Journal of Building Engineering 28 (2020) 101064

Contents lists available at ScienceDirect

Journal of Building Engineering

journal homepage: http://www.elsevier.com/locate/jobe

Life cycle assessment of seismic retrofit alternatives for reinforced concrete frame buildings

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ARTICLE INFO

Keywords:
Life cycle assessment
Reinforced concrete
Seismic retrofit
Frame structures
Recycling

ABSTRACT

Reinforced concrete structures designed prior to modern building codes are still in use today. These structures are known for their inadequate design and fragile performance during earthquakes. Over the past decades, several seismic retrofitting alternatives have been proposed as strengthening solutions for these buildings. Since the construction industry has a significant environmental burden, the impacts of the retrofit solutions should also be considered in the decision-making process of a possible seismic strengthening intervention. In this study, we performed a life cycle assessment (LCA) analysis of three seismic retrofit alternatives for reinforced concrete structures, namely, RC column jacketing, beam weakening, and shear walls. An 8-story reinforced concrete case-study building available in the literature was adopted for the LCA analysis. The environmental impacts of the selected alternatives were quantified from cradle-to-grave and two disposal phase options were studied in a sensitivity analysis: landfilling and recycling. Detailed calculations and assumptions were made in order to obtain the inventory data for the impact assessment of the three alternatives. The calculated LCA results were compared and interpreted among the analyzed retrofit alternatives. The shear wall total environmental impacts were the highest of all the studied alternatives. The pre-installation (i.e., production) and disposal of the materials required by each alternative were the phases with the highest environmental impacts, while transportation impacts were comparatively small. Recycling of the construction and demolition waste reduced the environmental impacts in the disposal phase by 29%–53%, with a lower total environmental impact reduction of 12%–42% for all the retrofit alternatives studied.

1. Introduction

Reinforced concrete (RC) buildings constructed in the 1970s and earlier are still in use today in both the developing and developed parts of the world. These buildings present a risk of poor performance in earthquakes because they were designed before the 1976 Uniform Building Code which was the first to include design guidelines for ductile behavior during seismic conditions [1–3]. There is a significant concern about inadequate seismic load resistance of these RC buildings. During the past decades, earthquakes of various intensities (e.g.; 1989 Loma Prieta, 1994 Northridge, Indonesia and Italy, 2009; Haiti, 2010; Nepal 2015) have demonstrated the seismic vulnerability of the building stock and caused extensive human and economic losses. Consequently, considerable efforts have been directed towards seismic retrofit alternatives so as to reduce the seismic hazards posed by in-service old RC buildings. For example, in the USA, in 1984, the Federal Emergency Management Agency (FEMA) began its seismic hazard reduction program which resulted in comprehensive rehabilitation design guidelines such as the FEMA 356 [4]. In addition, the state of California has issued mandatory retrofit programs for pre-1978 RC buildings to reduce structural deficiencies and improve the performance of these buildings during earthquakes.

Seismic retrofit actions for RC structures require the production of new materials (e.g., concrete, reinforcing steel bars, bricks, etc.) and construction processes to implement them onto existing structures (e.g., pouring of concrete, transportation of materials to the building site, etc.). The construction industry is responsible for a considerable environmental impact across the globe in the form of nonrenewable resource depletion, waste generation, energy consumption, and CO_2 emissions [5–7]. When considering the large number of seismically deficient

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https://doi.org/10.1016/j.jobe.2019.101064
Received 4 July 2018; Received in revised form 16 October 2019; Accepted 8 November 2019
Available online 11 November 2019

buildings eligible for retrofitting, it is expected that the environmental impacts caused by these retrofit operations will have a detrimental contribution to the environmental footprint in the U.S. and around the world. Consequently, there is a need for the assessment of the impacts on the environment created by the available alternatives for the seismic retrofit of RC structures.

The life cycle assessment (LCA) framework is a valuable tool for evaluating the environmental impacts of products, systems, or processes while considering its entire life cycle. Many different aspects of the civil infrastructure have been studied using the LCA framework and much of the literature focused on new buildings. Some example studies include RC compared to structural steel buildings [8–11], RC compared to wood buildings [12,13], the use of precast concrete alternatives [14], energy consumption of buildings with standard or green roofs [15,16], impacts of low-energy-use buildings [17], and impacts of efficient insulation techniques [18]. There is also some literature on life cycle aspects of retrofits but most of these focused on the life cycle cost characteristics [19–25] and very few studies addressed environmental impacts. Sibanda and Kaewunruen [26] studied the life cycle environmental performance of three retrofit solutions to enhance the resilience of reinforced concrete infrastructure at railway stations subjected to two unique extreme events, flooding and terror attacks. Napolano et al. [27] assessed the life cycle impacts of four different retrofit alternatives for masonry buildings: local replacement of damaged masonry, mortar injection, steel chain installation, and grid-reinforced mortar application. To the authors' knowledge, Vitiello et al. [28] is the only study that presented the life cycle environmental assessment of different seismic retrofitting alternatives for a reinforced concrete building. Their LCA was comprised of a cradle-to-gate analysis of four seismic retrofit alternatives: FRP-based strengthening, FPR-RC jacketing, insertion of RC shear wall, and base isolation. One limitation of their study is that the end-of-life, or disposal phase, was not considered in their analysis. Consequently, additional LCA studies of seismic retrofit alternatives for reinforced concrete buildings are required in order to expand the current knowledge and contribute to the emergence of general trends in this field. In addition, there is also a lack of knowledge related to the environmental impacts of the disposal phase of these retrofit alternatives.

In 2014, RC and bricks accounted for 73.2% of the total construction and demolition (C&D) waste generated in the United States, 22.6% of which (i.e., 84 million tons) originated from RC buildings [29]. Although there is not an official number indicating where the majority of this C&D waste is disposed of, European agencies have reported that 75% of the C&D waste was being landfilled in 2011 [30]. Landfilling, however, is quickly becoming a nuisance since it is estimated that, at the current disposal pace, the United States will run out of landfilling space in the next 17 years [31]. As a result, there has been an increasing effort in preventing landfilling of C&D waste and providing a more environmentally friendly alternative such as recycling, which has the potential to reduce C&D landfilling and preserve natural resources. Consequently, it is of critical importance to include and assess different disposal (i.e., end-of-life) phase alternatives such as landfilling and recycling when environmentally assessing RC retrofit alternatives. Given how retrofit efforts have increased in the past decades, the availability of such data is crucial to fully understand the environmental impacts while providing a basis for an effective decision-making process towards a less environment-degrading retrofit alternative.

In this study, we compared the life cycle environmental impacts of three different retrofit techniques: RC column jacketing, beam weakening, and the addition of RC shear walls. We based our analysis on an existing, seismically deficient, 8-story building in Los Angeles, California, which was originally analyzed by Shoraka et al. for these three retrofit options [32]. We also investigated the environmental impact benefits of recycling the C&D waste generated by each alternative as opposed to landfill disposal. We developed detailed cradle-to-grave LCA models with the objective of assisting practitioners in choosing an effective retrofit alternative and making more informed decisions.

2. Methodology

The Life Cycle Assessment (LCA) methodology was used to quantify the environmental impacts of the processes and products of the three retrofit alternatives during their life cycle. The methodology is based on the guidelines contained ISO 14,040 [33] and ISO 14,044 [34] and consists of four steps: 1) goal and scope, 2) life cycle inventory, 3) life cycle impact analysis, and 4) interpretation of the results.

2.1. Goal and scope definition

The goals of this study comprise: 1) establish a comparative LCA study on the environmental impacts associated with three different seismic retrofit alternatives for reinforced concrete buildings, 2) draw conclusions and recommendations to assist the decision-making process of each retrofit alternative studied, and 3) perform a sensitivity analysis to evaluate the environmental impact benefits of recycling the C&D waste of the retrofit alternatives.

It is important to note that there are several additional aspects that play important roles in the practical decision-making process related to which seismic retrofit alternative analyzed in this study should be implemented. Such aspects include, but are not limited to, the construction speed of each alternative, the costs associated with each alternative, the possible relocation of the building occupants, the possible temporary shutdown of commercial facilities that operate on the building, etc. The main focus of this study, however, is to provide valuable data in the form of environmental impacts to assist in the decision-making process related to each retrofit alternative studied herein.

2.1.1. Retrofit alternatives considered

FEMA 547 - *Techniques for the Seismic Rehabilitation of Existing Buildings* [1] recommends different seismic retrofit alternatives for reinforced concrete (RC) buildings. In this study, three alternatives for RC buildings were analyzed: 1) the RC column jacketing, 2) the addition of RC shear walls, and 3) the beam weakening. These alternatives were selected as possible solutions to the most common failure mechanisms identified for RC buildings under seismic loads [35,36]: 1) column failure due to inadequate flexural or shear strength, 2) shear wall failure, and 3) inadequate structural response mechanisms such as weak-column strong-beam (i.e., columns fail before the beam, resulting in a brittle and undesired failure mode).

The RC column jacketing alternative is one of the most frequently used retrofit solution that aims to increase the strength and deformation capacity of a column in order to avoid shear, axial or flexural failure [32]. It can be classified as an 'add element' technique and consists of adding concrete and steel reinforcement to the exterior of an existing column's cross-section (see Fig. 1). A few advantages of this alternative are that the increased stiffness of the structure is uniformly distributed and that there is no need for the execution of new foundations (i.e., the added reinforcing bars of the jacket can be anchored to the original footings). Special attention must be taken to ensure proper bonding of

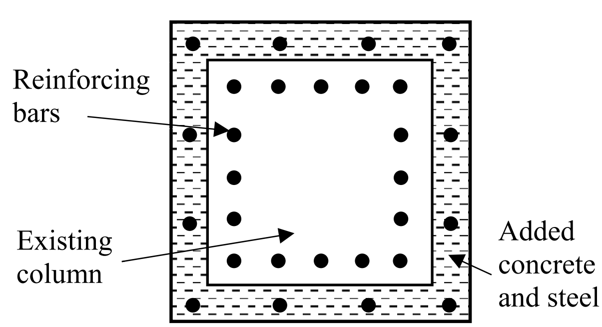

Fig. 1. RC column jacketing alternative.

the new structural elements to the original structure since the success of the procedure is dependent on the monolithic behavior of the composite element. In addition, if required to cross multiple floors, holes in the slabs are needed to allow the longitudinal bars to pass through [37].

The shear wall alternative consists of erecting an entirely new lateral load resisting system through the removal of existing partition walls of the building and construction of a high strength RC shear wall instead (see Fig. 2). Shear walls are effective in resisting the lateral loads such as those produced by earthquakes and are also effective in resisting uplift forces created by the horizontal loads applied to the top of the wall. The shear wall massive configuration – often top-to-bottom of the building – allows for an effective load transfer to the next shear wall and down to the foundation [38]. In retrofit applications, shear walls resist most of the earthquake loads and limit the displacement behavior of the building while the RC frame system resists very low amounts of earthquake loads [39]. Depending on the height of the building, this alternative can demand large amounts of materials; thus, it is also classified as an 'add element' technique. The shear wall can be constructed on the perimeter or on the inside of the building. Regardless of the location of the shear wall, this alternative typically requires new foundation construction.

The last alternative studied, the beam weakening technique consists of 'lowering' the strength and stiffness of existing beams in order to shift the building's structural behavior from a brittle strong-beam weak-column to a more ductile strong-column weak-beam behavior (i.e., beams accumulate the damage and provide additional ductility). This alternative is classified as either an 'enhanced performance of existing elements' or 'remove selected components' technique. The beams are weakened by cutting off a portion of the concrete's cross-section and reinforcing steel rebars (see Fig. 3). By weakening the beams, the structure relies on its capacity to redistribute the loads to the adjacent beams and columns. As such, this technique requires the adjacent structural elements to have enough extra capacity to sustain the added loads. Consequently, the beam weakening alternative might not be suitable to attain strict performance levels as the beams would need to be weakened to a degree greater than the building can safely sustain [28, 32].

2.1.2. Retrofitted structure

As a case study for the three retrofit alternatives, a non-ductile seismically deficient RC structure was selected and summarized in Table 1 [32]. The RC building is an 8-story moment frame structure with 3 in-plane (see Fig. 4) and 4 out-of-plane bays (not shown in Fig. 4). Each floor and each bay (i.e., in- and out-of-plane bays) are spaced at 4.6 m and 7.6 m, respectively. The building is located in downtown Los Angeles, California, over class D soil and was designed using the 1967 Uniform Building Code (UBC). The defined earthquake hazard level for

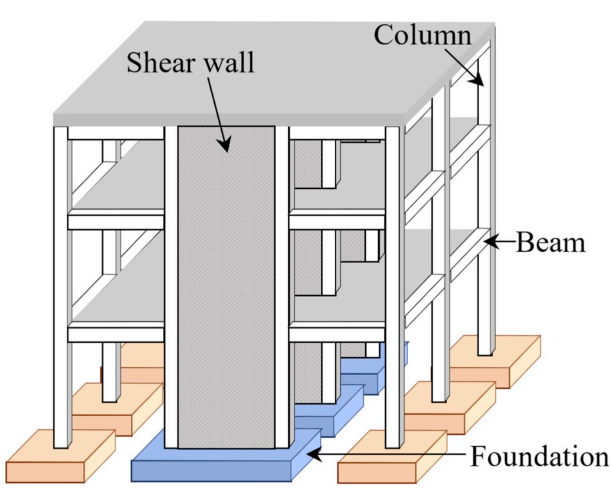

Fig. 2. Shear wall alternative.

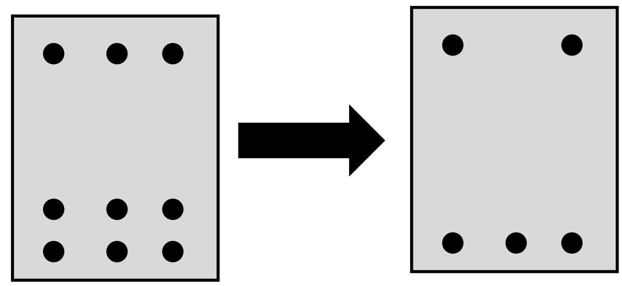

Fig. 3. Beam weakening alternative.

the selected performance objectives has a 2% probability of exceedance in 50 years.

The design of the three retrofit alternatives was performed by Shoraka et al. [32] according to the ASCE 41–13 [40] guidelines considering the earthquake conditions of the building and the target limit state of collapse prevention. Table 2 summarizes the design characteristics for each retrofit alternative and Fig. 4 indicates which structural elements of the original structure required modification. For the RC column jacketing alternative, the calculated retrofit design required modifications on the columns of the first and second floors of all out-of-plane bays, while for the beam weakening alternative, the beams of the first four stories of all out-of-plane bays required weakening. Finally, although Shoraka et al. [32] designed the shear wall retrofit to be placed outside of the building's original structure and connected with it using steel truss elements, in this study, the shear wall was considered to be placed in the middle bay of the building, as in Figs. 2 and 4, for all out-of-plane bays. This consideration aims to avoid the drawbacks of the external shear wall approach such as the noise, dust, and vibration associated with the construction, the potential disruption of access and egress, as well as the requirement that the sides of the buildings be unobstructed for the installation of new shear walls [1,41], which might not be possible in a downtown area. In addition, shear walls constructed outside the original building's frame require careful connection design, since they are responsible to transfer the loads from the new lateral load resisting system to the main building's frame. There have been recent cases of bad performance of these connections under cyclic loads in recent earthquakes, such as the CTV building case in the 2011 New Zealand earthquake, where the entire building's frame collapsed during the earthquake while the exterior shear walls remained standing [42,43].

2.1.3. System boundaries

A frequently adopted functional unit for LCA studies on buildings is the unitary internal-useable floor area (e.g., 1 m^2 of net floor area) or the unitary mass (e.g., 1 m^3 of material) for LCA studies of materials. These functional units provide standardization for comparisons and scalability for buildings with different floor areas or material quantities. In this study, however, three fundamentally different retrofit alternatives that require different amounts of materials and impact a different number of building components are compared. Consequently, the discussed functional units could not accurately compare the impacts amongst the different retrofit alternatives. To enable the direct comparison, the functional unit was considered as a function of their common design goal: to enable the building to meet the collapse prevention limit state (see Section 2.1.2). Thus, in this study, the functional unit was chosen as the retrofit design specifications (i.e., the dimensions and materials required by each of the three alternatives) to conform the original structure to the target limit state of collapse prevention.

To estimate the environmental impacts, each retrofit alternative was separated into three distinct phases: pre-installation, installation, and disposal (see Fig. 5). Previous studies have subdivided the installation phase into two groups of processes, namely, the processes required to be performed in order to prepare the original structure to receive the

Table 1
Characteristics of the case-study building [32].

Column Size, h x b (in x in)	Column rebar ratio, ρ_{rot}	Column hoop spacing, s (in)	Beam size, h x b (in x in)	Beam rebar ratio, ρ (ρ′)	Beam hoop spacing, s (in)	Floor height (ft)	Bay width (ft)
30 × 36	3.3%	15	26 × 36	0.8% (1.0%)	17	15	25

Note: 1 in. = 0.0254 m and 1 ft = 0.3048 m

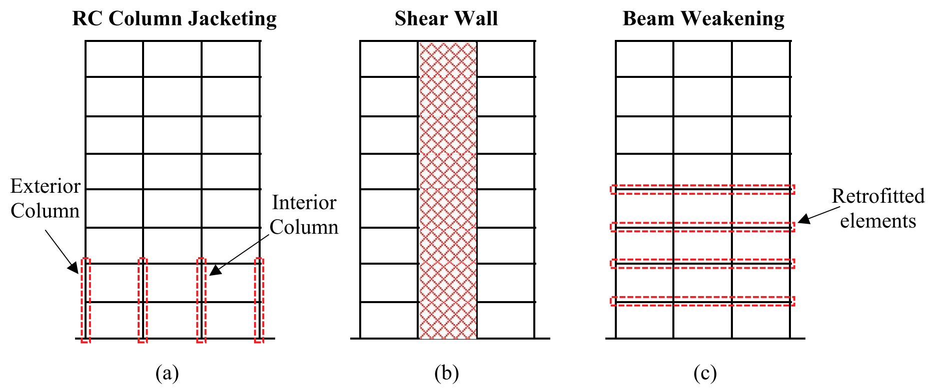

Fig. 4. Affected elements of the original structure in the calculated design of (a) RC column jacketing, (b) shear wall, and (c) beam weakening retrofit alternatives for the collapse prevention limit state.

Table 2
Design properties of each retrofit alternative. ρ_{sh} is the shear reinforcement (i.e., stirrup) ratio; b_f is the width of the flange of the shear wall; t_f is the thickness of the flange of the shear wall; L is the total length of the shear wall; L_w is the length of the web of the shear wall; t_w is the thickness of the web of the shear wall; ρ_f is the longitudinal reinforcement ratio of the flange of the shear wall; ρ_w is the longitudinal reinforcement ratio of the web of the shear wall; ρ is the longitudinal bottom reinforcement ratio of the beam; and ρ' is the longitudinal top reinforcement ratio of the beam [32].

RC Column Jacketing

Floor	Columns	Original			Retrofitted		
		ρ_{sh}	b (in)	h (in)	ρ_{sh}	b (in)	h (in)
1	Exterior	0.36%	26	28	*0.60%*	*27*	*32*
	Interior	0.50%	30	36	*1.00%*	*31*	*40*
2	Exterior	0.31%	26	28	*0.60%*	*27*	*32*
	Interior	0.40%	30	36	*1.00%*	*31*	*40*

Shear Wall

b_f (in)	t_f (in)	L (in)	L_w (in)	t_w (in)	ρ_f	ρ_w
12	5	50	40	8	0.04	0.0025

Beam Weakening

Floor	Original				Retrofitted			
	b (in)	h (in)	ρ	ρ′	b (in)	h (in)	ρ	ρ ′
1	26	36	0.75%	1.00%	*26*	*30*	*0.75%*	*0.75%*
2	26	36	0.75%	1.00%	*26*	*30*	*0.75%*	*0.75%*
3	26	36	0.755	1.00%	*26*	*30*	*0.75%*	*0.75%*
4	26	36	0.70%	0.93%	*26*	*30*	*0.70%*	*0.70%*

Note: 1 in. = 0.0254 m

retrofit (i.e., preparation processes) and the processes required to construct the retrofit on the structure itself (i.e., construction processes) [28]. Table 3 shows all the installation phase's processes identified in this study for the three retrofit alternatives separated into the preparation and construction processes groups.

The use phase of the retrofit alternatives was not included in the analysis as it is not expected that the retrofit actions will have any significant impact on the energy consumption of the building during its normal usage. In addition, due to the difficulty in estimating the potential maintenance processes that the retrofit alternatives might require in the case of an earthquake of lower-than-designed magnitude hitting the building during its life, each retrofit alternative was considered to perform optimally until the end of its desired lifespan.

The lifespan (i.e., time boundary) of the retrofit alternatives was considered from the moment the retrofit is implemented on the building to the point where the building is demolished (and so is the retrofit system), or the retrofit system needs to be demolished due to damage caused by an earthquake. This lifespan consideration was possible since all the retrofit alternatives were designed to meet the same limit state, which enforces a similar structural performance (e.g., if an earthquake causes one retrofit system to have to be demolished, all the others would need to be demolished as well). Consequently, this lifespan consideration excludes the possibility of one retrofit alternative having a longer lifespan than the others.

In the end-of-life phase – and when processes of the installation phase require demolition of part of the original structure – the

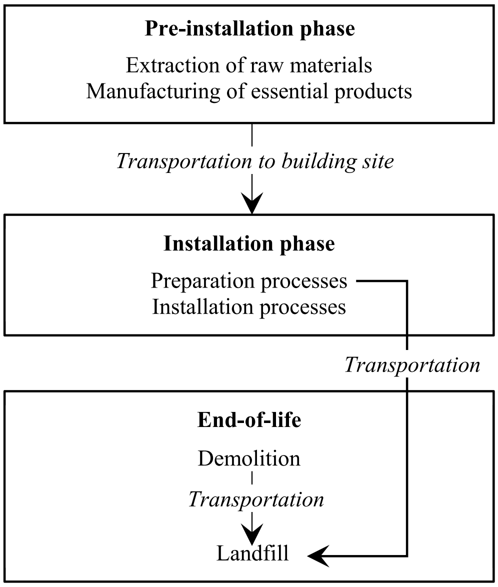

Fig. 5. LCA phases considered.

Table 3
Preparation and installation phases discrete processes.

Preparation processes	Construction processes
Partial demolition of slab	Concrete cast in place
Brick removal	Slab reconstruction
Column/beam concrete cover removal	Foundation construction
Excavation for foundation strengthening	Steel reinforcement placement
Transport of ruins to landfill	Transport of construction materials
	Brick wall reconstruction

construction and demolition waste of the retrofit alternatives was considered to be transported to a landfill facility. By including the disposal, or end-of-life, phase of the retrofit alternatives materials, the boundary condition of the LCA performed can be classified as cradle-to-grave analysis.

2.2. Life cycle inventory

To collect and calculate the life cycle inventory of the three retrofit alternatives, global (i.e., applies for all retrofit alternatives) and alternative-specific assumptions are considered. The global assumptions are:

- The building is located in downtown Los Angeles. Based on the building's location and existing concrete and rebar industries, the transportation distances for each of these materials are 6.4 km and 4.8 km, respectively.
- A lightweight concrete brick with common measurements of 20.32 × 20.32×40.64 cm, weight of approximately 5.5 kg, and thickness of the sides of 2.54 cm is used for the wall demolition and reconstruction processes.
- The brick mortar (i.e., cement) necessary to reconstruct the brick walls have commonly used mortar dimensions of 10 mm high by 10 mm wide along the edges of the concrete brick. The mortar mix is also based on common practice, where 1 part of cement is mixed with 6 parts of sand.
- Two commercially available demolition trucks are used for the demolition of the entire building with a workday of 8 h per day and taking 8 days to demolish the entire building. The engine power of the trucks is 270 kWh. This energy demand was converted into fuel requirements (i.e., diesel), based on an engine thermal efficiency of 35% and assuming that, on average, the engine works at 65% of full power during the 8 h of work (i.e., to consider that the machine will not work at full power during the entire workday).

Each life cycle phases considered were broken down by their specific unit processes, which are presented in a flowchart configuration in Fig. 6 and are discussed next together with their alternative-specific assumptions.

2.2.1. RC column jacketing

The pre-installation phase of the RC column jacketing alternative requires the production of concrete and reinforcing steel bars, and their shipping to the building site (see Fig. 6). In the installation phase, partial demolition of the slabs that intersect the affected columns is required to structurally 'connect' the new column to the existing slab. In addition to the new column size, 13 cm are added to the demolished dimension of the slabs to allow formwork placement for the column jacketing. Only the concrete portion of the slabs is demolished while the steel reinforcement was kept in place to support the rest of the slab. This demolition process is done using a commercially available concrete saw with a power rate of 2.4 kWh at an assumed operator rate of two demolished slabs per hour.

Following the slab demolition, the bricks of the walls that surround the affected columns are removed to enable the expansion of the column dimensions and the position of the formwork. One brick from each side of the column – throughout the floor height – is manually removed (e.g., hammering), with no need for electrical tools. Subsequently, the removal of the concrete cover of the existing column is performed to ensure proper adherence of the new concrete to the core of the existing column. The same saw used to demolish the concrete slabs and an operator productivity of two columns per hour were considered in this process. Once the column's core is exposed, new steel reinforcement is manually placed on the retrofitted columns. New concrete is then cast on the columns and on the partially demolished slabs. A commercially available truck-mounted concrete pump capable of pumping 100 m^3 of concrete per hour at an energy rate of 150 kWh is used for electricity calculation. Finally, the brick wall is manually reconstructed following the global assumptions stated in this section (see Fig. 6).

2.2.2. Beam weakening

Because the beam weakening alternative removes concrete and steel reinforcement from existing beams of the building, the pre-installation process produces and ships concrete bricks only, necessary for the wall reconstruction process in the installation phase. The installation phase starts with the removal of the bricks from the walls that intersect the affected beams. Three rows of bricks are removed from the walls below the beams – throughout the length of the beam – to comfortably allow for the sawing tools and human operation. The concrete cover of the existing beams is then removed in order to reach the affected longitudinal reinforcement, which is also removed. The same saw used to demolish the concrete slabs in the RC column jacketing alternative and an operator productivity of two beams per hour were considered in this process. Finally, the brick wall is manually reconstructed following the global assumptions stated in this section (see Fig. 6).

2.2.3. Shear wall

For the shear wall alternative, the pre-installation phase requires the production and shipment of a large quantity of concrete and reinforcing steel bars to the building site. The installation phase starts with partially demolishing the slabs that intersect with the new walls (see Fig. 6). Differently from the additional 13 cm used in the RC column jacketing, 25 cm were added to the demolished dimension of the slabs to accommodate the formwork in the shear wall alternative. All the bricks of the walls where the shear wall is constructed are then manually removed, similarly to all the other alternatives.

Due to its load-bearing structural characteristics, new foundations

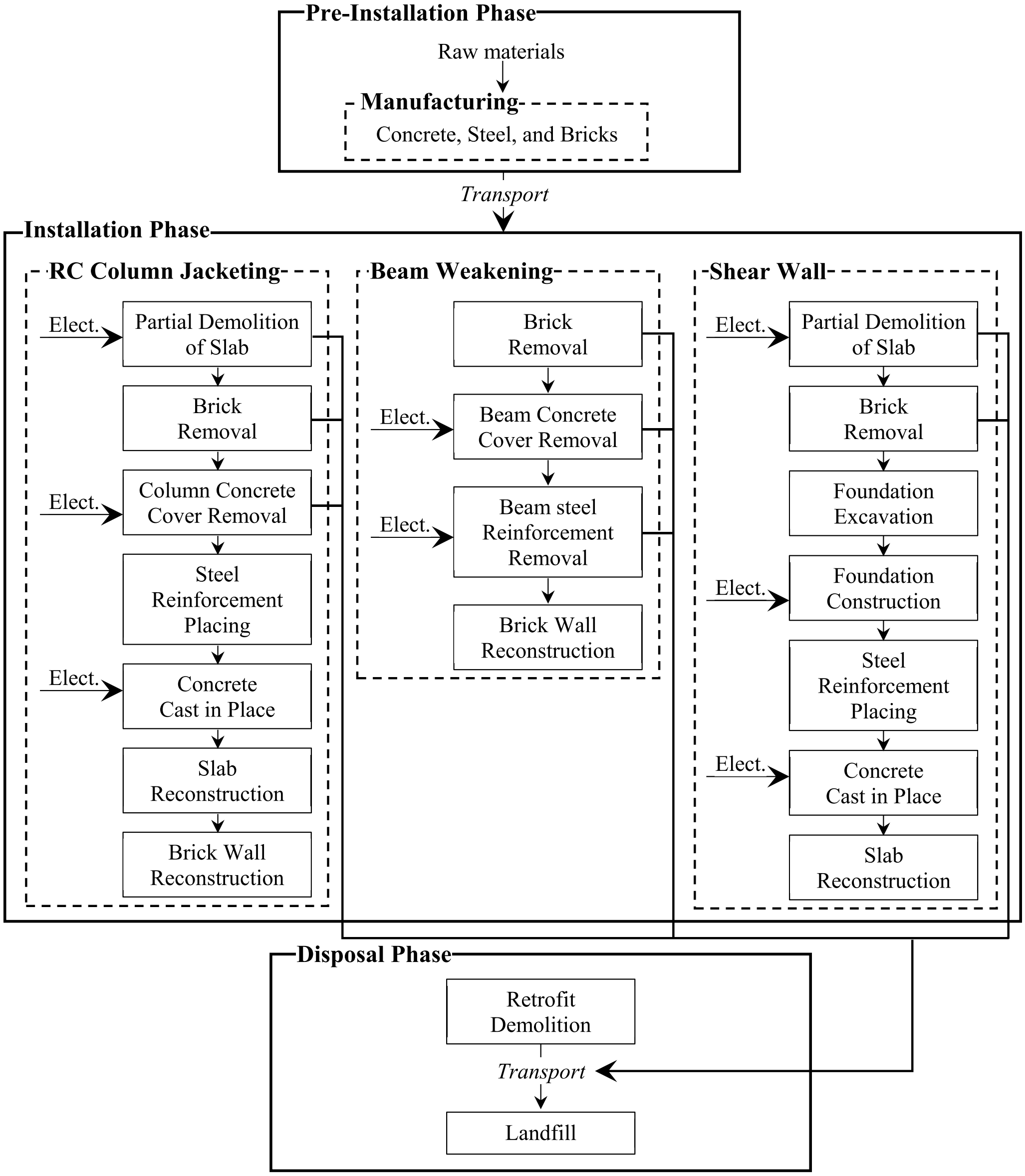

Fig. 6. Flowchart for the RC column jacketing (A), shear wall (B) and beam weakening (C) alternatives.

are required to accommodate the shear walls. The construction of the foundations is comprised of two processes: excavation and foundation construction (i.e., concrete and steel reinforcement placing). Since the details of the foundation required to withstand the loads of the added shear wall used in this study were not given, a shear wall foundation design from the literature was used [41]. To be conservative, the amount of steel reinforcement considered in this study was doubled in comparison to the amount reported in the literature foundation design. The soil removed from the excavation was assumed to be re-used on the construction site. Once the foundation is constructed, the shear wall steel reinforcement is manually placed, and the new concrete is cast. The same truck-mounted concrete pump used to cast concrete in the RC column jacket alternatives was considered for all the concrete pumping operations in the shear wall alternative.

2.2.4. Disposal phase

To allow the direct comparison of the impacts generated by each retrofit alternative, the calculation of the environmental impacts of the disposal phase was isolated to each retrofit alternative and did not include the disposal impacts associated with the rest of the building, which is independent of the chosen retrofit alternative. At the end of their lives, each retrofit alternative produces construction and demolition (C&D) waste when they are demolished. In addition, C&D waste is also produced during their installation phase, as a result of processes such as slab demolition, brick wall removal, concrete cover removal, etc. (see Fig. 6). In this study, the C&D waste generated by the retrofit alternatives is considered to be comprised of only concrete crumble and steel (i.e., other construction materials are such as wood, plastic, metals, glass, etc. is not considered). This consideration is reasonable given that this study focuses on the environmental impacts generated by the retrofit alternatives themselves, which mainly involve reinforced concrete and concrete bricks.

The inventory calculations for the disposal phase were performed using the following approach: first, the energy required to demolish the entire building is calculated based on the global assumptions stated in this section. The ratio between the mass of the materials required by each retrofit alternative and the total mass of the building is used to isolate the demolition energy required by each alternative. The produced C&D waste generated by each retrofit alternative is then transported to an existing landfill facility located 27 km from downtown Los

Angeles.

2.2.5. Inventory calculation

All LCI data used in this study were site-specific data, based on the recent technologies and normal production conditions mentioned before in this section. The inputs and outputs of each unit process of all the studied retrofit alternatives were calculated and are shown in Table 4. Detailed calculations are shown in the supporting information section (see Appendix A). The LCA software GaBi [44] was used to calculate the environmental impacts given the inventory inputs and outputs. The life cycle impact assessment was calculated using the TRACI 2.1 [45] impact assessment categories, which are: acidification (AC), ecotoxicity (EC), eutrophication (ET), global warming excluding biogenic carbon (GW-EB), global warming including biogenic carbon (GW-IB), human health particulate air (HHPA), human toxicity cancer (HT-C), human toxicity non-cancer (HT-NC), ozone depletion air (ODA), resources and fossil fuels (R–FF), and smog air (SA).

3. Life cycle impact analysis and interpretation

3.1. RC column jacketing

Fig. 7a shows the contributions of each phase to the total environmental impacts of the RC column jacketing retrofit alternative. The results show that the pre-installation and disposal phases accounted for, on average, 64.9% and 34.8% of the total environmental impacts, respectively, while the installation phase contributed to the 0.3% remaining. As shown in Fig. 7a, the main reason for the high environmental impact of the pre-installation phase was primarily the manufacturing of reinforcing steel for the new columns and the concrete bricks required in the process of wall reconstruction after the columns are jacketed. In general, the manufacturing of the construction materials has a large environmental impact due to the cement's calcination process in the clinker production, fossil fuel usage, and the amount of energy and CO_2 emitted by the steel production. The impacts due to the transportation of the required materials to the building site had an insignificant environmental contribution in the pre-installation phase. It can be easily inferred from the results of the impacts of the disposal phase in Fig. 7a, which was the second most impactful phase, that the energy required for the demolition of the retrofit and the subsequent disposal of the construction and demolition (C&D) waste on a landfill are the processes that contributed the most to the impacts in this phase. On average, the demolition of the retrofit contributed to 56% and the landfill disposal of the C&D waste contributed to 40% of the total environmental impacts in the disposal phase. Similar to the pre-installation phase, the transportation of the C&D waste to the landfill had an insignificant environmental contribution, representing only 4% of the total environmental impacts on the disposal phase.

Table 4
Inventory data for each retrofit alternative.

	RC Jacketing	Shear Wall	Beam Weakening
Pre-Installation Phase			
Material Required			
Concrete (kg)	22434	406056	–
Steel (kg)	1954	2760	–
Bricks (kg)	8394	–	26254
Mortar (kg)	387	–	1786
Installation Phase			
Partial Demolition of Slab			
Energy (kWh)	38.4	76.8	–
Column/Beam Concrete Cover Removal			
Energy (kWh)	38.4	–	57.6
Concrete Cast in Place			
Energy (kWh)	10.5	62.3	–
Slab Reconstruction			
Energy (kWh)	3.5	–	–
Foundation Construction			
Energy (kWh)	–	4.6	–
Disposal Phase			
From Partial Demolition of Slab			
Concrete Waste (kg)	5670	3851	–
From Brick Removal			
Brick Waste (kg)	8394	466725	26254
From Column/Beam Concrete Cover Removal			
Concrete Waste (kg)	13139	–	88349
From Beam Steel Reinforcement Removal			
Steel Waste (kg)	–	–	3630
Demolition			
Concrete (kg)	16764	398702	–
Steel (kg)	1954	2431	–
Energy (kWh)	8640	16924	–

3.2. Beam weakening

As shown in Fig. 7b, the pre-installation and disposal phases accounted for the highest environmental impacts of the beam weakening alternative. On average, the pre-installation phase represented 68.8% and the disposal phase represented 31.1% of the total environmental impacts. Similar to the observed in the RC column jacketing alternative, these phases concentrated the production, demolition, and disposal of the construction materials required by the retrofit alternative. Differently from the other two retrofit alternatives, the beam weakening alternative did not require the production of new reinforced concrete material, only concrete bricks to reconstruct the walls once the beams are sawed. Consequently, in the pre-installation phase impacts shown in Fig. 7b, the manufacturing of the bricks was responsible, on average, for 66% of the total impacts and the manufacturing of the brick mortar (i.e., cement and sand) was responsible, on average, for 34% of the impacts. Because more bricks are required to be removed along the length of each beam for the sawing process (discussed in Section 2.2.2), the impacts for the manufacturing of bricks were even higher than that for the RC column jacketing alternative. On the other hand, similar to the RC column jacketing alternative, transportation of the materials to the building site had an insignificant environmental impact contribution in the pre-installation phase, accounting for less than 1% across all categories. Since the beam weakening alternative performs all of its demolition during the 'installation' of the retrofit (i.e., sawing of the beams), there are no demolition impacts related to this alternative once the building is demolished. Consequently, the disposal phase was comprised only of the transportation and landfilling of the C&D waste generated during the installation phase (see Fig. 7b). The environmental impacts of the landfilling process were responsible for 91%, on average, of the total impacts in this phase while, again, the transportation of the waste to the landfill had a relatively low environmental contribution of, on average, 9% of the total impacts.

3.3. Shear wall

Differently from the previous retrofit alternatives, the disposal phase was the most environmentally impactful phase of the shear wall alternative (see Fig. 7c). On average, the disposal phase comprised 73.7% of the total environmental impacts, while the pre-installation and installation phases accounted for 26.2% and 0.1%, respectively. The main reason for the high impacts of the disposal phase was the large amounts of reinforced concrete C&D waste that is required to be landfilled. Consequently, as shown in Fig. 7c, the landfilling of the C&D waste generated by the demolition of the shear walls represented 72%, on average, of the total environmental impacts while the demolition of the walls contributed to 19%, on average. This result deviates from the conclusions of Vitiello et al. [28], which stated that the pre-installation phase was responsible for 90% of the total environmental impact of the shear wall retrofit alternative. In their study, however, the disposal (i.e., end-of-life) phase was not included. For the pre-installation phase, Fig. 7c shows that 99%, on average, of the impacts, were a result of the concrete and reinforcing steel manufacturing. Despite significant

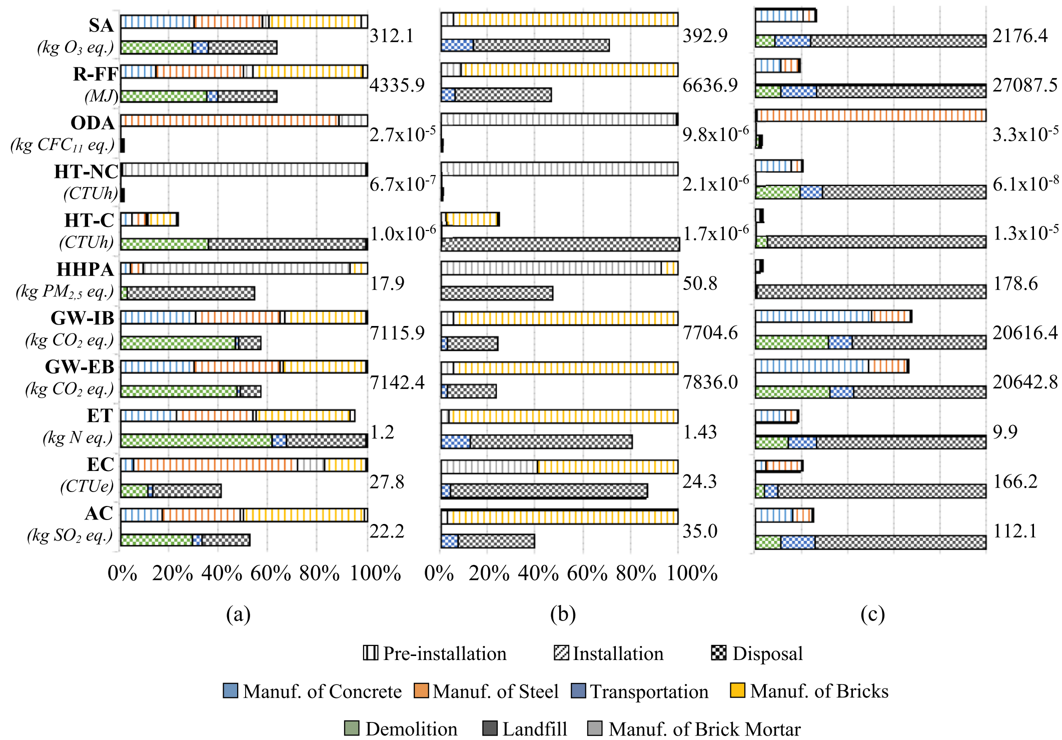

Fig. 7. Detailed environmental impacts of the (a) RC column jacketing, (b) beam weakening, and (c) shear wall alternative.

amounts of material manufacturing required in the pre-installation phase, it is evident that the disposal environmental impacts significantly outweighed the material production impacts, which helps visualize the environmental disadvantage of the use of landfills.

3.4. Comparison of all retrofit alternatives

When the total impacts of the three retrofit alternatives are compared (see Fig. 8), the shear wall alternative results in significantly higher environmental impacts than the RC column jacketing and beam weakening alternatives. On average, the shear wall alternative was 3.6 times higher than the RC column jacketing and beam weakening alternatives. The shear wall alternative impacts are considerably higher than the other two alternatives due to the massive amount of reinforced concrete material that is required to build the walls and, subsequently, be disposed of in a landfill. This agrees with the results of Vitiello et al. [28] which, despite comparing the shear wall alternative with three alternatives not analyzed in this study, also concluded that the shear wall alternative was the most environmentally degrading alternative. The RC column jacketing and the beam weakening alternatives resulted in similar total environmental impacts, with, on average, 27.3% and 27.5%, respectively, of the total impacts of the shear wall alternative. The comparison between the RC column jacketing and beam weakening retrofit alternatives revealed that despite the beam weakening alternative not requiring the creation of new members like the other alternatives (e.g., new column sizes in the RC column jacketing alternative, and new shear walls in the shear wall alternative), its environmental impacts were slightly higher than the RC column jacketing alternative. The main reason for these higher impacts was the larger amount of concrete bricks produced in order to reconstruct the walls after the installation is finished. Recall that three rows of bricks were assumed to be removed, throughout the length of the beams, to comfortably fit the sawing tools and human operation in the beam weakening alternative versus one brick from each side of the columns, throughout the height of the floor, in the RC column jacketing alternative.

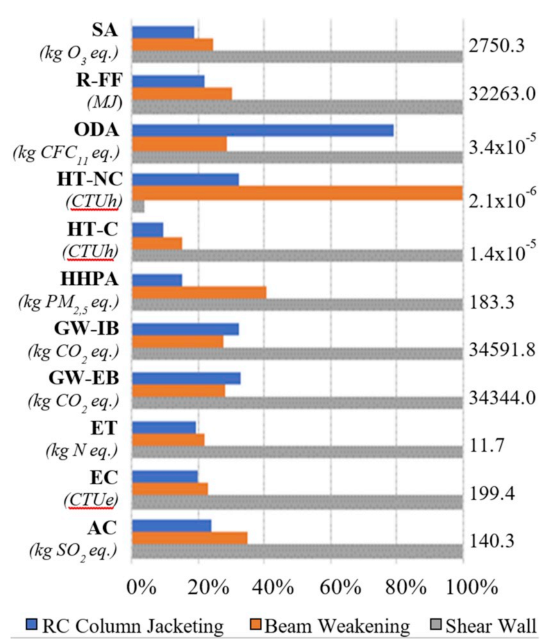

Fig. 8. Total environmental impacts of the three retrofit alternatives.

Amongst the three retrofit alternatives, a trend of three process categories contributed with the majority of the environmental impacts: 1) the manufacturing of the construction materials, 2) the demolition of the retrofit (i.e., except for the beam weakening alternative), and 3) the landfilling of the C&D waste. Together, these three categories comprised the pre-installation (i.e., Category 1) and the disposal phases (Categories 2 and 3), which were shown throughout this section to be the most impactful phases of all the retrofit alternatives. Because the manufacturing of the concrete and reinforcing steel materials in Category 1 are directly tied to the retrofit design of each alternative, it cannot be easily avoided or reduced, without a complete reconsideration of the retrofit alternatives studied. On the other hand, the manufacturing (and consequently disposal) of the concrete bricks is directly related to the type of building considered in this study. In cases where the considered building uses a different wall material (e.g., glass, drywall, etc.), or cases where no walls intersect the retrofitted elements in the moment-resisting frame system, the environmental impacts related to wall demolition and reconstruction could be reduced or avoided. The analysis of building systems that use wall materials other than concrete bricks is out of the scope of this study. However, the environmental impacts of all the processes related to the considered concrete bricked walls can be easily excluded from the performed analysis to illustrate the best-case scenario, where no walls intersect the retrofitted elements in the moment-resisting frame. Under this condition, the reduction in total environmental impacts would be approximately 35%, 75% and 32% for the RC column jacketing, beam weakening, and shear wall alternatives, respectively (see Fig. 9). In this scenario, the shear wall would continue to be the most environmentally degrading alternative; the beam weakening impacts, on the other hand, would be considerably lower, which would grant this alternative the position of least environmentally degrading of all the three studied alternatives, with 40% less impacts, on average, than the RC column jacketing.

The demolition of the retrofits in Category 2 is also linked to the assumptions made in Section 2 regarding the machinery involved in the demolition process, which the authors believe is representative of current practices. Additional studies could be performed to evaluate the impacts using faster and more efficient demolition techniques such as demolition by explosions, which is out of the scope of this study. Finally, an alternative for the impacts generated by the Category 3 processes would be directing the C&D waste to reinforced concrete recycling plants in order to lower the environmental impacts caused by the use of landfills. In the next section, the recycling of the C&D waste is considered and the LCA results are compared as an alternative to landfill disposal.

3.5. Recycling

The C&D waste generated by each retrofit alternative was considered to be disposed of in a landfill facility, which resulted in one of the process categories with higher environmental impacts across all alternatives. In this section, the recycling of the generated C&D waste is incorporated in the analysis in order to quantify its environmental benefits when compared to landfilling. Consequently, a new LCA was performed in which the C&D waste was sent to a reinforced concrete recycling facility to be further processed and become recycled concrete aggregate and recycled steel. These recycled materials can then be used in a variety of future applications such as new concrete production, new reinforcing bars, concrete for pavement, asphalt base layer, etc., replacing the need for the extraction of virgin raw material.

In general, the recycling processes of building's C&D waste (i.e., primarily reinforced concrete crumble) starts with the break of the concrete waste into smaller blocks by an excavator machine. Then, the collected concrete waste is put into a crushing equipment and, through a two-phase crushing process provided by a jaw crusher and a hammer crusher, the concrete waste is produced into recycled concrete aggregate (RCA). During the same time, the rebar and metal connector contained in the concrete waste can be separated by a magnetic separator and shipped to a steel mill, where it will be part of the production of new steel and used in various applications (including new reinforcing bars). Lastly, the reinforced concrete aggregate goes through sieving technologies to produce different particle sizes [46–48].

The recycling of reinforced concrete C&D waste into RCA is not 100% efficient in the sense that 1 kg of C&D waste does not produce 1 kg of RCA. Previous studies have reported that, in general, the recovery percentage of recycled concrete is about 60% of input C&D waste, while the rest (i.e., 40%) are fine particles produced as a result of the recycling processes [46,49]. These fine particles are generally not recommended to be used as RCA [49] and are usually disposed of in a landfill. Reinforcing steel, on the other hand, can be fully utilized as recycled scrap metal to be used in the production of good quality steel bars with roughly the same characteristics as virgin steel [50]. A case study of a building demolition in Italy identified that 70% of the steel waste was immediately recovered at the worksite after demolition, while the other 30% was recovered as a result of the magnetic separation process in the reinforced concrete recycling plant [50].

Based on the information presented in this section, the disposal phase LCA of each retrofit alternative was modified to include the environmental impacts of the recycling operations using the following approach: the reinforced concrete C&D waste generated by each alternative (i.e., including the concrete bricks) is transported to the recycling plant, where 60% becomes RCA and 40% becomes fine particles, which are sent to landfilling (the recycling plant and landfill are 21 km apart). Similarly, 70% of the steel waste is assumed to be immediately recovered at the worksite and transported to a steel mill plant that accepts recycled scrap metal located 26 km from downtown Los Angeles. The remaining 30% of the steel waste is assumed to be recovered during the recycling of the reinforcing concrete and subsequently shipped to the steel mill (the recycling plant and steel mill are 26 km apart). The environmental impacts associated with the recycling of the C&D waste are calculated using the LCI data per kg of recycled material provided by Marinković et al. [49].

Fig. 10a, b, and 10c show the impacts of the recycling the C&D waste of each retrofit alternative as a ratio of the impacts originally calculated considering landfilling. The results indicate that the beam weakening and the shear wall alternatives benefit the most from recycling, with a reduction of, on average, 53% and 52% in the disposal phase environmental impacts. On the other hand, the reduction in the disposal impacts of the RC column jacketing alternative reaches, on average, 29%. The reduction in total environmental impacts for each alternative is shown in Fig. 10d where, on average, the impact reductions were 12%, 16%, and 42% for the RC column jacketing, beam weakening, and shear wall alternatives. Despite the beam weakening and shear column alternatives presenting similar ratios of impact reduction due to the recycling of the C&D waste, the reduction in total environmental impacts of the shear wall alternative was significantly higher than the beam weakening

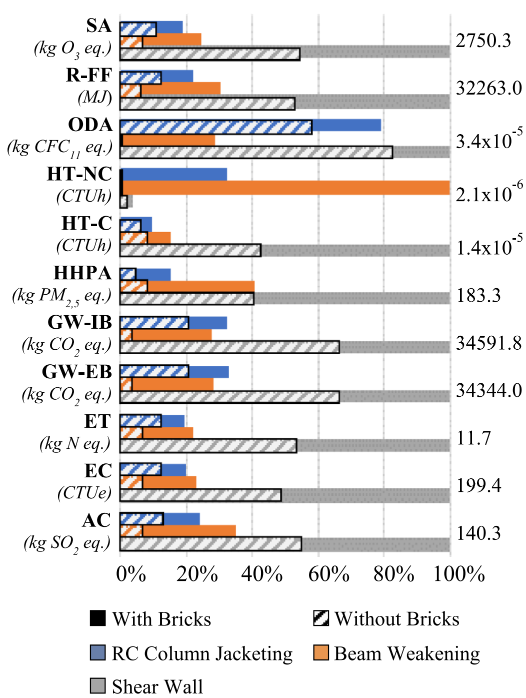

Fig. 9. Total environmental impacts of the three retrofit alternatives with and without concrete bricked walls.

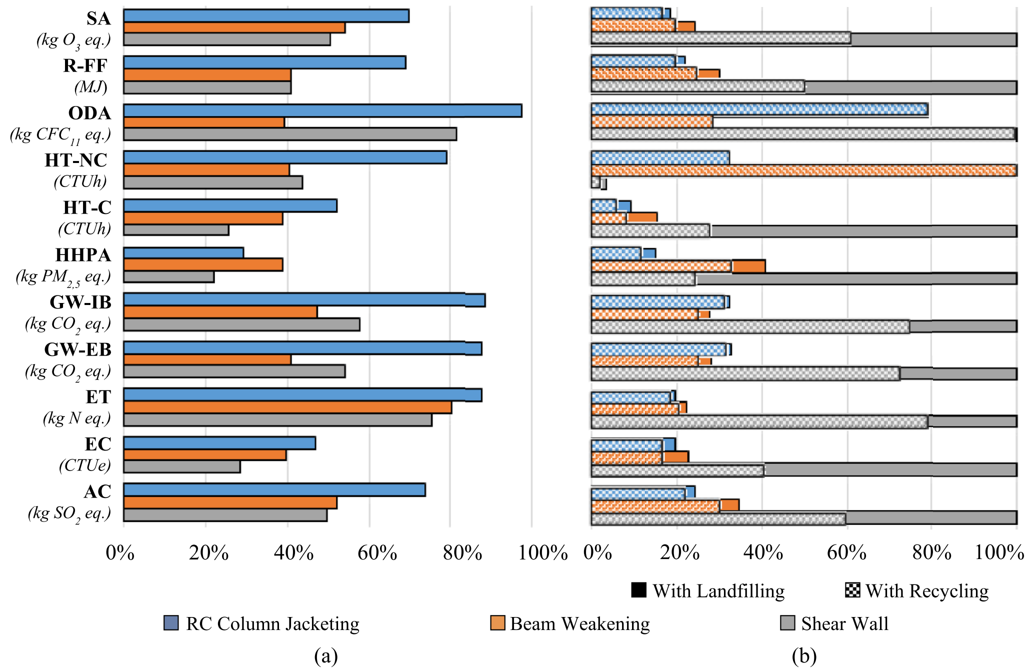

Fig. 10. (a) Recycle/landfill ratio of environmental impacts for the disposal phase of each retrofit alternative and (b) total environmental impact comparison with and without consideration of recycling.

alternative (see Fig. 10d). This occurred because the environmental impacts of the disposal phase of the shear wall alternative were significantly higher (i.e., due to the large volume of C&D waste generated by the demolition of the walls) than the impacts of the beam weakening alternative, which led the same percentage reduction to result in considerably higher impact reduction. Regardless of the significant reduction in total environmental impacts, the shear wall alternative remained two to three times more environmentally degrading than the RC column jacketing and beam weakening alternatives. The results indicated that the recycling of the C&D waste can reduce the environmental impacts of the disposal phase in, on average, 45% for all the retrofit alternatives studied; however, unless the disposal phase accounts for a significant part of the impacts across all phases (e.g., the shear wall alternative), the reduction in the total environmental impacts introduced by recycling can be significantly lower. Finally, a quick comparison with Fig. 9 reveals that the removal of the environmental impacts related to the concrete bricked walls from the analysis (i.e., simulating a scenario where the retrofit alternatives are performed on a building where no walls intersect the retrofitted elements) resulted in an higher total environmental benefit than the recycling of the C&D waste (i.e., 47% reduction versus 23% reduction due to removal of bricked walls and recycling, respectively).

4. Conclusions

This study performed a life cycle assessment of three seismic retrofit alternatives of an eight-story seismically deficient reinforced concrete frame structure. The retrofitted alternatives were: RC column jacketing, beam weakening, and shear wall addition alternatives. The retrofit designs were performed in the literature to provide compliance with the collapse prevention limit state. The study presented a detailed description of the cradle-to-grave processes considered, and relevant assumptions, for each retrofit alternative. Two distinct disposal, or end-of-life scenarios, were assessed for the construction and demolition (C&D) waste generated by each retrofit alternative: landfilling and recycling.

The shear wall alternative had the highest environmental impact amongst the three alternatives, where the disposal to a landfill was the most environmentally degrading phase, accounting for, on average, 73.7% of the total impacts. This occurred due to a large amount of C&D waste comprised of reinforced concrete and bricks that were required to be landfilled. Similarly, the pre-installation phase accounted for 26.2% of the total impacts due to the manufacturing of large quantities of concrete and steel reinforcement. The RC column jacketing and the beam weakening alternatives resulted in similar total environmental impacts, with, on average, 27.3% and 27.5%, respectively, of the total impacts of the shear wall alternative. Despite the beam weakening alternative not requiring the creation of new reinforced concrete elements like the other alternatives (e.g., new column sizes in the RC column jacketing alternative, and new shear walls in the shear wall alternative), its environmental impacts were slightly higher than the RC column jacketing alternative due to the larger amount (i.e., in comparison to the RC column jacketing alternative) of concrete bricks required to be produced in order to reconstruct the walls after the installation is finished. As a general trend amongst all the investigated retrofit alternatives, the environmental impacts associated with the processes required for the installation of each alternative and the transportation of the materials (i.e., from manufacturing site to building site, or from the building site to disposal) were negligible in comparison with the pre-installation and disposal phases impacts.

The magnitude of the impacts related to the used concrete bricks was investigated by removing all the impacts associated with them (i.e., as if no walls in the building intersected the retrofitted elements), and concluded that approximately 35%, 75%, and 32% of the total environmental impacts could be reduced for the RC column jacketing, beam weakening, and shear wall alternatives, respectively. This study also investigated the change in environmental impacts of all the alternatives when recycling, instead of landfilling, of the generated C&D waste is performed. It was observed that recycling reduced the environmental impacts of the disposal phase between 29% and 53% amongst the retrofit alternatives. The beam weakening and shear wall alternatives were the alternatives that benefited the most from the recycling, with 53% and 52% impact reduction in the disposal phase. When assessing the difference in total environmental impact due to the recycling consideration, the impact reductions were more modest, ranging from 12% to 42% amongst the retrofit alternatives. This reduction was lower than the reduction provided by the removal of the concrete bricked walls from the analysis. Despite the shear wall and beam weakening alternatives presenting the same impact reduction rate in the disposal phase, the shear wall alternative presented considerably higher total environmental reduction than the beam weakening alternative (i.e., 42% versus 16%, respectively) due to recycling. This occurred because the environmental impact of the disposal phase of the shear wall alternative was significantly higher than the disposal phase of the beam weakening alternative. Thus, the recycling effects on the total environmental impacts were more pronounced for the alternatives with high disposal phase environmental impact.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jobe.2019.101064.

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