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ScienceDirect
Procedia Engineering 145 (2016) 525 – 531
Procedia Engineering
www.elsevier.com/locate/procedia

International Conference on Sustainable Design, Engineering and Construction

Optimization of Sustainability and Flood Hazard Resilience for Home Designs

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Abstract

Life-cycle analysis is a beneficial tool that can be utilized to quantify the performance of buildings within the context of environmental impact metrics (e.g. carbon footprint). While typical life-cycle analysis incorporates regular building maintenance, structural repairs made as a result of natural hazard damages are largely ignored. This study presents an environmental impact design optimization model that can be used to compare multiple coastal, single-family residential (SFR) building designs subjected to coastal flood hazards based on environmental impact factors. For each design, the model measures the environment impact (i.e. embodied energy and carbon footprint) of initial construction plus flood-induced repairs. Repairs are quantified using a probability-based methodology and life-cycle analysis is used to measure environmental impacts. Design options can then be compared and optimal designs that meet performance-based resilience and sustainable design objectives can be selected. A case study is presented for an SFR building located in coastal St. Petersburg, Florida, USA, and demonstrates that up to a 64% reduction in embodied energy and carbon footprint can be achieved over a 50 year building life through more resilient component configurations and materials and by increasing first floor elevations.

Peer-review under responsibility of the organizing committee of ICSDEC 2016

Keywords: Resilience; Sustainability; Life-cycle Assessment; Residential

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Peer-review under responsibility of the organizing committee of ICSDEC 2016
doi:10.1016/j.proeng.2016.04.040

1. Introduction

Life-cycle assessment or life-cycle analysis (LCA) is a commonly accepted methodology for objectively investigating the environmental impacts of products. In process-based LCA, the environmental impact of a product's lifecycle is determined by identifying the environmental flows (i.e., resources and emissions or wastes) within a defined system boundary of a product life-cycle. The product life-cycle is typically defined by four phases or stages; 1) acquisition of raw materials and material production, 2) manufacturing/construction, 3) use, reuse or/and maintenance, and 4) disposal/waste management, end-of-life, and/or recycling [1,2,3]. The methodology for LCA is outlined in the international standard ISO 14040.

Many have utilized LCA to estimate the environmental impacts of multi-family and SFR buildings [e.g. 4, 5, 6, 7]. While most residential LCA studies consider maintenance over the useful life of a building, the type of maintenance considered is not related to natural hazard related damage. Considering that almost 40% of the 2010 U.S. population lived in counties that constitute the shoreline of the country (10% of the total U.S. land area) [8] and that significant portions of coastlines are at risk from the effects future sea level rise [9, 10, 11] and increases in the frequency of stronger tropical cyclones [12], it is important to consider natural hazard damage when conducting LCAs of coastal, residential building designs.

More recent work [e.g. 13, 14, 15, 16, 17] has addressed the development of models for quantifying environmental impacts from earthquake damage-related repairs. In the studies that present case studies, multi-story reinforced concrete and steel structures in general are considered, which are more typical of commercial or multi-family residential construction, but SFR buildings have not received sufficient attention. Also, one study developed a framework for assessing the social, environmental and economic impacts associated with seismic and flood induced damages of reinforced concrete bridges [18], while another presented a model for assessing environmental impacts associated with damage from multiple hazards to bridges [19]. One study compared the environmental impacts of wind damage resulting from the use of either standard or hazard-resistant windows [20]. While these studies begin to weigh sustainable performance design objectives against hazard-resistant building designs, there is still a tremendous need to address coastal hazards within the context of SFR buildings.

This paper presents an environmental impact design optimization model that can be used to compare multiple coastal, single-family residential (SFR) building designs subjected to coastal flood hazards. For each design, the model measures the environment impact (i.e. embodied energy and carbon footprint) of initial construction plus repairs. Repairs are quantified using a probability-based procedure and life-cycle analysis is used to measure environmental impacts. A one-story home in Saint Petersburg, Florida, is evaluated as a case study to demonstrate the capability of the model for optimizing flood performance-based designs.

2. Flood Optimization Model Methodology

Environmental impact can be calculated using multiple metrics; however, for this study, environmental impacts are expressed in terms of embodied energy and global warming emissions (e.g. methane, carbon dioxide). Embodied energy is the estimated energy associated with producing a product and is expressed in units of energy (MJ). Global warming emissions (i.e. carbon footprint) are typically expressed in kg CO_2 equivalent (eq.), which includes an estimate of all global warming contributing emissions released in the production of a product. The flood model is designed to compare multiple designs to identify optimal performance by evaluating the environmental impact (embodied energy and CO_2 footprint) of initial construction and flood-induced repairs over the life of the building. The output of the optimization model is the selection of the design with the lowest total environmental impacts associated with the initial construction (C) and repairs (R).

The environmental impact of initial construction is calculated utilizing a life-cycle inventory (LCI) database, which provides the environmental impact per unit of material. The quantities of all materials used in the construction of the building are estimated and the impacts are calculated. Flood repairs are assessed using a lifecycle material damage estimator which simulates flood events (i.e. flood depths) over a building's design life utilizing Monte Carlo analysis and calculates the expected mean material repair quantities through a process of convolving the set of probable flood depths and the damage associated with those flood depths (Equation 1).

$$E(D) = \int_0^{\infty} D(v)\, p_f(v)\, dv \tag{1}$$

where *E(D)* is the expected damage, *D(v)* is the relationship between flood depth and damage, and $p_f(v)$ is the probability density function (PDF) for flood depth. The main input parameters utilized in the estimator include site and design specific parameters. Site specific parameters include the probability of extreme flood events, relative sea level rise rate, and ground elevation. Design specific parameters include the building elevation and component depth-damage curves that provide a measure of damage over a range of flood depths. When including all the parameters, Equation 1 is transformed into Equation 2.

$$\overline{QR_m} = \frac{1}{K}\sum_{k=1}^{K}\sum_{n=1}^{N}\left\{F^{-1}\left[Rand()_n\right] + S_n - (G+E)\right\} D_m(v) Q_m \tag{2}$$

where $\overline{QR_m}$ is the average of *K* iterations of cumulative damage for material component *m* over building life *N*, $F^{-1}[\ ]$ is the inverse of the cumulative Gumbel distribution, $Rand()_n$ *is* a uniformly distributed random variable between 0 and 1 for each year *n*, S_n is the relative sea level rise at the site for year *n* considering global sea level rise and local ground settlement or subsidence, *G* is the ground elevation, *E* is the height of the top of the first floor of the building relative to *G*, $D_m(v)$ is the functional relationship between flood damage for material component *m* and flood depth (i.e. component-level depth-damage function), and Q_m is the total material quantity for component *m*.

Once expected mean material repair quantities are determined, the environmental impacts of the repairs are calculated using the material unit data stored in the LCI database.

3. Case Study - Environmental Impacts of Initial Construction and Coastal Flood Damage

A case study SFR building was developed to provide a demonstration of the flood optimization model. The location of the building site is Saint Petersburg, Florida, USA (27°45'14.4"N 82°37'51.6"W). Saint Petersburg is located on the west side of Tampa Bay between Clearwater and Tampa, Florida. The site is exposed to potential surge flooding propagating from the Gulf of Mexico into Tampa Bay. The approximate ground elevation of the site is 2.13 meters [21] and the site is located in flood zone AE EL 8, where AE denotes the site is subject to a 1% chance of flooding each year and EL 8 indicates the minimum base flood elevation of the building in feet (i.e. 8 feet; 2.44 meters) required by the National Flood Insurance Program. [22]. The historic relative sea level rise trend for the site is 2.36 mm/year [23].

The case study building is a one-story, slab-on-grade, wood-framed, hipped roof SFR structure with three bedrooms and two baths (Figure 1) with layout and configuration representative of typical residential construction in coastal, southeastern United States. The foundation is placed on built-up fill elevated to the specified design elevation. The building is assumed to have a lifespan of 50 years.

The LCI database was developed for this case study based on two main sources [24, 1]. The LCI database includes environmental impacts associated with extraction of raw materials, manufacturing, and transportation of construction materials to the building site. Transportation distances were estimated by calculating the distance between material manufacturers and the site. Environmental impact data for the construction and installation of building materials were also included for each material if data were available. Environmental impacts of flood-damaged material removal were not considered.

Two design alternatives were evaluated for the case study. Design 1 represents typical construction materials and installations, while Design 2 uses more flood-resistant materials and installations and follows design recommendations described in FEMA guidance [25] for wet flood proofing (Table 1). These recommendations include using non-paper faced gypsum instead of paper-faced gypsum wallboard on all interior walls and ceilings; installing closed-cell spray foam insulation instead of fiberglass batt insulation; elevating the hot water heater, washer and dryer; and using ceramic tile for all flooring instead of mixed flooring types. Also, to demonstrate the effect of design elevation, multiple lowest floor elevations (2.44, 2.74 and 3.05 meters [8, 9 and 10 feet]) were investigated for both designs.

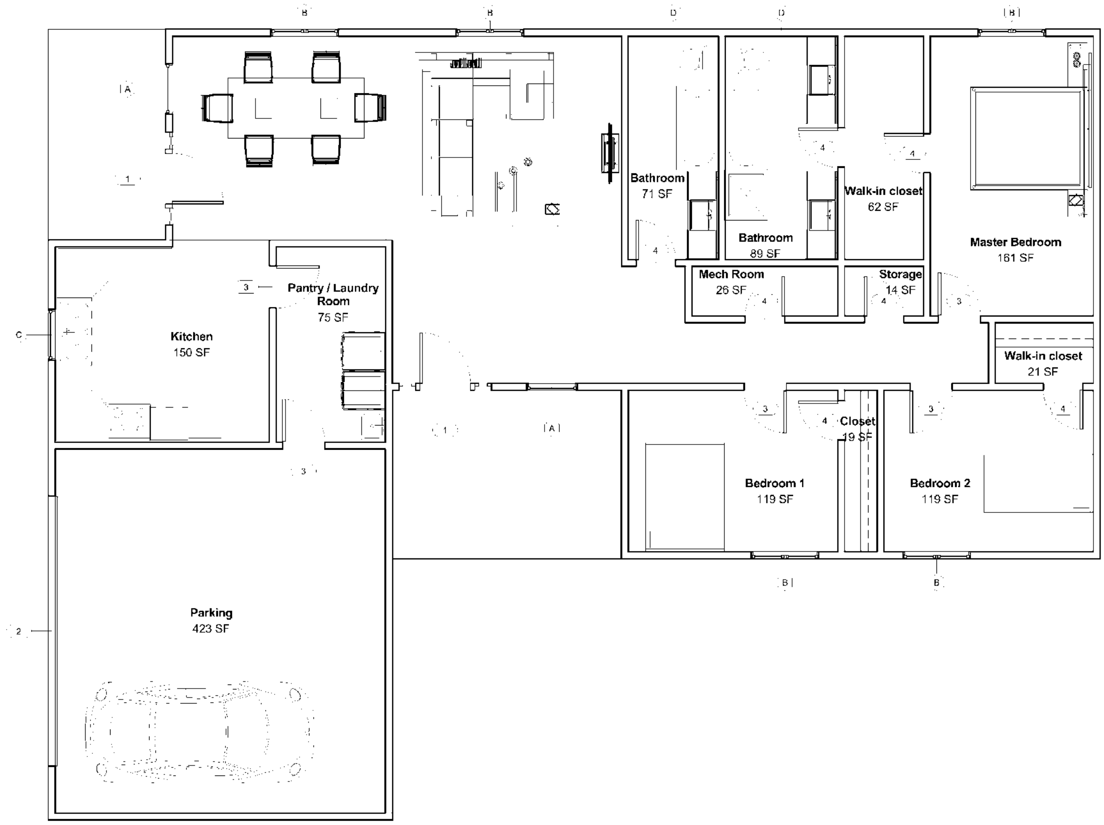

Fig. 1. Case study SFR structure floor plan.

Table 1. Case study design parameters.

Design 1 – Typical	Design 2 – Flood Resistant
Paper-faced gypsum wallboard	Non-paper-faced gypsum wallboard
Fiberglass batt insulation	Closed-cell spray foam insulation
Hot water heater located on first floor	Hot water heater in attic
Flooring types: wood, ceramic & carpet	All ceramic flooring
Electrical outlets at 1.5 feet	Electrical outlets elevated to 4 feet
Washer & dryer set on first floor level	Washer & dryer elevated 1 foot

The embodied energy and carbon footprint results for construction plus repairs over the lifespan of the building (50 years) are shown in Figure 2. From the findings, Design 2 demonstrates a reduction in energy (64%, 61% and 56%) and emissions (64%, 62% and 57%) at top of first floor elevations of 2.44, 2.74 and 3.05 meters, respectively, when compared with Design 1.

As the elevation of the building increases from 2.44 to 3.05 meters, the embodied energy and carbon footprint of both designs decrease. This is expected, as buildings elevated to higher levels would experience fewer flood-related damages over time, but this is not captured in current sustainability analyses. When Design 1 is raised from 2.44 to 3.05 meters, the design benefits from a greater reduction in environmental impacts (63% less embodied energy and carbon footprint) compared with Design 2 (55% less embodied energy and carbon footprint). While this case study evaluates a limited number of designs, multiple design alternatives can be considered to determine optimal design(s) considering both performance-based resilience targets and environmental sustainability. As determined by this case study, improved designs can be achieved simply through the use of more flood-resistant materials or through increased design elevation

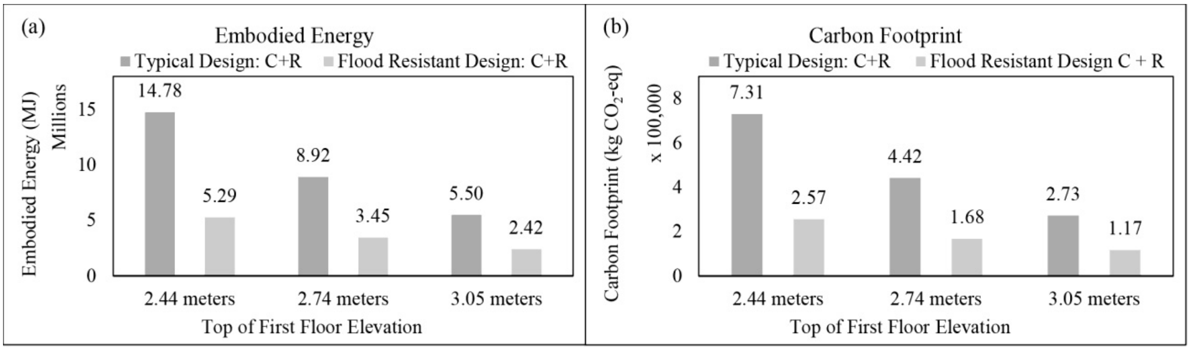

Fig. 2. Case study (a) embodied energy and (b) carbon footprint initial construction and repairs over a 50 year building life for typical and flood resistant designs.

4. Discussion

The case study analysis reveals a couple key findings. First, design concepts (i.e., component configuration and material selections) utilized during initial construction of an SFR building have a tremendous impact on the number of hazard related repairs necessary over a structure's lifetime and thereby influence the overall life-cycle impacts of the building. The case study analysis demonstrated up to a 64% reduction in energy and emissions when the more flood resistant design was chosen over a typical SFR design. Furthermore, while more robust designs may in general have higher environmental impacts because of the type and/or quantity of materials needed for initial construction, the case study demonstrates that reductions in repair impacts could potentially offset the additional impact associated with investments in more resilient structures. This finding is in significant contrast with the current state of the art, where sustainable construction aims to reduce materials and/or use low impact materials, which can be less resistant to natural hazards [26].

Second, in addition to the configuration and types of materials selected, the elevation of the building can also influence the environmental performance of the SFR building. Buildings raised to higher elevations can result in fewer flood repairs and thus reductions in life-cycle environmental impacts as demonstrated by the case study building. The results of the model indicate up to a 63%/55% reduction and in environmental impacts for typical/flood resistant design, respectively, when both designs are elevated 0.61 meters above the base flood elevation (2.44 meters). While the results shown are specific to the Saint Petersburg case study, the model methodology presented can be applied to other SFR buildings and locations.

The findings from this research demonstrate that is critical to consider hazard-related repairs when completing a life-cycle analysis (LCA) of coastal, single-family residential (SFR) building designs. As demonstrated by the case study, there is a gap in current LCA approaches for residential structures because existing methods focus mainly on typical maintenance repairs and do not consider the environmental impacts of repairs made as a result of hazard events.

5. Limitations

This study provides a unique perspective in its LCA approach to address both coastal flood resilience and environmental sustainability for SFR buildings; however, there are certain limitations, uncertainties and assumptions. First, the study is limited in that it only considers embodied energy and carbon footprint to represent environmental impacts. This allowed the LCA process to be streamlined, but it may be beneficial to consider other metrics. Additionally, other than initial construction and hazard repairs, there are life-cycle impacts that were not considered (e.g. operational energy, end-of-life impacts), but could be added. There are also uncertainties related to the estimation of repair quantities that are unavoidable (e.g., rate of RSLR, hazard forces, structural performance). The probabilistic approach addresses the uncertainty of the occurrence of hazard events (i.e. flood depth); however, some assumptions were made related to other variables. Damage assumptions associated with the hazard events were based on data and information from literature and assumptions about sea level rise were based on historical data. Finally, environmental impact data were derived from multiple sources so that a more complete LCI database could be built for the case study building designs.

6. Conclusions

This paper presents the assessment of environmental impacts of SFR initial construction and hazard-related repairs, which have been largely ignored in other LCA building studies. An environmental impact design optimization model was presented that can be used to compare multiple coastal, SFR building designs subjected to coastal flooding. The model was applied to a case study SFR building in Saint Petersburg, Florida. The findings of the study show that environmental impacts of initial construction and hazard-related repairs should both be considered, since reductions in life-cycle environmental impacts can be achieved when considering more resilient designs versus typical/weak designs. In the case study presented, the evaluated flood resistant SFR design resulted in up to a 64% reduction in embodied energy and carbon footprint over a typical design, considering building materials used, installation of materials during initial construction, and the transportation a materials to the building site.

The findings of this study underscore the importance of considering hazard-related repairs for SFR buildings subjected to coastal hazards and demonstrate that the resilience of component configurations and materials used should be considered within life-cycle analysis, as more resilient designs may result in reduced environmental impacts over a building's life. The study also lays the groundwork for future studies considering other hazards and structure types. Additionally, future models should consider multiple-hazard conditions and the variability of environmental impacts over the life of the structure.

Acknowledgements

The authors gratefully acknowledge funding from the Louisiana Board of Regents Fellowship Program and FEMA Grant Number 1603-DR-LA, Project 0039 Statewide Hazard Mitigation Community Education and Outreach Project, CFDA # 97-039 through the Louisiana Governor's Office of Homeland Security and Emergency Preparedness (GOHSEP) "Get a Game Plan" Program as a subrecipient through the LSU AgCenter.

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