Simplified structural design and LCA of reinforced concrete beams strengthening techniques

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Abstract

This work provides the Life Cycle Assessment (LCA) of four commonly used strengthening techniques of reinforced concrete beams. Firstly, it provides a simplified methodology to size the strengthening, overcoming the need of extensive knowledge in structures. Secondly, it provides the application of LCA to the selected techniques. The method improves the applicability of LCA to buildings, analyzes the environmental differences between techniques, and reveals the importance of the anchoring method as well as the enormous benefit in reusing building structures. Results obtained for conventional beams are displayed in tables ready to use in LCAs with broader boundary systems.

KEYWORDS: Life cycle assessment; building structures; concrete strengthening; sustainable construction; construction and demolition waste; building refurbishment

NOMENCLATURE

Variables and units:

Latin upper-case letters

ΔC: increase of the bending capacity

A_r: Area of the added strengthening piece

M_0: Original beam bending capacity

M_T: Required bending moment

$N^p{}_c$: Axial force in concrete considering a parabolic distribution

$M^p{}_c$: Bending moment in concrete considering a parabolic distribution

$N^r{}_c$: Axial force in concrete considering a rectangular distribution

$M^r{}_c$: Bending moment in concrete considering a rectangular distribution

MJ-Eq: MJ of non-renewable primary energy

E_r: Young modulus of the new strengthening material (steel or CFRP)

E_s: Young modulus of the existing rebars steel

L: Length of the beam

L_T: Total length of the reinforcement

L_s: Length of the part of the beam with insufficient bearing capacity

L_a: Anchorage length

$V_{rd,anch}$: Design shear stress of the anchorage

T_{sd}: Required shear stress

Greek lower-case letters

ε_c^{max} : Maximum strain in concrete

ε_{s1}: Strain in the tensile rebar

ε_{s2} : Strain in the compression rebar

ε_r: Strain in the strengthening material

Latin lower-case letters

b: overall width of a beam cross-section

d: distance between the most compressed concrete fiber and the most tensioned rebar

d': rebar cover

f_{dr}: yielding stress of the new strengthening material (steel or CFRP)

f_{cd}: design value of concrete compressive strength

f_{yd}: yielding stress of the existing rebars steel

h: overall depth of a beam cross-section

h/b: relation between depth and width of a cross-section beam

kgCO_2-eq: kilograms of CO_2 equivalent

s_1: Tensile rebars

s_2: Compressive rebars

x: neutral axis depth

z: distance between the most compressed concrete fiber and the reinforcement axis position

Acronyms:

CED: Cumulative Energy Demand

CF: Carbon Fiber-reinforced polymers placed with epoxy resin strengthening technique

CFRP: Carbon Fiber Reinforced Polymer

FM: Failure Mode

FRP: Fiber reinforce polymer

GWP: Global Warming Potential

LCA: Life Cycle Assessment

RC: Reinforced Concrete section increasing strengthening technique

SA: Steel placed with mechanical Anchorages strengthening technique

SE: Steel placed with Epoxy resin strengthening technique

1. Introduction

Building stock accounts for nearly 40% of final energy consumption and about 35-50% of CO_2 emissions of EU in 2011 [1]. This places the building sector, in general, but specially the renovation activity, as one of the biggest challenges in Europe, where energy saving is a major concern. Life cycle approach is considered by the scientific community as a suitable methodology to assess environmental impacts, as it takes into account both direct and indirect impacts of buildings whole life. The general methodology for LCA is defined in the ISO 14040:2006 [2] and ISO 14044:2006 standards [3].

Due to the convenience of applying this methodology to buildings, abundant research has been produced in recent years (among others [1,4,5]). Most of the Life Cycle Assessment (LCA) studies regarding buildings focus on energy refurbishment, whereas the environmental impact of building systems reparations, such as that of structures, remains studied to a lesser extent [1]. Some studies can be found in the literature relating to structures LCA in general, and just a few regarding strengthening techniques in particular. Among the general studies, different approaches can be found. Some of them focus on concrete structures technology as a whole, e.g. [6–8]. Others focus mainly on slabs [9]. Caruso et al. [10] propose a methodology for LCA of building structures as a whole, comparing different structural options. Acree and Arpad [11] conduct a comparative LCA between different structural technologies: concrete-frame and steel-frame.

As mentioned before, not many studies can be found regarding strengthening techniques. Maxineasa et al. [12] apply LCA methodology to assess reinforced concrete beams strengthened with Carbon Fiber-Reinforced Polymers (CFRP) concluding that strengthening with CFRP is less harmful than new construction. Napolano et at. [13] study structural retrofit options for masonry buildings.

Most of the papers found in the literature are based on particular cases providing valuable conclusions about them. However, they are not easily replicable. This is due to two main reasons. On the one hand, inputs considered in the different stages, especially in the construction process stage, are not always clearly specified. On the other hand, a LCA assessment of a structure is strongly dependent on the structural assessment that allows to obtain the materials that are needed. The structural assessment is time-consuming and not easy to apply by a LCA technician that normally has no expertise in structures. As no simple methods are proposed to replicate their structural assessment, LCA becomes difficult to extrapolate to other cases.

Different methods for structural assessment are generally accepted and described in codes and recommendations, such as [14,15]. In these general procedures, first, the neutral axis depth, x, is calculated from strain compatibility and internal force equilibrium, and then the design moment is obtained by moment equilibrium. The analysis must take into account that the RC element may not be fully unloaded when strengthening takes place, and hence an initial strain in the extreme tensile fiber should be considered [15]. Some aspects involved, as the accepted parabolic-rectangular stress-strain distribution in concrete and the large number of failure modes that are possible (bonded plates are susceptible to about thirty mechanisms of failure according to [16]) render this process into a complex one. Additionally, in this procedure the design moment is obtained at the end turning this calculation into an iterative process until the suitable area of the piece is found. Due to the broad knowledge of structures required, this method is not easily applicable by a conventional LCA technician or designer, who is not often an expert in the field. Furthermore, the process is highly time-consuming, what can be a burden when the final objective is not the strengthening calculation itself, but the environmental analysis. A simplified non-iterative method for structural assessment is therefore required.

One of the main applications of LCA is to compare different solutions in order to provide environmental data to enrich the decision-making process. No comparative study of building structures strengthening techniques has been found.

Among the most representative building materials, concrete dominates in the share of the total embodied energy of buildings [17] even though the impact per kilo is not excessive [18]. This is primarily due to the high amount of concrete that is used. Upgrading existing structures implies a reduction in their environmental impact as it extends their service life. This leads to a reduction of the construction process stage impact per year through the whole life of the building. Moreover, when a building reaches the end of its service life due to structural reasons and demolition is recommended, other non-separable components must be demolished too, regardless of whether the end of their service life itself is reached or not. On the other hand, the upgrading process also has some environmental burdens as new materials and energy consumption are required. These burdens depend mainly on the kind of intervention needed and the selected technology that is applied.

A structural intervention may be required for several reasons related to human errors or degradation caused by environment, human action and others, but also due to functional requirements and codes updating. Structural interventions are often classified as protection, repair, substitution, or strengthening, depending on the specific objective of the operation. Strengthening is carried out when bearing capacity of the element is insufficient due to several reasons such as technical wear or new functional requirements.

This paper focuses on beams strengthening techniques. Available strengthening techniques are abundant and decision criteria are needed regarding different parameters such as economy, functionality or environment. In this paper four reinforcing techniques are analyzed regarding environmental criteria: adding steel sheets, either with epoxy resin (SE) or with mechanical anchorages (SA), stacking CFRP laminates materials with epoxy resin (CF), and increasing the bearing capacity enlarging the beam section by adding new concrete and rebars (RC). In Table 1, a comparison between the technologies properties according to different criteria is presented.

Table 1 Comparison between bending strengthening techniques

Technique	Bending capacity increase	Deflection reduction	Execution ease	Fire resistance	Size increase
Steel-Anch.	Good	Medium	Medium	Medium	No
Steel-Epoxy	Good	Medium	Good	Bad	No
Carbon Fiber Reinf. Poly.	Good	Medium	Good	Bad	No
Reinf. Concrete	Good	Good	Bad	Good	Yes

Y: Yes / N: No / B: Bad / M: Medium / G: Good

To summarize, two different steps must be taken to conduct a LCA of structural strengthening interventions. Firstly, a structural assessment of the solution, or solutions in the case of different techniques comparison, must be undertaken. This is needed to obtain required materials and to ensure equivalent structural behavior when comparing. The existing general method is difficult to apply by a conventional LCA technician because of the high expertise in structures needed. Because of that, a proposal of a simplified methodology for structural assessment is presented.

Secondly, a LCA that involves all the different stages and that takes into account all the associated inputs and impacts must be conducted. LCA is applied to four commonly used strengthening techniques (SE, SA, CF, RC) to provide criteria to enrich decision making from the environmental point of view. Additionally, results from applying the LCA methodology to strengthen several frequently used beams according to the four analyzed techniques are displayed in tables, ready to be used by other technicians in LCAs with broader boundary systems, such as a whole building LCA. Selected beams are: three flat beams (hxb:150x300, 200x400, 250x500), three square beams (hxb: 250x250, 300x300, 500x500) and three suspended beams (hxb: 400x200, 500x250, 600x300). All the beams have a length of 6 meters.

This paper aims to make a contribution to the consideration of environmental criteria in building refurbishment, specifically concerning the structure, one of its parts damaging the environment the most. The specific objective is to develop a replicable method of LCA and comparative data of different techniques easily applicable to other cases.

2. Material and methods

2.1. Simplified method for structural assessment

The objective of this simplified methodology is to size each reinforcing material by just replacing values in simple polynomic equations when the design bending moment is known.

The proposed methodology is summarized in Figure 1:

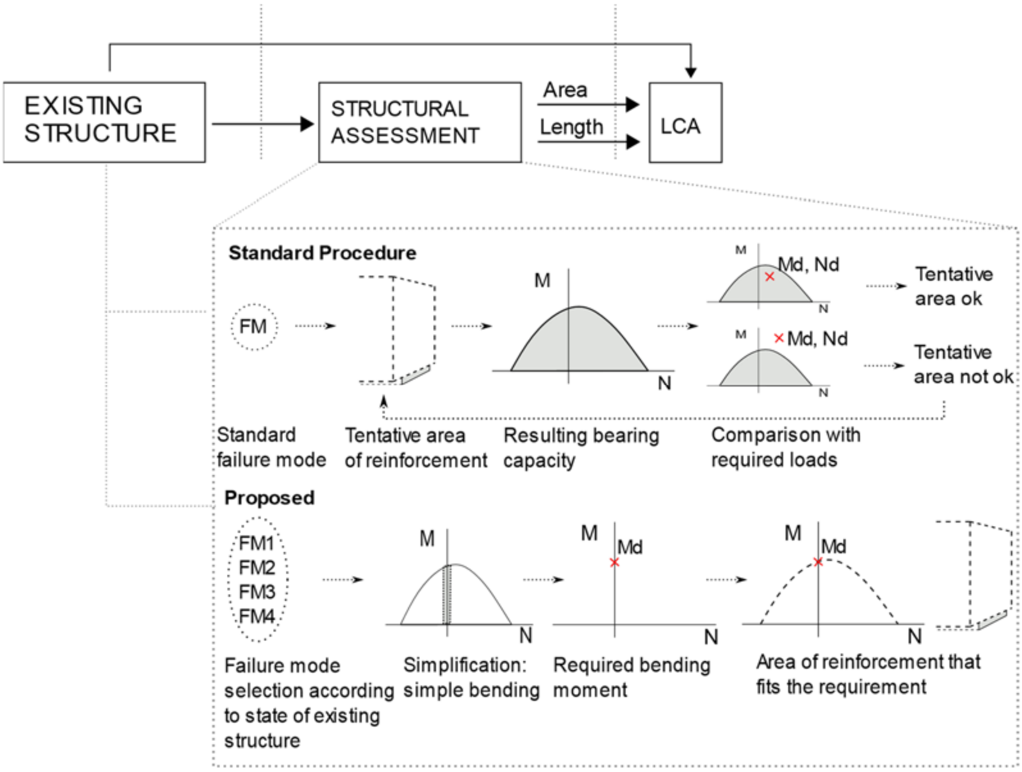

Figure 1 Summary of the proposed methodology

Some simplifications are made in the model:

1. Simple bending is supposed.
2. Existing stress in the fiber where reinforcing is placed is not considered in the simplified model (the beam is fully unloaded when strengthening takes place).
3. Ultimate strain of existing and new rebars steel is supposed to be 0.01.

The methodology applied to define the model can be divided in two parts:

1. Procedure for calculating the area of the strengthening piece (section 2.1.1).
2. Procedure to determine the length of the reinforcing piece (section 2.1.2).

2.1.1. Procedure for calculating the area of the strengthening piece

The methodology used to obtain the model for calculating the area of the strengthening piece can be summarized as follows: (i) defining the failure mode (FM), (ii) determining materials behavior and strains compatibility between elements, (iii) determining axial force and bending moment in the elements, and (iv) applying equilibrium equations.

(i*) Defining the failure mode*

The confidence level in the elements of an existing structure (concrete and tensile and compressive rebars) and therefore, its expected contribution, is especially relevant in old structures due to the grade of uncertainty of existing materials properties and state of conservation. Because of that, four different failure modes have been considered in the model. The technician should choose which one is more suitable for each specific case.

1. Failure mode 1 (FM1). Contribution of existing rebars (both tensile and compressive) is neglected. Therefore, the new added reinforcement must be able to bear all the loads: those that previously were hold up by the original rebars plus the desired increase.
2. Failure mode 2 (FM2). The new reinforcing is at the limit of its elastic behavior, $\varepsilon_r = f_{dr}/E_r$.
3. Failure mode 3 (FM3). Existing tensile rebar (s_1) is at the limit of its elastic behavior, $\varepsilon_{s1} = f_{yd}/E_s$.
4. Failure mode 4 (FM4). Existing tensile rebar (s_1) is at the limit of its plastic behavior, $\varepsilon_{s1} = 0.01$.

(ii) Determining materials behavior and strains compatibility between elements

Ideal elastoplastic behavior is supposed for steel (both in existing rebars and new reinforcing elements) and CFRP. For concrete, parabolic-rectangular behavior is assumed for maximum strain in concrete, ε_c^{max}, $0.002 < \varepsilon_c^{max} < 0.0035$. When ε_c^{max} is lower than 0.002, the parabolic distribution is transformed into an equivalent rectangular one, through α and β coefficients. This is needed because the general accepted rectangular distribution, $\sigma_c = 0.8 f_{cd} x$, is not valid as concrete is not at the limit of its admissible strain. This transformation allows the resulting equations to be greatly simplified. Doing $t = \varepsilon_c^{max}/0.006$, to simplify, the value of α(x,t) and β(x,t), equations (1) and (2), respectively, are obtained by doing $N^p_c = N^r_c$ and $M^p_c = M^r_c$.

$$\alpha(x,t) = \frac{f_{cd} 3t(1-t)^2 x}{k E_c 0.006t} \tag{1}$$

$$\beta(x,t) = \frac{k}{(1-t)x} \tag{2}$$

with

$$k = 2d\left[\frac{x}{3d} + t\left(1 - \frac{x}{4d} - t\right)\right] \tag{3}$$

Although the value of α and β depends on x and ε_c^{max}, which are unknown, they can be simplified as constant values. The values that can be applied depending on the type of concrete are shown in Table 2.

Table 2. Values of α and β for different concrete types

f_{cd} [MPa] / E_c [MPa]	α [-]		β [-]	
	mean	deviation	mean	deviation
16 / 29000	0.18	0.008	0.73	0.007
20 / 30000	0.25	0.008	0.70	0.005
25 / 31000	0.30	0.008	0.70	0.004
30 / 33000	0.37	0.008	0.70	0.003
35 / 34000	0.42	0.008	0.69	0.003
40 / 35000	0.47	0.007	0.69	0.002

A linear strain distribution according to Navier-Euler-Bernouilli beam model was assumed for compatibility. The strain of the elements is expressed as a function of the strain of the limiting element, for each FM, by applying the compatibility equation.

2.1.2. Procedure to determine the length of the reinforcing piece

In the case of the strengthening techniques based on adding steel plates (SE and SA) and CFRP laminates (CF), the total length of the reinforcement, L_T, is composed of the sum of two different parameters. The first one, L_s, is the length of the part of the beam that needs to be strengthened because its bearing capacity is insufficient. The second one, L_a, is the anchorage length that must be added to every edge of the reinforcement to avoid peeling-off at the end anchorage (Figure 2). L_s is obtained from the bending moment diagram by calculating the cut-off points, *a* and *b,* between the envelope line of the bending moment of the strengthened beam and the maximum moment that the original beam can bear, M_0.

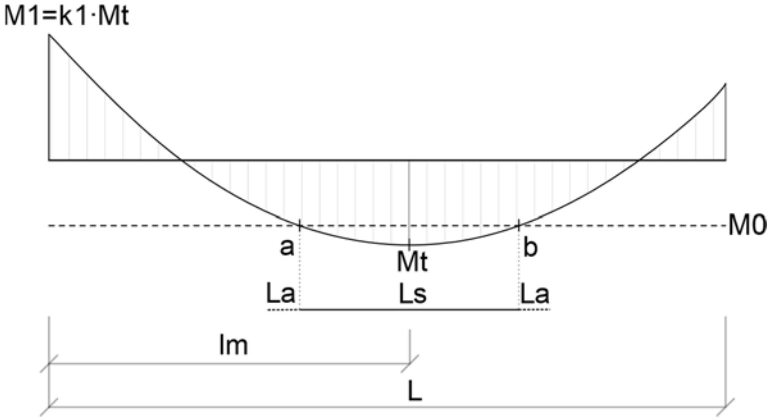

Figure 2 Relation between the length of the strengthening and the maximum positive moment line

2.1.2.1. Determining L_a

To calculate the minimum anchorage length, L_a, there are three different cases: (i) adhered techniques (SE and CF), (ii) mechanical anchorages technique (SA) and (iii) increase of reinforced concrete section (RC).

(i) In the case of adhered reinforcements, minimum L_a is obtained from equation (4),

$$L_a^{min} = \frac{N_r^a}{\tau_{ad} * b} \tag{4}$$

where $N_r^a(x_a)$ is the tensile force in the strengthening piece in *a* (or, alternatively, in *b*) and τ_{ad} is the maximum admissible tensile stress. The value of τ_{ad} is the lowest between the admissible tensile stress in the concrete, in the epoxy resin, and in the strengthening material. Usually, concrete is the limiting material and according to [19], a value of $\tau_{\mathrm{ad,max}} = 2\frac{f_{ctm}}{\gamma}$ is taken for the anchorage area.

(ii) When steel sheets are placed with mechanical anchorages, $L_a = 0$, as $N_r^a (x_a)$ is transmitted to the original beam by the anchorages. Because of this, $N_r^a (x_a)$ must be considered as a shear force in the anchorages calculation.

(iii) In the case of RC technique, for the concrete, L_T is that of the beam. For the added rebars, L_a is determined by national codes. In the case of Spain it is defined in EHE-08 [20].

2.1.3. Application to a case study

To validate the accuracy of the model results compared to general accepted method, the model is applied taking as a case study a RC beam.

2.2. LCA of the strengthening techniques

The general methodological approach regarding LCA is described in the ISO 14040:2006 standard [2]. The application of this approach to buildings can be found in the CEN/TC 350 standard, EN 15643-2 [21]. This paper is based on it.

To be able to make any environmental comparison between techniques, an equivalent fulfilment of the structural requirements must be ensured. Simplified structural assessment method is applied, choosing FM 1, where contribution of existing rebars is neglected, because it is suitable for all the analyzed techniques.

LCA is applied to strengthen several frequently used beams by different techniques (SE, SA, CF, RC). In this paper, beams of 6 m of span, constrained in both edges are taken as a case study.

The proposed method can, nevertheless, be extended to other cases by applying either the general method or the simplified one proposed in this paper, to obtain the data regarding structural assessment.

The use of a large set of indicators can make decision-making process more difficult as it increases the number of parameters. On the other hand, the use of a single indicator may result in loss of important information [22]. In this paper, solutions are evaluated according to the Cumulative Energy Demand (CED) v.1.08 indicator (in MJ-Eq or kWh-Eq) and the Global Warming Potential (GWP) indicator, based on 2007 IPCC v1.02 methodology, and using the software tool SimaPro v7.3. These indicators are chosen because these are among the most widely used [23], as in [24,25]. Moreover, they are the first indicators suggested by the standards developed by CEN/TC 350 on the sustainability of construction works in the categories of i) Indicators describing environmental impacts, and ii) Indicators describing resources use. Additionally, these are the only indicators that are nowadays provided by simulation software for the use phase of buildings, and therefore the only ones that allow comparison between different stages.

2.2.1. Goal and scope of the LCA

The objective of all the performed LCAs is to obtain the non-renewable primary energy consumption (MJ-Eq) and kilograms of CO_2 equivalent ($kgCO_2$-eq) of every strengthening technique when applied to different beams. Results could be used in further LCAs of systems with larger boundaries as a complete building or even a set of buildings.

2.2.2. Functional unit

In every one of the LCAs developed in this paper, the functional unit consists of a particular increase of the bending capacity of a specific reinforced concrete beam. Different bending capacity increases are studied (10%, 30% and 50%) in order to determine if there is a dependency between the required increase and the technique environmental suitability.

2.2.3. Boundaries of the system

According to EN 15643-2, life cycle stages of a building are: (i) product stage, (ii) construction process stage, (iii) use stage and (iv) end-of-life stage. All the impacts associated to them must be evaluated in a LCA. In this paper, the impact of use stage is assumed to be zero, as no operational energy or water is consumed when using the strengthening and no maintenance or repair is expected under normal conditions during the service life, set as 50 years, to be aligned with European structural code [26].

(i) Product stage

The product stage includes all the impacts associated to the products manufacturing, Cradle-To-Gate. Products included are those needed for the strengthening itself but also for placing and coating.

(ii) Construction process stage

It comprises non-renewable primary energy consumption and equivalent CO_2 emissions associated to transport from the gate to the building site and strengthening operation execution on-site. The last one specifically comprises impacts associated to previous concrete surface treatment or damaged concrete reparation and restitution, the strengthening operation itself, and protection from fire and corrosion when needed. A generic working site placed in Zaragoza (Spain) has been selected for transport evaluation purposes. For the calculation of the transport distance, the average between the three most common supply companies in the area has been taken into account for traditional materials.

On the other hand, as previously mentioned, strengthening is often also needed in beams with degradation problems. Inner-rebar corrosion is between the most popular degradation problems in residential RC structures [27,28]. Because of that, the impact associated to original RC section restitution and repair is analyzed. Its contribution to final energy consumption and equivalent CO_2 emissions must be added to previous data. In this paper, the restitution process has been modelled considering: deteriorated concrete cutting manually; inner rebar cleaning, passivation and treatment against corrosion; original concrete section restitution and sandblasting of concrete surface for cleaning and preparation. For calculation purposes, the final volume of restituted concrete has been considered to be equal to 5 cm deep, 150 cm long and width equal to that of the beam.

In the case of the RC technique, the impacts associated to restitution and repair are different. Some of them should not be added because they are needed even if there is no degradation, and therefore, they have already been accounted for. A part of the original concrete must be cut even if no degradation is present, in order to obtain a suitable contact between the old and the new concrete. This contact is often ensured adding epoxy resin between the new and the old material.

(iv) End-of-life stage

In general terms, a simplified end-of-life scenario with no recycling and disposal to landfill is used. This is often the real case in practice [29]. There is a considerable variation in the literature data, above all, regarding CFRP end-of-life. Because of that, to model this landfill scenario, data from Ecoinvent v.2.2 database are used. No additional waste treatment operation has been considered.

Construction and demolition waste is a big environmental challenge and in recent literature increasing attention has been paid to this matter [29–32]. Among the treatment alternatives for waste generated at construction sites, the most desirable option is the re-use of products obtained in new constructions [33]. Nevertheless, this is not always possible, and techniques must be designed to allow it. Recycling is the conversion of waste into a new raw material that can be used in the manufacturing of new products for use in new constructions [33]. This is more often possible, but associated impacts compared to reusing are bigger due to the needed processing. The potential benefits of recycling are analyzed in this paper. As the paper focuses on non-renewable primary energy consumption and kilograms of CO_2 equivalent, recycling is introduced in the model as a way of avoiding raw materials and, consequently, reducing impacts in the product stage. All processes associated with recycling (including separation of the element to be recycled, transport to the recycling plant and processing) are included in the product stage. This is done by applying a weighting coefficient of consumption associated with recycling as a whole, compared to the extraction and processing of raw material. These coefficients are obtained from the literature.

Steel is sometimes reused without processing [34], but in the case of steel sheets, the usual method is to recycle the material after processing. This is already a common practice. Gao et. al. [34] states that the use of recycled steel reduces by 40% its energy consumption compared to non-recycled one.

In the case of CFRP, as Pimenta and Pinho state, most of the CFRP waste is actually landfilled because, among others, recycling composites is inherently difficult because of their complex composition and thermoset resins used that cannot be remoulded [35]. Improvements are being made in that direction [36], and there are some data in the literature. Howarth et al. [37] state that the specific energy of mechanical recycling is around 2.03 MJ/kg. Witik et al. [38], state that in comparison with landfilling, impacts are reduced by 78% and 84% for the climate change (kg of CO_2 equivalent) and resource (MJ primary of non-renewable energy) categories respectively. Suzuki et al. [36], takes into account that mechanical properties of recycled CF are reduced, and analyses a hybrid made from both recycled and virgin material with a final energy intensity of 36 MJ/kg. Although recycling is not a usual practice in construction and no data of recycled CFRP specifically applied to structural elements has been found, CFRP recycling is studied on a hypothetical base. Aligned with the literature, a reduction in the product stage of 80% of the non-renewable energy and 75% of the kg of CO_2 equivalents is taken, although these are just approximate data and further research is required.

In the case of concrete, recycling is justified because it can reduce some environmental impacts as, among others, soil pollution, but it does not reduce energy consumption. In fact, the energy intensity of recycled concrete is 5% higher than that of virgin material because of the energy required to break the old concrete [34]. Even though the concrete recycling technique has been known for more than 50 years, nowadays it is not widely used due to some drawbacks [39].

In this paper, according to the literature, [34] and [38], non-renewable primary energy consumption in the corresponding plant when recycling steel, CFRP and concrete is taken as 40%, 20% and 105%, respectively, with regard to the virgin material. It must be noted that these are tentative data and that whereas steel recycling is a fairly common practice, CFRP and concrete recycling in small construction works is not. In addition, our hypothesis is, for transport calculation, that the production plants from raw materials are themselves capable of recycling. This is not always true, especially for materials that are not currently being normally recycled, as CFRP. However, this criterion has been assumed to study, at a theoretical level, possible benefits of this practice, in a scenario where, at least, this possibility exists.

2.2.4. LCI inputs and outputs

For all the strengthening techniques analyzed in the paper, unit embodied values are obtained taking Ecoinvent 2.2 database as a source. Unit embodied values of construction works and products that are not directly included in this database are obtained by modeling them as an assembly of materials, energy and transformation processes that are already in Ecoinvent. The model proposed by Das [40] is used to model the CFRP production. From the inventory of raw materials, energy and processes obtained from Ecoinvent, the impact assessment methodologies (CED and GWP respectively) are applied to obtain non-renewable primary energy and CO_2 emissions.

Processes and materials that have been taken into account to model impacts associated to CFRP, steel-anchorages and reinforce concrete are displayed in Table 3, Table 4 and Table 5, respectively. In the no-recycling scenario, 100% of the materials are obtained from raw materials. Data relate to plants in the EU.

Table 3 Main LCI inputs and outputs associated to carbon fiber reinforce polymer (CF) strengthening

Stage/process	Description
(i) product stage	
Material of reinforcement cradle to gate	CFRP laminate (70% carbon fiber + 30% epoxy resin, modelled from PAN [40])
	Epoxy resin applied to CFRP and concrete surface to attach the material
	Protection against fire for 120 minutes with light mortar (60 mm thickness), density=500 kg/m³)
	Plaster gypsum for final surface coating
(ii) construction process stage	
Transport gate to site	Transportation of CFRP laminate to building site
	Transportation of epoxy resin to building site
	Transportation of light mortar to building site
	Transportation of gypsum to building site
Original concrete repair	Deteriorated concrete cutting *
	Inner rebar cleaning, passivation and treatment against corrosion *
	Original concrete section restitution *
	Epoxy resin junction between new and existing concrete *
	Sandblasting of concrete surface for cleaning and preparation
CFRP laminate treatment	Cutting of laminates on site.
(iv) end-of-life stage	
Landfill	Transportation to landfill
	Disposal to landfill

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* Construction works included just when original concrete is damage by corrosion

Table 4 Main LCI inputs and outputs associated to steel with anchorages (SA) strengthening

Stage/process	Description
(i) product stage	
Material of reinforcement cradle to gate	Hot-laminated steel sheet S235JR Stainless steel anchors Protection against fire for 120 minutes with light mortar (24 mm thickness), density=500 kg/m³) Plaster gypsum for final surface coating
(ii) construction process stage	
Transport gate to site	Transportation of steel sheet to building site
	Transportation of anchors to building site
	Transportation of light mortar to building site
	Transportation of gypsum to building site
Original concrete repair	Deteriorated concrete cutting *
	Inner rebar cleaning, passivation and treatment against corrosion *
	Original concrete section restitution *
	Epoxy resin junction between new and existing concrete *
	Sandblasting of concrete surface for cleaning and preparation
Steel sheet treatment	Anti-corrosion paint
Anchoring process	Drilling of concrete and steel
Protection	Moisture protection of the edges with mortar
(iv) end-of-life stage	
Landfill	Transportation to landfill

	Disposal to landfill

* Construction works included just when original concrete is damage by corrosion

Table 5 Main LCI inputs and outputs associated to reinforce concrete (RC) strengthening

Stage/process	Description
(i) product stage	
Material of reinforcement cradle to gate	Concrete
	Reinforcing steel and wire
	Plastic spacers to ensure concrete cover
	Plaster gypsum for final surface coating
(ii) construction process stage	
Transport gate to the site	Transport of concrete to building site (including energy consumed in the continuous mixing of concrete during transport)
	Transportation of rebars to building site
	Transportation of spacers to building site
	Transportation of gypsum to building site
Construction works	Concrete cutting (when corrosion is present, the thickness of concrete to be cut may be greater)
	Inner rebar cleaning, passivation and treatment against corrosion
	Original concrete section restitution (when corrosion is present, the thickness of concrete to be restored may be greater)
	Epoxy resin junction between new and existing concrete
	Sandblasting of concrete surface for cleaning and preparation
	Shoring
	Formwork
(iv) end-of-life stage	
Landfill	Transportation to landfill

Disposal to landfill

LCI inputs and outputs for SE strengthening are similar to those of SA but replacing construction works associated with anchoring with those due to epoxy resin (also in construction, where needed steel sheet treatment includes application of detergent and solvent, sandblasting and anti-corrosion paint).

Finally, the worst scenario from the strengthening point of view, where the two environmental indicators considered are higher, is compared with demolition and reconstruction of a new beam, with the desired bending resistance. For simplification purposes, data from BEDEC database [41] are taken for the energy consumption and kg CO_2/m^3 associated to demolition and reconstruction. In this paper, the worst scenario is when a 50% of increasing in the bending capacity is needed and degradation caused by corrosion is present, so previous restitution of the original state is also needed.

3. Results

3.1. Results of simplified method for structural assessment

3.1.1. Equations for calculating the area of the strengthening piece

Results for FM1 are presented below. Results for FM 2, FM3 and FM4, when admissible, are included in the Appendix. It must be noted that in the CF technique just the FM1, FM3 and FM4 are admissible. In the case of FM3 the CFRP material is wasted, so it is not advisable to use CF technique when FM3 is desirable

3.1.1.1. Steel plates reinforcement (SE and SA) and increasing reinforced concrete section (RC) techniques

To obtain the area of the strengthening piece, firstly, x must be calculated from equation (5). Among the three mathematically possible values of x, the one inside the section must be chosen ($0<x<h$). The coefficients a_1, a_2, a_3 and a_4, will depend on the selected failure mode and can be obtained by substituting known values in equations below.

$$h^{s}(x) = a_1x^3 + a_2x^2 + a_3x + a_4 = 0 \tag{5}$$

Coefficients obtained in the case of FM 1 are obtained from equations (6), (7), (8) and (9), respectively.

$$a_1^{FM1} = -\frac{1}{2}\alpha\beta^2 bE_c\frac{f_{yr}}{E_r} \tag{6}$$

$$a_2^{FM1} = \alpha\beta bE_c\frac{f_{yr}}{E_r}z \tag{7}$$

$$a_3^{FM1} = M_T \tag{8}$$

$$a_4^{FM1} = -M_Tz \tag{9}$$

Once that x is known, the needed area of reinforcing piece, A_r, can be obtained from equation (10).

$$A_r^{FM1} = \frac{1}{f_{yr}}\left[\alpha\beta bE_c\frac{f_{yr}}{E_r}\frac{x^2}{(z-x)}\right] \tag{10}$$

3.1.1.2 CFRP laminates strengthening technique

Firstly, *x* is obtained from equation (11).

$$h^{CFRP}(x) = b_1x^2 + b_2x + b_3 = 0 \tag{11}$$

The coefficients b_1, b_2 and b_3 for FM1 are obtained from equations (12), (13) and (14), respectively.

$$b_1^{FM1} = -0.33672f_{cd}b \tag{12}$$

$$b_2^{FM1} = 0.809524zf_{cd}b \tag{13}$$

$$b_3^{FM1} = -M_T \tag{14}$$

By applying equation (15) the needed area of the strengthening piece is found.

$$A_r^{FM1} = 231.293\, f_{cd}b\frac{1}{E_r}\frac{x^2}{(z-x)} \tag{15}$$

3.1.2 Equations for calculating the length of the strengthening piece

The total length, L_T, of the reinforcing element can be obtained from equation (16).

$$L_T = L_s + 2L_a \tag{16}$$

In the case of the RC technique, composed of new concrete and rebars, equation (16) is applied just to the rebars while L_T of added concrete is that of the original beam.

3.1.2.1. Calculation of L_s

For all the analyzed strengthening techniques, L_s is calculated through equation (17), where x_1 and x_2 are the solutions of equation (18).

$$L_s = x_2 - x_1 \tag{17}$$

$$-\frac{M_T(1+k_1)}{l_m^2}x^2 + \frac{2M_T(1+k_1)}{l_m}x - k_1M_T - M_0 = 0 \tag{18}$$

k_1 is the ratio between bending force in the left edge, M_1 and M_T ($k_1 = M_1/M_T$;), L is the length of the beam and l_m is the distance between the left edge and M_T (Figure 2).

For a single beam with constraints in both edges, $k_1 = 2$ and $l_m = L/2$, and equation (18) can be simplified as equation (19).

$$-\frac{12M_T}{l^2}x^2 + \frac{12M_T}{l}x - 2M_T - M_0 = 0 \tag{19}$$

3.1.2.2. Calculation of L_a

(i) Adhered techniques

In the case of steel sheets adhered with epoxy resin, minimum L_a is obtained from equation (20), for all the analyzed FM.

$$L_{a,min} = \frac{f_{ys}A_r}{\tau_{ad}b} = \frac{f_{ys}A_r}{2\frac{f_{ctm}}{\gamma}b} \tag{20}$$

In the case of CFRP adhered with epoxy resin, $L_{a,min}$ can be obtained for the FM1 from equation (21). In FM4, equation (22) is obtained.

$$L_{a,min}^{LS1} = \frac{0.0035(z - x_A)A_rE_r}{2\frac{f_{ctm}}{\gamma}bx_A}\frac{M_0}{M_T} \tag{21}$$

$$L_{a,min}^{LS4} = \frac{0.01(z - x_A)A_r E_r}{2\frac{f_{ctm}}{\gamma} b(d - x_A)} \frac{M_0}{M_T} \tag{22}$$

(ii) In the case of steel sheets placed with mechanical anchorages, $L_a = 0$

(iii) Added rebars in RC section increase technique

L_a in the case of European Standard [42], for a rebar of corrugated steel anchored by straight extension with good adhesion, is obtained from equation (23).

$$L_a = \max \left\{ \begin{matrix} m\emptyset^2 \geq \frac{f_{yk}}{14}\emptyset \\ 10\emptyset \\ 200 \end{matrix} \right\} \tag{23}$$

3.1.3. Mechanical anchorage calculation

When steel sheets are placed with mechanical anchorages, the number of anchorages is obtained from equation (24).

$$n_{anch} = \frac{T_{sd}}{V_{rd,anch}} = \frac{N_r^A(x_A)}{V_{rd,anch}} \tag{24}$$

where $N_r^A(x_A)$ is the tensile force in the strengthening piece, $N_r^A(x_A) = f_{ys}A_r$.

3.1.4 Application to a case study

The model is applied taking as a case study a RC beam of 6.00 m of span and cross section of 300 mm x 300 mm (b x h), with a concrete cover (c) of 24 mm, and for the strengthening technique based on adding steel sheets adhered with epoxy. A_{s1} is 653.45 mm² and A_{s2} is 100.53 mm². A RC of $f_{cd} = 20\ MPa,$ commonly used around 1960 in Spain, is selected [43]. The rest of the properties are taken from Table 3.1 Eurocode 2. Mechanical properties of existing and strengthening materials are shown in Table 6.

Table 6 Materials mechanical properties

Material	f_d [MPa]	γ	E_c [MPa]	f_{ctm}[MPa]
Existing materials				
Concrete	20	1.5	30000 (1)	2.20 (1)
Inner rebar (ϕ20) (2)	400	1.15	200000	
Strengthening materials				
Steel sheet (S 355 N/NL)	355	1.10	200000	

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(1) Table 3.1 Eurocode 2 [42]

(2) Supposed similar to B 400 S [44]

(3) Product MasterBrace LAM 165/3000, company BASF, Construction Chemicals Spain.

The original bearing capacity of the beam, M_0, is 57.4 kNm and the required bearing capacity increase is of 30%: M_T = 74.62 kNm.

To validate the suitability of the model a generic bending moment distribution is supposed where the maximum positive bending moment is placed at x = 3.2 m and negative moment at the left edge is M_1 =111.93 kNm.

3.1.4.1. *Area of the strengthening piece*

According to Table 2, α = 0.25 and β = 0.70. In the case of steel sheets strengthening technique, results for the different FM are presented in Table 7. The steel sheet has a thickness of 2 mm, (z = 301 mm).

Table 7 Results for steel-sheets strengthening technique

	Simplified method						General method
	a_1	a_2	a_3	a_4	x [mm]	A^s_r [mm²]	A^g_r [mm²]
FM1	-0,851	731,724	74620,000	-22460620,000	140.03	959.3	960
FM2	-0,034	29,269	3723,785	-966993,256	136.49	445.2	450
FM3	-0,851	731,724	93094,614	-22485763,241	123.39	278.9	270
FM4	0,000	-2,277	1363,614	-88105,491	73.68	220.5	222

3.1.4.2. *Length of the strengthening piece*

According to the bending moment distribution k_1 = 1.5 and l_m = 3.2 m. With these data, equation (18) is $-18.22x^2 + 116.59x - 169.33 = 0$, resulting x_1 = 2.23 m and x_2 = 4.17 m. Therefore, $L_s = x_2 - x_1 = 1.94\ m$. The anchorage length, L_a, is obtained from equations (20), (21), (22) and (23). As an example, in the FM1, with γ = 1.5, in the case of steel sheet technique, L^s_a= 0.33 m. Applying equation (16), total length, L_T, equals to 2.27 m for steel sheets.

3.2. Results of LCA

Results obtained in structural assessment are introduced in the LCA model to calculate the final non-renewable energy consumption and emitted kilograms of equivalent CO_2, associated with each one of the strengthening techniques considered when an increase of the 10%, 30% and 50% of the flexural bearing capacity in a particular beam is needed. In the no-degradation scenario, the need of original concrete section restitution and inner rebar reparation is not considered. This is the case when strengthening is needed because of functional reasons, as a change in the use of the building, but with no degradation in the concrete or rebars. Results are presented in Table 8, Table 9 and Table 10, for beams with a h/b relation of 0.5, 1 and 2, respectively.

Table 8 MJ-Eq and kg eq-CO_2 when strengthening beams h/b = 0.5, with steel/epoxy (SE), steel/anchorages (SA), CFRP (CF) and adding RC (RC)

h x b	Steel/epoxy		Steel/anchorages		CFRP		RC	
ΔC	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2
150x300								
10%	150.15	14.49	129.79	10.68	140.43	31.70	965.25	79.97
30%	232.39	18.95	168.60	13.75	160.23	32.75	976.04	80.66
50%	340.70	24.96	220.92	17.89	183.88	33.99	990.19	81.57
200x400								
10%	238.18	21.43	178.26	14.58	198.83	42.89	1,334.36	109.82
30%	419.00	31.38	264.83	21.43	238.59	44.99	1,359.99	111.46
50%	657.09	44.67	380.46	30.57	286.51	47.52	1,393.03	113.58
250x500								
10%	302.85	26.97	214.38	17.51	254.03	53.91	1,745.76	141.58
30%	578.48	42.23	347.17	28.01	311.53	56.95	1,787.48	144.25
50%	960.22	63.58	532.99	42.70	384.16	60.78	1,843.68	147.84

Table 9 MJ-Eq and kg eq-CO_2 when strengthening beams h/b = 1, with steel/epoxy (SE), steel/anchorages (SA), CFRP (CF) and adding RC (RC)

h x b	Steel/epoxy		Steel/anchorages		CFRP		RC	
ΔC	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2
250x250								
10%	149.70	13.45	133.56	10.63	131.33	27.20	945.32	72.79
30%	284.23	20.89	198.29	15.75	164.03	28.93	966.06	74.11
50%	469.18	31.24	288.38	22.88	206.73	31.18	994.07	75.91
300x300								
10%	193.61	16.92	159.10	12.63	162.94	32.93	1,175.41	89.83
30%	399.96	28.37	258.76	20.51	211.46	35.49	1,208.42	91.94
50%	689.74	44.61	400.11	31.68	275.93	38.89	1,253.75	94.84
500x500								
10%	398.39	32.41	275.34	21.71	294.54	56.12	2,329.71	168.96
30%	1,068.99	69.85	601.16	47.46	431.88	63.36	2,446.80	176.45

50%	2,093.14	127.38	1,101.88	87.03	622.85	73.43	2,621.02	187.60

Table 10 MJ-Eq and kg eq-CO_2 when strengthening beams h/b = 2, with steel/epoxy (SE), steel/anchorages (SA), CFRP (CF) and adding RC (RC)

h x b	Steel/epoxy		Steel/anchorages		CFRP		RC	
ΔC	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2	MJ-Eq	kg eq-CO_2
400x200								
10%	154.74	12.72	142.71	10.89	127.74	23.00	925.72	65.62
30%	332.23	22.62	228.82	17.70	172.65	25.37	956.32	67.58
50%	579.72	36.52	349.79	27.26	234.10	28.61	998.30	70.27
500x250								
10%	215.08	17.11	178.98	13.61	167.53	29.18	1,237.90	86.52
30%	518.89	34.09	326.77	25.29	241.85	33.10	1,291.94	89.98
50%	957.09	58.73	541.17	42.23	346.21	38.60	1,368.34	94.87
600x300								
10%	280.88	21.80	217.90	16.53	208.36	35.41	1,596.83	109.60
30%	744.09	47.73	443.55	34.37	317.42	41.16	1,681.18	115.01
50%	1,432.85	86.48	780.73	61.02	473.33	49.38	1,804.03	122.87

The contribution to the different stages involved (products, construction and end-of-life) is different for every one of the reinforcing techniques. The trend is similar for all the studied beams. On the other hand, as previously mentioned, strengthening is sometimes needed in beams with degradation problems. The impacts associated to the restitution of the beam to its original state must be added. As an example, results for a beam with a cross section of 30x30 (bxh) when its bending capacity is increased a 10%, 30% and 50%, are presented in Figure 3.

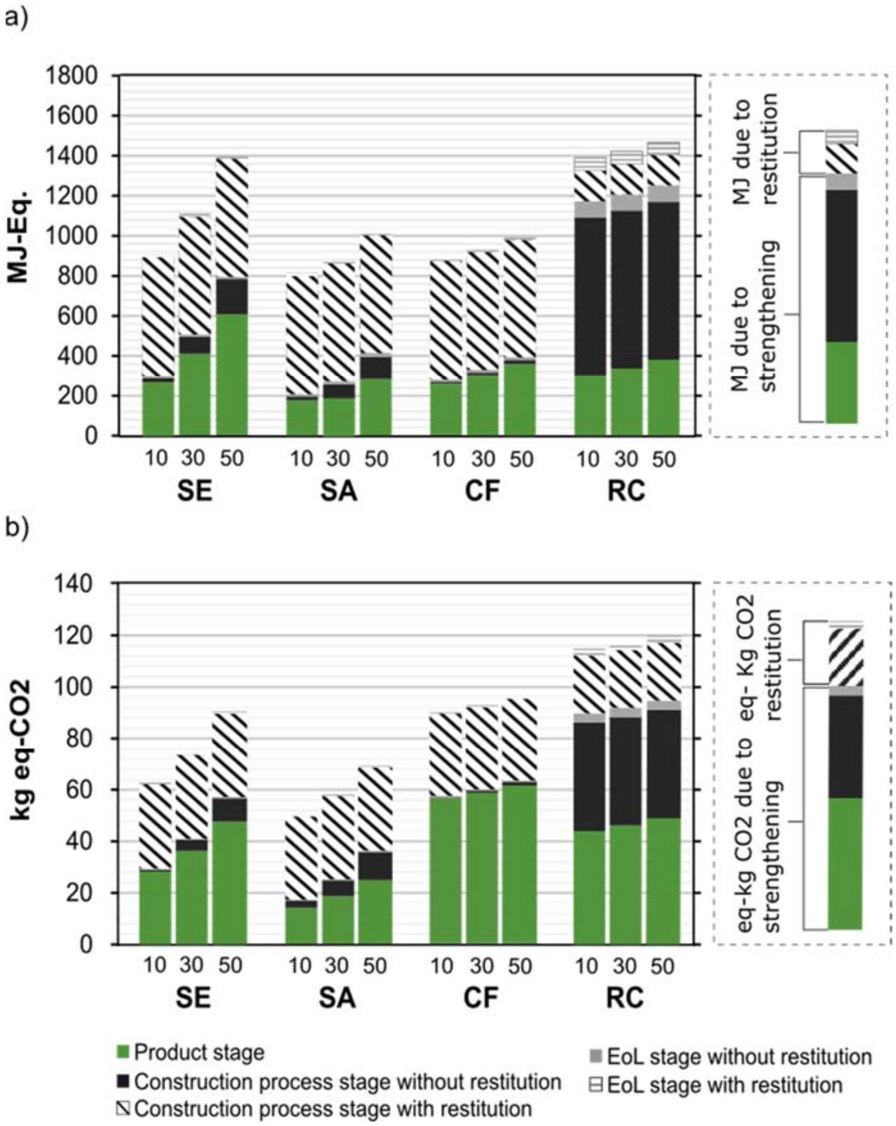


Figure 3 Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent (b) when strengthening a 300 x300 mm (hxb) beam

In Figure 4 and Figure 5 as an example, simplified results for a flat beam (h/b=0.5), 200x400 (hxb) and a hanging beam, 400x200 (hxb) are shown.

a)

b)

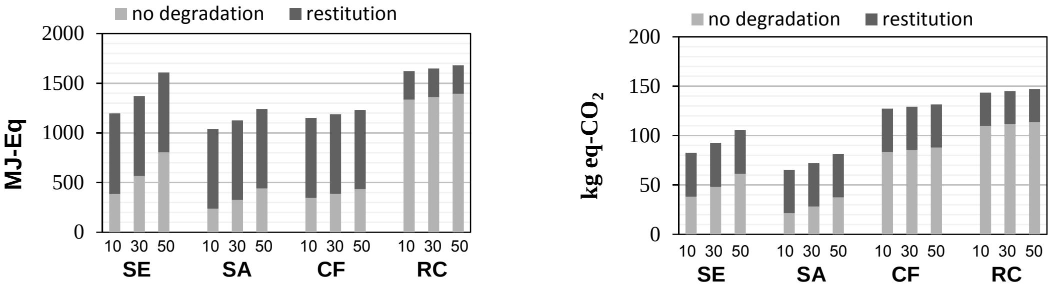


Figure 4 Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent emitted (b) when strengthening a 200x400 mm (hxb) beam

a) b)

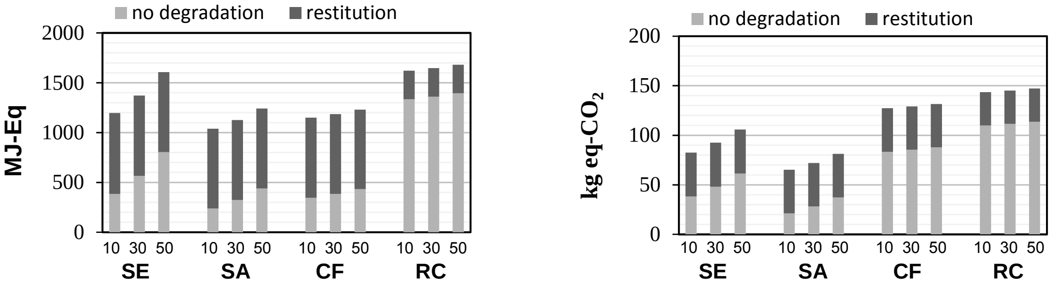
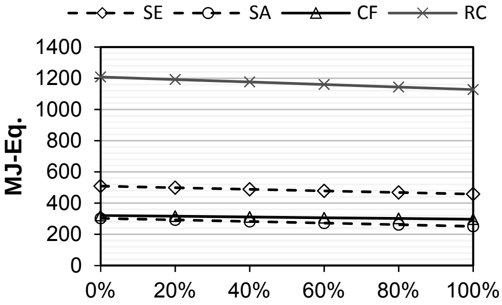


Figure 5 Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent emitted (b) when strengthening a 400x200 mm (hxb) beam

3.2.1. End-of-life scenarios

As already mentioned, disposal to landfill, with Ecoinvent 2.2 data, has been considered as the general end-of-life scenario. Nevertheless, potential benefits of recycling as a way of avoiding raw-materials are analyzed. A 300x300 mm cross section beam, with a 50% increase on its bending capacity has been taken as a case study. In Figure 6, the decreasing in the non-renewable energy consumption as the percentage of recycled material increases, in different technologies, is presented. In Figure 7 two different recycling scenarios that can be possible nowadays are presented. A third hypothetical future scenario where 100% of the material is recycled is also presented to serve as a reference.



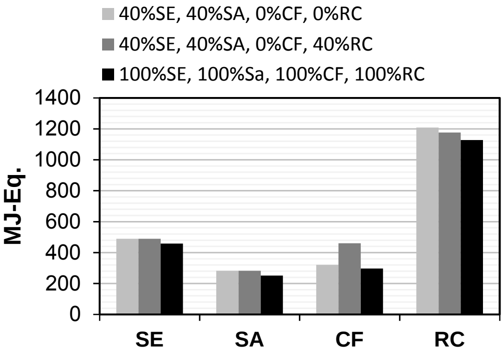


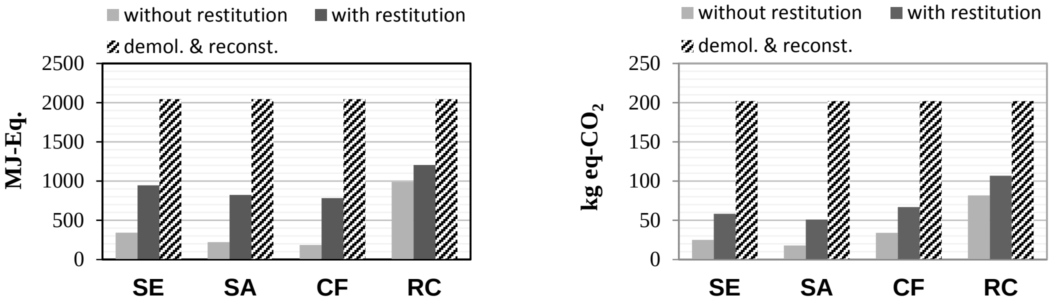
Figure 6 Non-renewable primary energy consumption of the study case beam (300x300) according to different % of recycled material.

Figure 7 Non-renewable primary energy consumption comparison between three different recycling scenarios.

3.2.2. Comparison between strengthening and restitution with demolition and new construction

Demolition and reconstruction of the original beam implies, according to BEDEC database [41], an energy consumption of 7,273.64 MJ-Eq/m³ and the emission of 714.91 kg CO_2/m^3. Those data are compared with strengthening and restituting the original section of the analyzed beams, when an increase of a 50% on its bending capacity is needed and none of the materials are reused or recycled.

According to the results, the difference between strengthening and reconstruction is smaller for 150x300 cross section beams. This scenario is summarized in Figure 8.


a)

b)

Figure 8 Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent (b) when increasing a 50% the bending capacity of a 150x300 mm cross section beam, with and without repairing process, compared to demolition and reconstruction.

4. Discussion

4.1. Structural simplified model

The main advantage of the proposed model is its ease of application. The user just needs to select the appropriate FM and solve simple polynomic equations. Very few simplified calculation models have been found in literature, and none of them considers different failure modes. As this model is focused on existing buildings, built in a wide range of periods, with different properties and state of conservation, being able to adapt the failure mode is an important advantage of the proposed model.

Nevertheless, some simplifications are made, and the model has some limitations. The main limitation of the model is that only simple bending is considered. This was assumed for simplification and also to be able to obtain directly the required area of the strengthening material, avoiding an iterative verification process. In the case of residential building beams, bending moment usually prevails over axillary stress. On the other hand, in the case of adhered techniques just the peeling-off at the end anchorage and at flexural cracks failure mode are considered. Other peeling-off failure modes, such as peeling-off caused at shear cracks or peeling-off caused by the unevenness of the concrete surface, were not considered in this simplified model.

Because of these limitations, when the objective is real intervention, this model cannot substitute the general complex one where all verifications must be done. Nonetheless, this model is a suitable alternative to obtain the data needed in a LCA, avoiding non-structural based estimations and promoting and facilitating the inclusion of the structural interventions, often neglected, in whole building retrofitting LCAs.

As the model focuses on a non-experienced technician, some guidelines for the decision-making of the FM are provided in Table 11.

Table 11 Guidance for FM selection

	Situation	Suitability
FM1	There is not much knowledge about the existing elements and properties or they are presumably low.	Applicable in steel, RC section increase and CFRP strengthening techniques
FM2	Information about existing elements properties is not complete, but they are presumably acceptable. No-control to materials and execution was made when built.	Applicable just in steel and RC section increase strengthening techniques
FM3	Information about existing structure is	Applicable in steel, RC section

	complete and materials and execution were controlled when built. Structure is, apparently, in good state of conservation.	increase and CFRP strengthening techniques, but not advisable in CFRP because the material is wasted
FM4	Existing structure has been deeply tested and its properties are completely known. Structure is in good state of conservation.	Applicable in CFRP strengthening technique and, sometimes, in steel sheets technique. Not applicable in the case of RC section increase if new rebars are of similar characteristics than existing ones.

Regarding the model accuracy compared to the general method, the only deviation comes from the simplification of α and β as constant for a particular concrete type. In CFRP there is no deviation as no simplifications is made and the parabolic-rectangular stress-strain diagram is used. The bigger deviation is produced in the FM2. This deviation from the general method is studied in 18 hypothetical beams, with different h/b relations (6 beams with h/b=1; 6 beams with h/b=0.5 and 6 beams with h/b=2). In Figure 9 relation between the area obtained in the general and simplified method is shown. The mean value of the differences obtained for these study cases is 1.19% with a standard deviation of 1.09%. This means that the deviation is very small, what shows the suitability of taking α and β as constant.

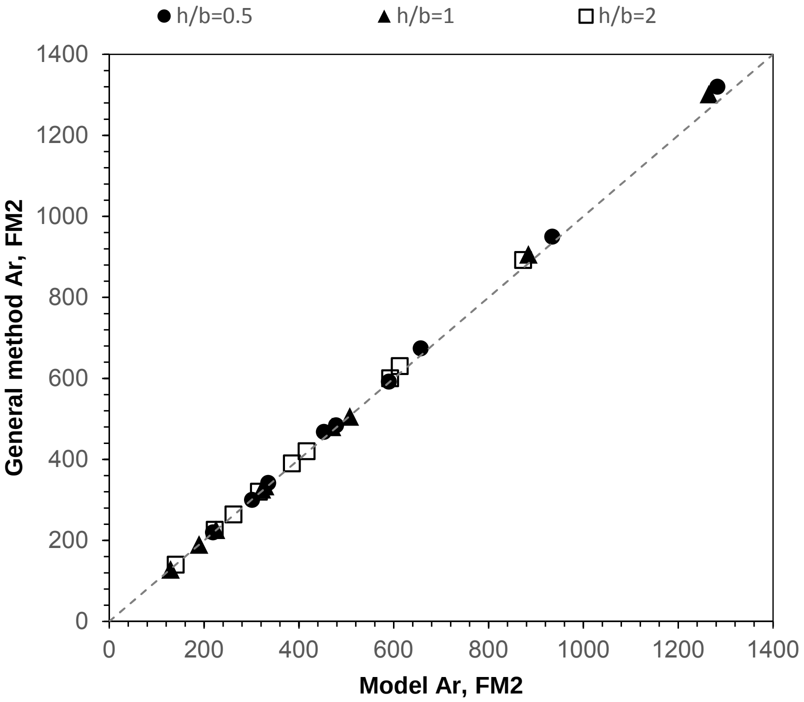


Figure 9 Relation between results of simplified and general method

4.2. LCA

4.2.1. No degradation scenario

When no degradation is present, the technique based on increasing the original cross section by adding new rebars and concrete obtain worse results than the rest of analyzed techniques, both in terms of non-renewable primary energy consumption and equivalent CO_2 kg emissions. On the contrary, the reinforcing technique based on steel plates attached with mechanical anchorages results in the best behavior, closely followed by the CFRP strengthening. This can be seen in Figure 3 for the case of a RC beam of 6.00 m of span and cross section of 30 cm x 30 cm (b x h), with a 10%, 30% and 50% increase of its original bending capacity. Similar results are obtained in the rest of cases.

Results obtained for RC can be explained mainly because of the constructive constrains and the construction stage contribution. On the one hand, due to constructive reasons it is not recommended to increase the edge of the beam less than 10 cm when normal concrete is used [19] while the width and length of the added concrete volume should be those of the original beam. Therefore, a great amount of concrete is needed for construction reasons even if it is not required for structural purposes. Besides, the construction stage itself also involves some highly impacting processes and products as the formwork or the releasing liquid that set the different with the rest of the techniques. It must be noted that tensile resistance of concrete has been neglected towards that of steel rebars. This means that in this case of simple bending concrete is acting just as a method to attach the added rebars. And concrete, mainly due to the great amount that is needed, is a too environmentally-expensive fixing method. On the other hand, as can be seen in Table 1, the RC technique has other advantages compared to the other techniques that are not being considered in this paper. When the strengthening main purpose is not to increase the bending capacity but the deflection reduction, this technique would be probably the most suitable.

Regarding steel and CFRP, producing 1 kg of steel from virgin material is considerably less harmful than producing 1 kg of carbon fiber (90% less) or CFRP matrix (which is made of carbon fiber and epoxy resin), also from virgin materials. Nevertheless, when comparing steel and CFRP techniques both stuck with epoxy resin (SE and CF), better results are obtained for

CFRP, what is due to the reduction on the material needed allowed by the higher mechanical properties of CFRP, compared to steel. However, when steel is placed with mechanical anchorages (SA), steel behaves better than CFRP (CF), because epoxy resin, a highly harmful material, is avoided as is no longer needed to attach the sheet.

4.2.1.1. Dependence on beam type

Regardless the type of beam, which will influence the result, the difference between techniques depends on the required increase of the bending capacity. This can be shown in Figure 5, Figure 6 and Figure 7 for beams with different h/b relation. In the 300x300 beam case study, when no degradation is present, final energy consumed when SE strengthening technique is applied is approximately the 16% of that of RC, when a 10% of increase in the bending capacity is considered. When a 50% of increase is needed, energy consumption of SE is the 55% of RC. In the rest of techniques this decrease in the difference with respect to RC also exists, although it is lower. This indicates that, from an energy consumption and CO_2 emissions point of view, RC technique is more suitable when big increases in the bending capacity are need than when small ones.

4.2.1.2. Contribution of the different stages

The contribution of every stage (product, construction process and end-of-life) to the global result is different for every technique and increase of the bending capacity, as can be shown in Figure 3. In the case of SE, SA and CF the stage that contributes the most is, by large, product stage, followed by construction. Furthermore, the contribution of the construction process stage increases with the rise of bending capacity. In the case of a 30x30 beam and no degradation scenario, this contribution ranges from 10% to 26%, in the case of SE, from 25% to 28% in the case of SA and from 4% to 7% in the case of CF reinforcement.

In the case of RC strengthening technique, the stage that contributes the most is construction process and its contribution slightly decreases for larger capacity increases, ranging from 65% to 61% for the selected beam. This is because some of the associated impacts are constant for all capacity increases what penalizes the results when small increments of the bending capacity are needed.

In any case, it can be observed that the contribution of the construction process stage, which is sometimes neglected, can be substantive, above all in the case of the RC technique.

Contribution of the end-of-life stage to the energy consumption and CO_2 emitted is not too relevant when a landfill scenario is applied. This is mainly motivated because no waste treatment has been considered, which results in a reduced non-renewable primary energy consumption of energy but important impacts according to other categories that have not been evaluated here. Nevertheless, recycling and reusing materials is also a way of avoiding impacts associated to product. By using recycled materials, product stage contribution can be reduced for the SE, SA and CF techniques, depending on the percentage of recycled material that is used. Nevertheless, this reduction is not much significant as product stage impact is also caused by the epoxy resin (non-recyclable) and other materials.

In the case of RC technique, using recycled concrete does not result in a reduction in the energy consumption of the product stage but an increase, due to the energy that must be consumed in the recycling process. Nevertheless, it causes a reduction in the end-of-life stage, that is relatively significant compared to SE, SA and CF techniques.

It must be noted, that recycling and reusing materials has, of course, other associated environmental benefits as reducing soil pollution, etc. that are not considered in this paper.

4.2.2. Degradation scenario

When corrosion is present and original beam needs to be repaired, results obtained are different. Original section reparation and restitution is a harmful process mainly because of the products involved, such as anti-corrosion repairing mortar, which includes epoxy resin and fibers, or epoxy resin for junction between old concrete and new mortar. It must be noted that reparation impacts do not depend on the capacity increase, as they are performed before any strengthening intervention upon the original beam. As already stated in section 2.2, in the technique based on increasing the RC cross section, some of those impacts are avoided. Because of this, the difference in the techniques results changes. In the case of a 200x400 mm cross section beam (hxb), flat beam, as can be shown in Figure 4, RC strengthening technique, obtain the best results for a from an energy consumption and CO_2 kg emissions point of view when degradation is present.

4.2.3. Comparison with demolition and reconstruction

Results show that flat beams behave worse than the others, from an energy consumption and CO_2 kg emissions point of view. In the case of strengthening and section restituting, higher impacts are obtained when the bending capacity of a 15x30 (hxb) beam is increased a 50% through RC reinforcing technique. In this process, final energy consumed is 59% of that of rebuilding and CO_2 kg emitted are 53% of those in rebuilding. This means that, regardless of the technique that is used among those analyzed in this paper, the strengthening process consumes less final energy than demolishing and rebuilding and also less equivalent CO_2 kg are emitted, even if the original beam must be repaired.

5. Conclusions

LCA is proven to be a suitable methodology to evaluate environmental impact of buildings and construction in general. In a frame where the building sector increasingly focuses on refurbishment, reliable data is needed to appropriately evaluate the different solutions from the environmental point of view.

Regarding structural strengthening, four different solutions are analyzed in this paper with an interdisciplinary focus that was found to be essential to obtain rigorous data. Firstly, a simplified model for structural assessment was proposed with the purpose of extending the applicability of the analysis. Secondly, LCA methodology is applied and the associated impacts are displayed. Additionally, data (non-renewable primary energy consumption and equivalent kg of CO_2 emitted) regarding several common situations are provided ready for use by other technicians as data source.

The main conclusions can be summarized as:

- The proposed simplified model is a suitable, no time-consuming and scientifically based option to obtain the data needed in a LCA of reinforced concrete beams strengthening.

- The suitability of a technique depends on the characteristics of the original beam, above all, its bending capacity and the increase that is needed, its geometry and the presence or not of a large extent of degradation.
- Results show that strengthening is better than demolishing and new building in all the studied cases, even though if degradation is present and original section must be repaired and restituted.
- When the main purpose is increasing bending capacity and no degradation is present, steel sheets placed with mechanical anchorages and CFRP laminates obtain the better results in terms of non-renewable primary energy consumption and kilograms of CO_2 equivalent. When degradation is present, the suitability of the solution strongly depends on the geometry of the beam. The RC technique is more suitable when a large increase in the bending capacity is required rather than for low ones.
- The Product stage contributes the most to global non-renewable primary energy consumption in the case of adhered techniques. Therefore, research should focus on more sustainable production processes as well as on recycling and, above all, reusing. Reusing without processing can lead to the greatest reductions in the environmental impact. However, the difficulty of reusing is also greater, since it involves the use of specific techniques that allow it.
- In the case of RC, the construction process is the most contributing stage in terms of non-renewable energy consumption. This is because the construction process is more complex and involves products and processes with a high embodied energy and CO_2 as the epoxy junction or the treatment of existing rebars for their protection from environment during construction works. The use of techniques that avoid or reduce these products and techniques, such as replacing the epoxy junction with the connection of new and existing rebars, can reduce its impact. However, the construction process becomes more complex.

Acknowledgements

This work was supported by the Spanish Ministry of Education, Culture and Sports, through a FPU research grant [grant FPU15/01069] and the Research Group GIA [T37_17R] of the University of Zaragoza (Spain).

Appendix

Resulting equations for calculating the area of strengthening piece in the case of FM2, FM3 and FM 4, when admissible, are presented below.

(i*) Steel plates reinforcement (SE and SA) and increasing reinforced concrete section (RC) techniques*

As already exposed, to obtain the area of the strengthening piece, firstly, *x* must be calculated from equation (5). The coefficients a_1, a_2, a_3 and a_4, for FM 2, FM3 and FM4 can be obtained by substituting known values in equations below. Once that x is known, the needed area of reinforcing piece, A_r, can be obtained by just substituting values in a one-grade equation.

- FM2:

In the case of FM2, coefficients of equation (5) can be obtained from equations (25), (26), (27) and (28), respectively.

$$a_1^{FM2} = -\frac{1}{2}\alpha\beta^2 bE_c \frac{f_{yr}}{E_r(z-d)} \tag{25}$$

$$a_2^{FM2} = \alpha\beta bE_c \frac{f_{yr}}{E_r}\left(1+\frac{d}{z-d}\right) \tag{26}$$

$$a_3^{FM2} = \frac{E_s}{E_r} f_{yr}\left(A_{s1} + A_{s2}\frac{z-d'}{z-d}\right) + \frac{M_T}{z-d} \tag{27}$$

$$a_4^{FM2} = -\frac{E_s}{E_r} f_{yr}\left(A_{s1}d + A_{s2}d'\frac{z-d'}{z-d}\right) + \frac{M_T z}{z-d} \tag{28}$$

The area of needed reinforcement is obtained from equation (29).

$$A_r^{FM2} = \frac{M_T}{f_{yr}(z-d)} - \frac{1}{E_r(z-x)(z-d)}\left[\alpha\beta bE_c\left(d-\frac{\beta x}{2}\right)x^2 + E_s A_{s2}(d-d')(x-d')\right] \tag{29}$$

- FM3:

In FM3, the coefficients of equation (5) are obtained from equations (30), (31), (32) and (33), respectively.

$$a_1^{FM3} = -\frac{1}{2}\alpha\beta^2 bE_c\frac{f_{ys}}{E_s} \tag{30}$$

$$a_2^{FM3} = \alpha\beta bE_c\frac{f_{ys}}{E_s}z \tag{31}$$

$$a_3^{FM3} = M_T + f_{ys}[A_{s2}(z-d') + A_{s1}(z-d)] \tag{32}$$

$$a_4^{FM3} = -M_T d + f_{ys}A_{s2}d'(d'-z) - f_{ys}A_{s1}d(z-d) \tag{33}$$

The area of needed reinforcement is obtained from equation (34):

$$A_r^{FM3} = \frac{f_{ys}}{f_{yr}}\left[\alpha\beta b\frac{E_c}{E_s}\frac{x^2}{d-x} + A_{s2}\frac{x-d'}{d-x} - A_{s1}\right] \tag{34}$$

- FM4:

In FM4, the coefficients of equation (5) are obtained from equations (35), (36), (37) and (38), respectively.

$$a_1^{FM4} = 0 \tag{35}$$

$$a_2^{FM4} = -0.5693\frac{f_{yr}}{d} \tag{36}$$

$$a_3^{FM4} = 1.1386f_{yr} + 1.066f_{cd}b(z-d) \tag{37}$$

$$a_4^{FM4} = -M_T - 0.0693\frac{f_{yr}}{d} + f_{ys}[A_{s1}(d-z) + A_{s2}(z-d')] - 0.0066f_{cd}bd(z-d) \tag{38}$$

The area of needed reinforcement is obtained from equation (39):

$$A_r^{FM4} = \frac{1}{f_{yr}}\left[f_{cd}b(x - 0.066(d-x)) + f_{ys}(A_{s2} - A_{s1})\right] \tag{39}$$

It must be noted that FM4 is not appropriate for the RC technique if added rebars are of the same properties than existing.

(ii) CFRP laminates strengthening techniques

In the CF technique just the FM1, FM3 and FM4 are applicable. In the case of FM3, the CFRP material is wasted, so it is not advisable to use CF technique when FM3 is desirable. Firstly, *x* is obtained from equation (11). The coefficients b_1, b_2 and b_3 in FM4 are obtained from equations (40), (41) and (42), respectively.

$$b_1^{LS4} = -0.5693f_{yr}b \tag{40}$$

$$b_2^{LS4} = f_{cd}b(1.066z + 0.0726d) \tag{41}$$

$$b_3^{LS4} = -M_T + f_{ys}[A_{s1}(d-z) + A_{s2}(z-d')] - f_{cd}bd(0.066z + 0.0033d) \tag{42}$$

The area of needed reinforcement is obtained from equation (43):

$$A_r^{LS4} = \frac{d-x}{0.01E_r(z-x)}\left[f_{cd}b(1.066x - 0.066d) - f_{ys}(A_{s1} - A_{s2})\right] \tag{43}$$

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