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Review article

Review of approaches for integrating loss estimation and life cycle assessment to assess impacts of seismic building damage and repair

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ABSTRACT

Interest in sustainability and resilience of buildings has led to a growing body of literature on merging environmental impact assessment methods with seismic loss estimation methods. Researchers have taken different approaches to connecting the two fields with the common goal of estimating the social, environmental, and economic impacts of damage to buildings subject to seismic events and thus enabling the study of tradeoffs between performance objectives. The differences among these studies include topics such as treatment of uncertainty, types of components and systems considered in the performance assessment, fidelity of structural analysis ranging from region-specific empirical fragility curves to detailed building-specific finite element analysis, scope of life cycle assessment, and so on. One of the aspects of the most diverse treatment has been in obtaining environmental impact data and relating it to pre-use impact estimates. For example, the translation of damage and repairs into life-cycle environmental impacts has been done by one of three approaches: (1) Economic Input-Output Life Cycle Assessment (EIO-LCA) has been applied to economic loss estimates; (2) repair cost-ratios have been applied to environmental impacts from the pre-use stage; and (3) repair descriptions have been used to model environmental impacts of damage scenarios directly using process life cycle assessment (LCA). All of the approaches are generally accepted but may pose limitations in certain applications and can potentially result in inconsistent conclusions from study to study. A review of existing literature in the area is presented and is followed by a comparative analysis and discussion of the outcomes of taking different environmental life cycle assessment approaches. This paper provides a comprehensive overview of the research efforts in this area and discusses opportunities for further development in order to make the implementation consistent and practical for design decision making.

1. Introduction

Buildings have long been known to consume significant amounts of the world's energy and material resources and are expected to provide people with healthy and safe working and living conditions [1–3]. Sustainability (i.e. the ability to maintain a certain level of function through responsible use of resources) and resilience (i.e. the ability to absorb and quickly recover from disturbances) have emerged as important characteristics being used to evaluate the performance of buildings. Advances in computer technologies and the development of various assessment methods related to sustainability and resilience allow us to analyze and optimize energy, material, health, and safety performance aspects of buildings in the design phase [4]. However, buildings are complex systems that are difficult to model and analyze holistically, which means that application of such assessment methods can yield results that may be incomplete, inconsistent, or difficult to validate. This issue of inconsistency between model results has occurred in building energy modeling [5], embodied energy estimates [6], and life cycle assessment [7–8], and has also been highlighted in the area of seismic damage environmental impact estimation [9]. Wei et al. [9] previously compared results from multiple studies estimating seismic repair related environmental impacts in terms of embodied energy and found that their results ranged from 2 to 50% of the total building life cycle embodied energy. The large range in the results between studies can be attributed, in part, to different buildings being analyzed, but also due to the differences in methods used for the life cycle assessment and embodied energy.

The literature in the integration of seismic loss assessment and life cycle assessment has grown substantially in the past few years, yet a consensus has not been formed on the best approach. This paper

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provides an overview of the approaches to estimating environmental impacts of seismic damage to buildings and investigates the main factors influencing the results and conclusions of this type of assessment. The core studies presenting such approaches are listed in Table 1 and have three aspects in common: (1) they include one or more environmental impact metrics, (2) they utilize damage assessment methods specific to earthquakes, and (3) they develop or apply the assessment methods to buildings. While a number of studies from 2014 and earlier defined their own loss estimation methods [10–16] (defined as 'other' in Table 1, performance-based earthquake engineering (PBEE) framework has been frequently cited in studies published in 2014 and later [17–25]. The Hazus software tool has been used by researchers in this field from the beginning, with only one study using the default regional data [26], while most applying building-specific information via the Advanced Engineering Building Module (AEBM) [9,27–29]. Environmental impacts have been assessed either by using life cycle assessment (LCA) tools and life cycle impact assessments results (e.g. global warming potential, eutrophication potential, etc.) or by applying greenhouse gas emissions factors (defined as 'CO_2 factors' in Table 1. Most studies focusing on the assessment of structural systems have used CO_2 factors or process-LCA to obtain environmental impacts, while studies including non-structural components have used Economic Input-Output-LCA (EIO-LCA) *or* process-LCA. The damage to impact conversion has been done either by using damage costs as an input to EIO-LCA, by using repair-cost ratios to convert from initial to repair impacts, or by developing data specific to damage descriptions [19–22].

More detail about the studies' use of seismic loss estimation methods and their applicability to LCA is discussed in Section 2, the integration of LCA and environmental impact assessment is discussed in Section 3, and additional topics on the application of the developed methods in building design and case studies is discussed in Section 4.

The development and further refinement of the integrated seismic loss and environmental assessment methods is important for improving the design of resilient and sustainable buildings, by enabling designers and stakeholders to evaluate tradeoffs and identify optimal design alternatives [30–31]. This paper aims to provide an overview of relevant methods, discuss the application of those methods to case studies and hypothetical scenarios, and identify areas needing further development in order for the approaches to have practical usefulness and consistency for design decision making.

2. Seismic loss estimation methods

Most of the studies considering environmental impacts of buildings due to damage from earthquakes have broadly based their approach on a variety of seismic loss estimation methods. As shown in Table 1, most studies have referred to the Performance Based Earthquake Engineering (PBEE) method [32], and have used tools and databases developed by the Pacific Earthquake Engineering Research Center (PEER) to relate the structural performance of a building with monetary and other losses (i.e. downtime and casualties) following an earthquake. Some studies have described independent means of estimating probabilistic seismic loss (described as 'other' in Table 1, integrating the different phases of seismic performance assessment to evaluate the environmental performance of buildings. Lastly, the software tool Hazus, developed by the Federal Emergency Management Agency (FEMA), has been used by some studies.

All three groups of seismic loss estimation methods (PEER, Hazus, and other approaches) broadly follow a four-step assessment: (1) hazard quantification at the site of interest, (2) evaluation of structural behavior under hazard, (3) estimation of damage in different building components conditioned on the estimated structural response, and (4) calculation of losses to repair/renew different components, as illustrated in Fig. 1. Although Hazus describes its calculation module as a six-step approach [33], its method of estimating direct building loss is similar to the general four-step approach, with the exception that hazard and damages are directly correlated by using empirical data and expert judgment, and structural analysis of a building is not explicitly performed. The other variations within studies using similar loss estimation methods are in the different approaches to structural analyses and the translation of damages to environmental impacts. Fig. 1 also shows examples of when and which software tools and databases are used in the earthquake engineering part of the assessment as well as the life cycle environmental impact assessment. The list of tools and

Table 1
List of studies bridging seismic loss estimation and environmental impact assessment for buildings. (PBEE = Performance-based Earthquake Engineering, AEBM = Advanced Engineering Building Module, LCA = Life Cycle Assessment, EIO = Economic Input-Output).

Authors	Year	Publisher	Seismic loss method	Environmental impact method	Damage to impact conversion method
Chhabra et al.	2017	J. Arch. Eng.	PBEE	Process LCA (SimaPro)	Description + LCA
Welsh-Huggins & Liel		Struct. Infrastruct. E.	PBEE	Process LCA (SimaPro)	Description + LCA
Alirezaei et al.	2016	ICSDEC Conf.	PBEE & Hazus	Process LCA (Tally)	Cost ratio
Welsh-Huggins & Liel		IALCCE Conf.	PBEE	Process LCA (SimaPro)	Description + LCA
Wei et al.		J. Arch. Eng.	Hazus AEBM	CO_2 factors	Description + factors
Wei et al.		J. Perform. Constr. Fac.	Hazus AEBM	CO_2 factors	Description + factors
Dong et al.	2015	Earthq. Eng. Struct. Dyn.	Other	CO_2 factors	Description + factors
Gencturk et al.		J. Arch. Eng.	PBEE	Process LCA (Other)	Description + LCA
Belleri & Marini		Energy & Buildings	PBEE	CO_2 factors	Description + factors
Arroyo et al.		Earthquake Spectra	Other	CO_2 factors	Cost ratio
Simonen et al.		Structures Congress	PBEE	EIO-LCA	EIO-LCA
Padgett et al.	2014	J. Perform. Constr. Fac.	Other	Process LCA (Athena IE)	Cost ratio
Welsh-Huggins & Liel		IALCCE Conf.	PBEE	Process LCA (Athena IE)	Description + LCA
Sarkisian et al.		Sustainable Struct. Symp.	Other	CO_2 factors	Description + factors
Hossain & Gencturk		Eng. Struct.	PBEE	Process LCA (Other)	Description + LCA
Feese et al.		J. Perform. Constr. Fac.	Hazus	Process LCA (Athena IE)	Cost ratio
Comber & Poland	2013	Structures Congress	Hazus AEBM	Input-Output LCA	EIO-LCA
Chiu et al.	2012	J. Arch. Eng.	Other	CO_2 factors	Cost ratio
Comber et al.		Structures Congress	Hazus AEBM	Input-Output LCA	EIO-LCA
Menna et al.		Int. J. LCA	Other	Process LCA	Description + LCA
Sarkisian et al.	2011	AEI Conf.	Other	CO_2 factors	Description + factors