyond repair, but anchorage is OK.	Replace and install equipment including new anchorage if anchorage is post-installed.	100 % AHU replacement, 4000 CFM or 19.5 m3/s
HVAC control panel	DS1a	Anchorage failure.	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)

	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad.	100 % replacement of control panel
	DS1c	Damaged. Inoperative but anchorage is OK.	Replace some components (relays, circuit boards)	100 % replacement of control panel
Fire sprinkler water pipe	DS1	Spraying & Dripping Leakage at joints. An average 0.02 leaks per 20 ft section of pipe.	Replace leaking joints and minor water cleanup.	No replacement, repair only (joint replacement)
	DS2	Joints Break. Major Leakage. An average 0.02 breaks per 20 ft section of pipe.	Replace 20 ft section of pipe, joints and major water cleanup at leaking joints.	2 % pipe replacement, 2-1/2 in diameter, schedule 40
Fire sprinkler drop	DS1	Spraying. Dripping Leakage at drop joints. An average 0.01 leaks per drop.	Replace sprinkler drops and minor water cleanup at broken joints.	100 % sprinkler drops replacement
	DS2	Drop Joints Break. Major Leakage. An average 0.01 breaks per drop.	Replace sprinkler drops and major water cleanup at broken joints	100 % sprinkler drops replacement
Transformer	DS1a	Anchorage failure.	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad. Transformer tower removed, repaired offsite, and reinstalled.	100 % transformer replacement
	DS1c	Damaged. Inoperative but anchorage is OK	Service and repair existing transformer. Transformer tower removed, repaired offsite, and reinstalled.	100 % transformer replacement

Motor control center	DS1a	Anchorage failure	If anchored, repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad if anchored.	100 % motor control center replacement
	DS1c	Damaged. Inoperative but anchorage is OK	Replace equipment.	100 % motor control center replacement
Low voltage switchgear	DS1a	Anchorage failure	Repair anchorage and concrete pad and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment including attached utilities in addition to repairing anchorage and concrete pad.	100 % switchgear replacement
	DS1c	Damaged. Inoperative but anchorage is OK	Replace fiberglass insulator supporting the vertical bus bars in the rear of the switchgear assembly	100 % switchgear replacement
Distribution panel	DS1a	Anchorage failure	Repair anchorage and concrete pad (if floor mounted and wall if wall mounted) and remount equipment.	No replacement, repair only (anchorage replacement)
	DS1b	Anchorage failure. Equipment damaged beyond repair.	Replace equipment in addition to repairing anchorage and concrete pad if floor mounted or wall if wall mounted.	100 % distribution panel replacement, 225 A
	DS1c	Damaged. Inoperative but anchorage is OK	Replace equipment.	100 % distribution panel replacement, 225 A