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Simplified structural design and LCA of reinforced concrete beams strengthening techniques

B. Palacios-Munoz[a], L. Gracia-Villa[a], I. Zabalza-Bribián[b], B. López-Mesa[c,*]

[a] University of Zaragoza, School of Engineering and Architecture, Department of Mechanical Engineering, María de Luna 3, C.P. 50018, Zaragoza, Spain
[b] University of Zaragoza, School of Engineering and Architecture, Department of Mechanical Engineering and CIRCE Research Institute, María de Luna 3, C.P. 50018, Zaragoza, Spain
[c] University of Zaragoza, School of Engineering and Architecture, Department of Architecture, María de Luna 3, C.P. 50018, Zaragoza, Spain

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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.

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 renovation 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 al. [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

* Corresponding author.
E-mail address: belinda@unizar.es (B. López-Mesa).

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Nomenclature

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_c^p	axial force in concrete considering a parabolic distribution
M_c^p	bending moment in concrete considering a parabolic distribution
N_c^r	axial force in concrete considering a rectangular distribution
M_c^r	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

$\varepsilon_c{}^{max}$	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

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

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.