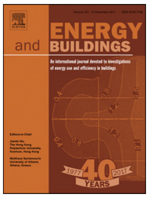
Energy & Buildings 164 (2018) 131–139

Contents lists available at ScienceDirect

Energy & Buildings

journal homepage: www.elsevier.com/locate/enbuild



Embodied carbon as a proxy for the environmental impact of earthquake damage repair

K. Simonen[a,*], M. Huang[a], C. Aicher[b], P. Morris[c]

[a] University of Washington, Department of Architecture, Box 355720, Seattle, WA 98195, USA
[b] University of Washington, Department of Statistics, Box 354322, Seattle, WA 98195, USA
[c] AECOM, 2020 L Street Suite 400, Sacramento, CA 95811, USA

ARTICLE INFO

Article history:
Received 22 June 2017
Revised 4 November 2017
Accepted 28 December 2017
Available online 13 January 2018

Keywords:
Life cycle assessment
Seismic analysis
Performance-based design
Economic input-output
Principal component analysis
Energy and climate change
Architectural Engineering
Buildings

ABSTRACT

In evaluating the life cycle environmental impacts of buildings, the contributions of seismic damage are rarely considered. In order to enable a more comprehensive assessment of a building's environmental impact by accounting for seismic events, this project developed an environmental impact database of building component seismic damage – the largest of its kind known to date – by combining data from Carnegie Mellon University's Economic Input-Output Life Cycle Analysis (LCA) database with cost estimates of repair previously developed for FEMA's Performance Assessment Calculation Tool (PACT), a software that models probabilistic seismic damage in buildings. Fifteen indicators of environmental impacts were calculated for the repair of approximately 800 building components for up to five levels of seismic damage, capturing 'embodied' impacts related to cradle-to-gate manufacturing of building materials, products, and equipment. Analysis of the data revealed that non-structural and architectural finishes often dominated the environmental impacts of seismic damage per dollar spent in repair. A statistical analysis was performed on the data using Principal Component Analysis, confirming that embodied carbon, a popular metric for evaluating environmental impacts in building LCAs, is a suitable proxy for other relevant environmental impact metrics when assessing the impact of repairing earthquake damage of buildings.

1. Introduction

There is a growing interest in understanding the effects of natural hazard mitigation on the environmental impact of buildings, particularly in assessing the effects of earthquakes [7,18,26,38,42,47]. Frameworks, tools, and methodologies have been developed to incorporate environmental impact assessment with earthquake hazard assessment [1,10,14,15,19,31–33,46–48], with some focusing on specific structural systems such as base-isolation [16] or reinforced concrete structures [19,22]. Seismic damage can be costly and irreparable, resulting in significant environment impacts and possible complete loss of a building. Performance-based design (PBD), however, addresses post-earthquake building survival by establishing building performance criteria in the event of an earthquake of a certain magnitude or return period [2]. The performance criteria may include certain drift or displacement limits, or allowing for immediate occupation after the event.

Through the Applied Technology Council (ATC), the U.S. Federal Emergency Management Agency (FEMA) has supported the development of methodology [3,4], databases, and analysis tools [6] to enable the probabilistic analysis of seismic performance, evaluating the metrics of repair cost, repair time, and more recently environmental impact. The work presented in this paper expands upon the existing PACT database of seismic damage estimates by calculating environmental impacts and also refining the methodology developed previously in Volume 4 of the PACT project [6]. In order to estimate the environmental impacts of different levels of seismic repair, existing construction cost estimates of the seismic repair of different building components under differing levels of seismic damage were aligned with Economic Input-Output Life Cycle Analysis (EIO LCA) databases developed by Carnegie Mellon University's Green Design Institute [13]. These 'embodied' impacts capture the cradle-to-gate emissions of building materials and products used in seismic damage repair. The ATC research team selected embodied energy and embodied carbon as the preferred environmental performance metrics due to perceived value to end users and the need to limit the number of environmental impacts tracked due to computational limitations of the probabilistic analysis. Others have identified that carbon may be a relevant proxy for commonly reported LCA impacts [7,20]. This paper presents an analysis of the

---

[*] Corresponding author.
E-mail addresses: ksimonen@uw.edu (K. Simonen), myth29@uw.edu (M. Huang), aicherc@uw.edu (C. Aicher), peter.morris@aecom.com (P. Morris).

https://doi.org/10.1016/j.enbuild.2017.12.065

developed database to assess if the limited metrics of embodied energy and carbon are appropriate proxies for a wider suite of environmental indicators.

This work differs from previous work done by others in that it:

1) creates a comprehensive database of the potential environmental impacts of seismic damage for over 800 building components, presenting the largest known database of its type;
2) uses Principal Component Analysis (PCA) to determine if embodied carbon (also known as greenhouse gas emissions, global warming potential, and climate change potential for the cradle-to-gate stages of the life cycle) can serve as an appropriate 'proxy' for other environmental impact measurements (such as acidification, eutrophication, human health effects, etc.) to represent the multi-faceted environmental impacts of seismic damage in buildings; and,
3) identifies building components from the database that are both seismically vulnerable and environmentally impactful.

This paper describes the data and methodology used to create the database, presents the environmental impact results for repair of seismic damage, and discusses the wider implications of the findings for evaluating the overall environmental impact of buildings.

2. Data, materials, and methods

2.1. Project background

This work is part of the Applied Technology Council Project 58 (ATC-58), *Seismic Performance Assessment of Buildings*, which aims to incorporate the uncertainty of seismic events into performance-based design of buildings by formulating guidelines and tools to better inform stakeholders. The Performance Assessment Calculation Tool (PACT) is a program that models buildings and outputs probabilistic damage in terms of cost of repair, time to repair, loss of life, and other performance measures (also known as *consequence functions* in the PACT terminology).

Key terms in the PACT terminology used in this paper include: 1) *fragility*, which is defined as "the vulnerability of structural and nonstructural components to damage", and 2) *damage state* (DS), which is defined as "a condition of damage associated with a unique set of consequences" [3]. Building components have between one and five damage states defined, and lower damage states (e.g. DS1) are associated with lower levels of seismic impact (acceleration and displacement) than higher damage states. A *fragility group* is defined as "a collection of similar components or systems (e.g. reinforced concrete elements) with the same damageability and consequences of damage", while a *performance group* is defined as "a subcategorization of fragility groups" (e.g. a concrete shear wall).

More information about the development and methodology of PACT can be found in Volumes 1 and 2 of FEMA's *Seismic Performance Assessment of Buildings* [3,4].

2.2. Goal

The overall goal of this research work is to develop a database of environmental impacts for a wide range of typical building components at different levels of seismic damage, to use the data to understand which types of building components result in higher environmental impacts per dollar spent in repair, and to determine if greenhouse gas emissions, or 'carbon', appropriately represents other environmental impact measures reported by LCA. The results are to be incorporated into PACT, enabling environmental impact to be used as another metric by which one can assess seismic performance. Structural engineers can use this data to assess the relative value of different structural design proposals for similar buildings in order to better inform architects, building owners, and policy makers of the associated environmental impacts of their decisions. However, because the data and methods have not been critically reviewed per ISO 14044 life cycle assessment standards [23], the results should not be used to make a 'comparative assertion', or declare that one type of system is environmentally preferable to another. The primary goal of the work described in this paper is to assess if reporting LCA environmental impact can be effectively represented by a single performance metric.

2.3. Data

2.3.1. Cost estimate data

Cost estimates had previously been developed by a professional construction cost estimator for the purpose of computing the costs of repairing seismic damage of the building components in the PACT database. These cost estimates were based on a reference location in Northern California and the reference year 2011. Higher damage states typically had higher repair costs. Contractor pricing strategies and construction cost escalation were not considered, but economies of scale and efficiencies in construction practices were included [3]. The costs used for the LCA calculations were based on the P50 values, or values with a 50% likelihood of exceedance. Generally, the cost estimates were provided for each applicable damage state for approximately 70 performance groups, with some cost estimate calculations being re-used for certain fragilities. Most fragilities had between 1 – 3 damage states, and some reached damage states 4 and 5. The grouping scheme used in this analysis is shown in Table 1. For the purposes of presenting results in this paper, similar groups that contained relatively few elements were combined; *Cold-Formed Steel Structural Elements* (B106) and *Wood Light Frame Structural Elements* (B107) were combined to form *Light Frame Structural Elements*, and *Special Structures Including Storage Racks* (F101) was included with *Interior Finishes*.

2.3.2. Environmental impact data

Early research into integrating environmental impacts into PACT evaluated two different methods of generating the environmental impact data: EIO LCA and process-based LCA [5]. EIO LCA links the energy and materials required for economic activities with the environmental emissions from contributing activities in the supply chain, establishing the environmental impact of an economic activity per dollar spent in that industrial sector. Processed-based LCA links quantities of materials and energy to LCA results for specific manufacturing and construction processes, and would provide advantages over EIO LCA, most notably by providing more certainty in both quantity inputs and accuracy in aligning those impacts with precise unit process LCAs.

EIO LCA was selected to model the environmental impacts of building repair because it enabled straightforward development of impacts based on the existing construction cost estimates, and also because it matched the level of detail and precision used in estimating cost and repair time in the existing PACT database. The goal and scope of the PACT tool did not required the added level of site- or material-specific precision associated with process-based LCA. Ideally, a next-generation version of PACT would generate bills of materials for repair and that would enable the efficient use of process-based LCA. Using a process-based LCA database would enhance the accuracy of the repair cost and time estimates, compare different transportation modes or material options (for example, different concrete strengths), and produce reasonable estimations of waste quantities.

The source of the environmental impact data used in this analysis was obtained from the online EIO LCA tool developed by the Green Design Institute at Carnegie Mellon University [13]. The data