TESIS DE LA UNIVERSIDAD
DE ZARAGOZA

2020

140

BEATRIZ PALACIOS MUÑOZ

A methodology to estimate buildings lifespan and its impact on ICA - the case of buildings with reinforced concrete structure

Departamento

811 Instituto Universitario de Investigación Mixto CIRCE

Director/es

Gracia Villa, Luis
López Mesa, Belinda

http://zaguan.unizar.es/collection/Tesis

ISSN 2254-7606

Prensas de la Universidad
Universidad Zaragoza

© Universidad de Zaragoza
Servicio de Publicaciones

ISSN 2254-7606

Universidad Zaragoza
1542

Tesis Doctoral

A METHODOLOGY TO ESTIMATE BUILDINGS LIFESPAN AND ITS IMPACT ON ICA - THE CASE OF BUILDINGS WITH REINFORCED CONCRETE STRUCTURE

Autor

BEATRIZ PALACIOS MUÑOZ

Director/es

Gracia Villa, Luis
López Mesa, Belinda

UNIVERSIDAD DE ZARAGOZA
811 Instituto Universitario de Investigación Mixto CIRCE

2020

Repositorio de la Universidad de Zaragoza – Zaguan   http://zaguan.unizar.es

TESIS DOCTORAL

A methodology to estimate buildings lifespan and its impact on LCA

The case of buildings with reinforced concrete structure

Beatriz Palacios Muñoz

Thesis supervised by Dr. Belinda López Mesa and Dr. Luis Gracia Villa. Doctoral programme tutor Ignacio Zabalza Bribián.

May 2020

Grupo de Investigación en Arquitectura
Gobierno de Aragón

Universidad Zaragoza
1542

PREFACE

This doctoral thesis comprises an introductory part and a compendium of the following papers:

1. **PAPER 1**. B. Palacios-Munoz, B. López-Mesa, and L. Gracia-Villa, "Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact," *Int. J. Life Cycle Assess.*, vol. 24, no. 11, pp. 1913–1924, Nov. 2019 https://doi.org/10.1007/s11367-019-01622-w [1]

2. **PAPER 2.** B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, and B. López-Mesa, "Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach," *Build. Environ.*, vol. 160, p. 106203, Aug. 2019. https://doi.org/10.1016/j.buildenv.2019.106203 [2]

3. **PAPER 3.** Palacios-Munoz, B., López-Mesa, B., & Gracia-Villa, L. (2018). "Structural design and comparative LCA of two strengthening techniques: Concrete beams under flexural loads". In L. Villegas, I. Lombillo, H. Blanco, & Y. Boffil (Eds.), Construction pathology, Rehabilitation technology and heritage management (Digital Book of Articles- REHABEND 2018, Euro-American Congress) (pp. 1609–1617). https://doi.org/2386-8198 [3]

4. **PAPER 4.** B. Palacios-Munoz, L. Gracia-Villa, I. Zabalza-Bribián, and B. López-Mesa, "Simplified structural design and LCA of reinforced concrete beams strengthening techniques," *Eng. Struct.*, vol. 174, no. July, pp. 418–432, Nov. 2018, https://doi.org/10.1016/j.engstruct.2018.07.070 [4].

The author of this thesis is Beatriz Palacios Muñoz, holding a B.Arch. and a M. Arch. (University of Zaragoza). This work was funded by the Spanish Ministry of Education, Culture and Sports, through a FPU research grant [grant FPU15/01069], by Gobierno

de Aragón (Research Group GIA T37_17R) and by FEDER 2014-2020 "Construyendo Europa desde Aragón".

The thesis supervisors are Luis Gracia Villa and Belinda López Mesa and the doctoral programme tutor is Ignacio Zabalza Bribián. The thesis is developed within the frame of the "Renewable Energies and Energy Efficiency" Doctoral Program that has a *Mención de Excelencia* (Mention of Excellence).

The authors of the papers are:

- The PhD candidate

- The thesis directors and supervisor

- Bruno Peuportier, research stay supervisor of the host University MINES ParisTech, CES- Centre d'efficacité Energétique des Systèmes, where I spent a three months research stay.

All of them (except from the PhD candidate) are doctors.

CONTENT

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDED TABLES

NOMENCLATURE

Variables and units:

b: overall width of a beam cross-section

h: overall depth of a beam cross-section

kgCO_2-eq: kilograms of CO_2 equivalent.

Acronyms:

AAR: Alkali-Aggregate Reaction

EU: European Union

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

CFRP: Carbon Fiber Reinforced Polymer

D&N: Demolition plus new building

LCA: Life Cycle Assessment

PR: Passive refurbishment

PD&R: Passive demolition and new building

R: Refurbishment

RC: Reinforced Concrete section increasing strengthening technique.

SA: Steel placed with mechanical Anchorages strengthening technique.

SD&N: Standard demolition and new building

SE: Steel placed with Epoxy resin strengthening technique.

SR: Standard refurbishment

SLP: Service Life Prediction

.

1 THESIS PRESENTATION

This thesis deals with the lifespan in buildings Life Cycle Assessment (LCA), which is a methodology to assess environmental impacts associated to a product or a process that considers energy, materials, and emissions over its whole life. In buildings LCA – and specially in comparative LCAs, the lifespan of the building –or the group of buildings that are compared– is a fundamental factor as environmental impacts are usually annualized for the sake of comparison. However, a methodology to rigorously estimate this parameter does not exist yet. The scientific community has reached the consensus that the lifespan of a building is that of its structure, as it is an inseparable part of it and of complicated intervention. Even national regulations on buildings state of conservation, as the Spanish one [5], associate the ruin state of conservation of a building with the state of conservation of its structure.

Because of this, the thesis aims to develop a methodology to estimate the lifespan of buildings structures. It focuses on reinforced concrete structures and specifically on beams. Firstly, the influence of service life in buildings LCA results is evaluated. Secondly, a methodology to estimate the lifespan of buildings structures is developed. This is done at beam (paper 1) and at whole building (paper 2) levels.

One of the conclusions of these studies is the environmental benefits of extending the lifespan of buildings (specifically its structure). Structure strengthening is one of the ways to do this but a lack of LCA studies regarding concrete structure strengthening techniques is detected. Because of this, a comparative LCA between usual strengthening techniques is done. Important conclusions are drawn and environmental results directly usable by other technicians in LCAs are displayed (papers 3 and 4). Additionally, it was observed that building structures LCA available in the literature are hardly replicable and scarce. This is due, among other reasons, to the need of structural assessment that is not always viable for LCA practitioners because of the specific knowledge in structures that is required. With the aim to make more replicable the LCA procedure proposed in this thesis , a simplified method for concrete beams strengthening assessment is also developed (paper 4).

Specifically, the content of the papers that comprises this thesis are as follows.

1.1 Paper 1. Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact

Service life strongly affects results of buildings LCA and is often considered as that of its structure. Quantitatively obtaining this parameter is a complex task that remains unsolved in the literature. This paper provides a methodology to estimate the service life of a beam and quantitative data related to the environmental impact of demolition plus new construction, and refurbishment, considering the potential service life and the ability of refurbishment to extend it.

This paper focuses on reinforced concrete structures, specifically on beams, as service life of buildings is taken as that of its structure. Firstly, a methodology to estimate the service life value to conduct the LCA is provided. The applied methodology is based on the definition of different scenarios that include four different approaches to reinforced concrete beams interventions in the long term. The methodology can be extended to a complete building structure. Secondly, LCA of demolition plus new construction and refurbishment in the different scenarios are carried out. Finally, the complete methodology is applied to a case study.

Concrete structures have a potential service life much longer than the minimum value prescribed in the codes. In this case study, more than five times. Reinforced concrete is subject to degradation and aging with time and several models exist to assess the effects. In addition, a structure can be refurbished, which strongly affects its lifespan. These different strategies when applied to a case study result in differences of up to 65% in non-renewable primary energy consumption in a 250 years period. Embodied energy (that needed to produce the materials and systems) and kgCO_2-eq (kilograms of CO_2 equivalent) per year of buildings, are not constant values. The appropriate strategy for a specific case study must be taken into account to select the value of service life in LCA.

Reinforced concrete is a highly impacting material, but also a material with a long potential service life. This durability is not considered in the LCA if the service life value is restricted to the minimum one prescribed in the codes. Demolishing a structure (and therefore, a building) that can last 250 years after just 50 or 80 is a highly impacting action. Refurbishment can ensure this durability and even extend it.

1.2 Paper 2. Sustainability assessment of refurbished vs. new constructions by means of LCA and durability-based estimation of buildings lifespans: a new approach

A common practice in LCA of buildings is to consider a default value for their lifespans. However, statistical data show longer lifespans and it is proved that the higher they are the lower the environmental impacts. Therefore, the common practice of considering a default value for lifespans in buildings LCA involves a high risk of programmed obsolescence in the building sector. This paper addresses a new approach to estimate buildings lifespans based on their structures durability using the method of the paper 1, improved. We extend the analysis of the influence of lifespan in LCA made in paper 1 for a beam to a complete building. Because of this, the use stage of the building is also considered in the analysis. We use a comparative case study of refurbishment vs. new construction to illustrate its use. The lifespans of the refurbished and the new buildings are estimated by applying degradation models of reinforced concrete structures. Two thermal performance levels are evaluated: standard and passive, in both alternatives, the refurbished and the new building. Comparisons are also made with other approaches to determine buildings lifespans based on default value and statistical data. Results show that a new building can have a lifespan more than six times longer than a refurbished one. A strong dependence of LCA results on the lifespan is revealed. Its value can alter the order of preference of the solutions when comparing alternatives and therefore default value approaches are unadvisable. There is in our case study a 11% potential of environmental improvement for new buildings behaviour by changing current practices and extending buildings' lifespan up to their physical limit.

1.3 Paper 3. Structural design and comparative LCA of two strengthening techniques: concrete beams under flexural loads

The recognized environmental benefits of upgrading existing reinforced concrete structures or extending their service life (paper 1 and 2) leads to the need of including environmental criteria when a structural intervention is designed. LCA

This study presents a LCA comparison between two techniques used when reinforcing concrete beams: steel sheets, placed with metallic anchors (SA) and epoxy resin (SE), and carbon fibre reinforced plastic laminates (CFRP laminates) attached with epoxy resin (CF). The objective is to provide environmental decision criteria as well as scientific data able to be incorporated in a whole building LCA.

Results reveal that the environmental impact of carbon-fibre production is greater than that of steel. Nevertheless, the whole CFRP reinforcement has a better environmental behaviour compared to steel/epoxy due to the mechanical properties of CFRP that leads to a reduction of the required material. The use of metallic anchors results in a significant reduction of environmental impact revealing the responsibility of epoxy resin and the importance of considering the constructive process.

1.4 Paper 4. Simplified structural design and LCA of reinforced concrete beams strengthening techniques

This work provides the LCA of four commonly used strengthening techniques of reinforced concrete beams: 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). Firstly, it provides a simplified methodology to size the strengthening, overcoming the need of extensive knowledge of reinforced concrete structures design. Secondly, it provides the application of LCA to the selected techniques. The method improves the applicability of LCA to buildings, analyses 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.

2 INTRODUCTION AND OVERVIEW

2.1 Background

One of the European Union's (EU) fundamental objectives is sustainable development [6]. The United Nations sustainable development goals include, among others, "Goal 13: Take urgent action to combat climate change and its impacts" and "Goal 11: Sustainable Cities and Communities".

Buildings have a strong impact on environment (**Figure 1**, based on [7] and [8]). On the one hand, they account for nearly 40% of energy consumption in European Union. On the other hand, they consume a large number of natural resources (materials, water, etc.) and represent an important source of harmful emissions to the environment. These reasons have made buildings one of the central points of the EU's energy efficiency and environmental policy [9]. This can be seen in the Energy Efficiency in Buildings Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings [10], modified by Directive 2012/27/EU [11] and Directive 2018/844/EU [12].

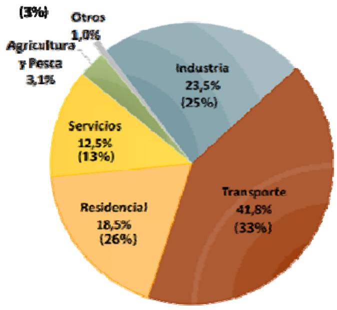


Figure 1 *Energy consumption of different sectors in Spain [7] and European Union [8]*

European policies on buildings have been mainly oriented towards the reduction of energy consumption and the increase in the use of renewable energies. This has led to a progressive hardening of energy regulations in the building sector. Additionally, energy regulations are more and more focused on existing buildings and refurbishment strategies. As an example, the last modification of the energy performance of buildings [12] has established the need of defining long-term buildings renovation strategies to get the complete decarbonisation of the building sector by 2050.

However, buildings contribute to environmental impacts not only during the use of the building (heating, cooling, lighting etc.), which is called use stage, but also during construction, demolition and reparation or substitution of its components.

Life Cycle Assessment (LCA) provides the best framework for assessing the potential environmental impacts of products, and therefore, buildings, according to the European Commission [6] as it takes into account both direct and indirect impacts of buildings whole life. In this document, the need for more consistent data and for consensus on building-specific LCA procedures is highlighted.

The general methodology for LCA is defined in the ISO 14040:2006 [13] and ISO 14044:2006 standards [14]. Specifically, its application to buildings is defined in the CEN/TC 350 standard, EN 15643-2 [15]. According to this standard, the environmental impacts associated to product stage, construction stage, use stage and end-of-life, must be accounted for.

European policies have mainly addressed the use stage as it is, traditionally, the most impacting one. However, in a near future when buildings become more and more energy efficient, LCA methodology is even more important as it considers the global problem. Some European countries have already started to introduce the need of developing an LCA in their building regulation, as in the Netherlands in the Dutch Building Decree 2012 [16].

Despite the suitability and the potential of LCA methodology, as the European Commission remarks [6], there is a need for more consistent data and consensus.

Due to the convenience of applying this methodology to buildings, abundant research has been done in recent years (among others [17]–[19]). One question recently posed in the field of buildings LCA is whether or not it is more sustainable to refurbish than to rebuild [4]. Most of the literature on LCA focuses on new construction [18], [20]–[23], whereas refurbishment is dealt with at a lower extent [24]–[27]. The comparison between the refurbishment of an existing building versus its demolition and new construction is a matter more recently studied [28]–[31]. The results of such a comparison depend on the impacts of the refurbishment/construction stage but also on the level of performance achieved after the refurbishment and the new construction, as well as on the quality and life span of the building elements.

The studies found in the literature often address the influence of the construction/refurbishment stage and the performance of the buildings, but that of the lifespan is seldom studied. Lifespan is a major factor in the LCA [32] and the results are strongly dependent on it [33].

Determining the lifespan of buildings is not an easy task and a methodology to properly estimate this value does not exist [34]–[36]. A building is made of different elements such as walls, ceilings, windows, etc. Those elements have different lifespan values. When an LCA of a whole building is done, a lifespan value for the complete building must be introduced. The general accepted criterion is to take the value of the structure lifespan as the one for the complete building [37] as all the other elements depend on its stability. However, lifespan of structures depends on many factors, not all of them completely known, and a methodology that can be applied in the LCA field does not exist. In usual practice, this value is taken by default.

As a consequence, when different solutions are evaluated and compared by means of LCA methodology, specially, when refurbishment and new construction are compared, no quantitative data related to their different lifespans are available. Using the same default value for all the solutions that are compared imply neglecting their actual different durability levels. Doing this goes against the recognition of the environmental benefit of longer lifespans.

One way of extending buildings structures' lifespan is structural strengthening. However, there is a lack of LCA results on the matter and it is not possible to environmentally compare different technologies. One of the burdens for the replicability and extension of building structures LCA is that a broad knowledge in the field of structures is required. Furthermore, the process is highly time-consuming and specific software is needed. A simplified method for structural assessment is therefore required.

To sum up, the main scientific gaps that this thesis aims to solve are:

- The lack of a methodology to estimate lifespans of buildings that can be used in LCA.
- The lack of comparative LCA results between refurbishment and demolition plus new building that consider the specific lifespans of every solution to obtain rigorous results.
- The lack of comparative LCA data between different strengthening options and simplified methods for structural assessment in order to make possible to replicate the LCAs in other case studies.

2.2 Objectives and scope

2.2.1 General objectives

The three main objectives of this thesis are:

1. To develop a methodology that allows estimating the lifespan of buildings, to be applied in the field of buildings LCA (papers 1 and 2).
2. To quantitatively evaluate the influence of the lifespan in the LCA results (papers 1 and 2).
3. To evaluate different methods to extend buildings lifespans (papers 3 and 4)

2.2.2 Specific objectives

In order to achieve the main objectives, the following specific objectives are established:

1. A. To identify the main degradation problems affecting reinforced concrete building structures.
1. B. To identify the available techniques to assess an existing structure and to extract the relevant parameters in durability that influence its service life.
1. C. To develop a model to estimate the lifespan of reinforced concrete structural elements affected by most common degradation phenomena.
2. A. To analyse a beam case study.
2. B To extend the analysis to a whole building scale. To apply it in a case study.
2. C To quantify the influence of lifespan in comparative LCAs between refurbishment and demolition plus new building, by introducing the estimated lifespan values of every solution in the analysis.
3. A To assess different techniques to extend the lifespan of buildings reinforced concrete structures and evaluate its environmental benefits.
3. B To propose a simplified method for structural assessment of strengthening techniques in order to turn the LCA results replicable in other case studies.

Those objectives that are not dealt with in the papers are developed in this introductory part.

2.2.3 Scope and hypothesis

As already mentioned, in buildings LCA it is broadly accepted that the value of the building lifespan is that of its structure. This thesis focuses on residential buildings with reinforced concrete structure. Just the above ground structure is considered while foundation remains out of the scope of this paper.

The following hypothesis are considered:

- Lifespan is a decisive factor in buildings LCA, which is a methodology to assess the environmental impact of the building.

- It is possible to estimate the lifespan of a specific building.

- The difference in the lifespans of existing and new buildings can modify the order of preference of solutions when comparing refurbishment with new building.

- Passive solutions for energy performance of buildings are better thatn standard ones, from an environmental point of view, even if the lifespan of the refurbished building is moderately short.

- It is possible to extend the lifespan of buildings and to evaluate the potential environmental benefits of this extension.

-

3 METHODOLOGY

The methodology used in this thesis is composed of the following steps.

3.1 Phase 1: State of the art

In this thesis, a multidisciplinary approach that includes buildings LCA and structures reinforcement techniques and calculation is needed. First of all, it is necessary to develop a state of the art of the different issues that this thesis addresses:

- State of the art of buildings LCA. Specifically, state of the art of the lifespan treatment in buildings LCA.
- State of the art of reinforced concrete buildings structures lifespans:
  - Properties of aged concrete
  - Degradation phenomena of concrete. To select the degradation phenomena that are going to be addressed in this thesis.
  - Modelling of the degradation processes with time.
- State of the art of available techniques to extend reinforced concrete lifespans.

3.2 Phase 2: Development of a model to estimate the lifespan of reinforced concrete buildings structures

The methodology followed to develop the model to estimate the lifespan of reinforced concrete building structures can be divided in five different sub-steps.

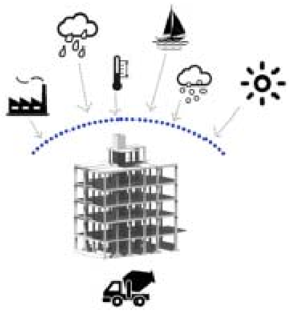
1. The first sub-step consists of assessing the vulnerability of the reinforced concrete structure. This is done to asses on the one hand, the external actions that act on it (environmental conditions) and on the other hand, the reinforced concrete structure and its quality itself. To do this, it is necessary to obtain different data. A state of the art of the available techniques to obtain environmental data as well as reinforced concrete data from existing structures (inspection techniques) are displayed in this introductory part (table A1).
2. The second step is selecting the most common degradation phenomena that can affect the structure, in accordance with the data that have been obtained

as well as data available in the literature. It is necessary to make a selection in order to limit the problem.

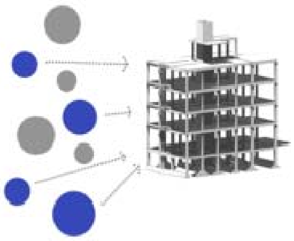
3. Once the degradation problems to be analysed have been selected it is necessary to know how these problems affect the mechanical properties of reinforced concrete and also the kinematics of the process. This is, how these processes, and their influence, evolve with time. To do this, it is necessary to obtain equations from the literature to model the chemical processes, their affection to mechanical properties and their evolution with time.
4. The next sub-step consists of assessing the structural performance of the element (or group of elements) when the mechanical properties are modified because of the degradation phenomena. These properties change with time (according to the equations named in step 3). Because of this, it is necessary to make several analyses taking into account in each of them the mechanical properties that correspond to every moment.
5. Finally, it is necessary to define a limit on the admissible structural behaviour from which it will be considered that the structure does not fulfil its function. The time that corresponds to that "limit structural behaviour" is taken as lifespan.

The methodology outlined above is summarised in **Figure 2**.

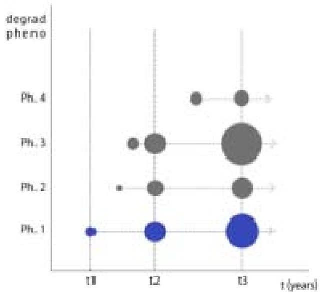
1. To assess environmental and structural conditions



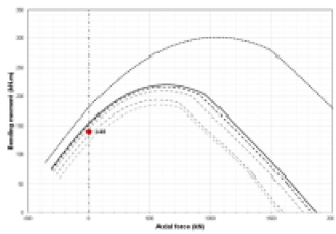
2. To determine the likelyhood of degradation phenomena



3. To estimate de evolution with time of the degradation phenomena



4. To assess structural performance with time



5. To set a limit on the admissible structural behaviour

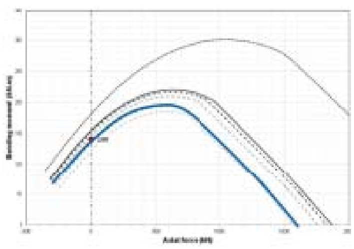


Figure 2 *Methodology used to develop a model to estimate the lifespan of reinforced concrete buildings structures*

3.3 Phase 3: Application of the model in the LCA of building elements

The model is developed and applied to a building element, in this case, a beam. LCA is done considering four different scenarios. Two of them consider that the beam is refurbished when it is needed according to the results of the durability model. The other two, consider demolition plus new building. The difference in LCA results can be quantitatively analysed.

3.4 Phase 4: Extension of the methodology to a whole building and application to a case study

The methodology is extended to a complete building. A case study is used. Refurbishment and new building are compared considering their estimated lifespans and two energy performance levels: standard and passive.

To do this the following steps are taken:

1. The case study is defined, including the selection of the existing building, the refurbishment operation and the new construction characteristics.
2. Thermal behaviour is analysed to obtain energy consumption during the use stage (operational energy).
3. The lifespan of the refurbished and the new buildings are estimated.
4. LCAs of the different options are done considering the estimated lifespans.
5. Solutions are evaluated in terms of cost-effectiveness by introducing economic aspects in a simplified way.

3.5 Phase 5: Environmental analysis of alternatives to increase the lifespan of structures (structural strengthening example).

Strengthening techniques of reinforced concrete beams are analysed as one available alternative to increase lifespan of existing structures. LCA is applied to four different strengthening techniques in order to assess their environmental behaviour.

In addition, a simplified method for structural assessment of the strengthening operation is developed. This is done in order to extend the applicability of LCA to structural operations. Usually, LCA technicians are not experts in structures but structural assessment is needed to size the materials and apply LCA.

4 RESEARCH RESULTS AND CONTRIBUTIONS

4.1 State of the art of lifespan in buildings LCAs

As stated in the papers that comprise this thesis, lifespan is a major factor in the LCA [32] and the results are strongly dependent on it [33]. Marsh [34] concludes that on average, a building lifespan of 80 years reduces environmental impact by 29%, 100 years by 38%, and 120 years by 44%, in comparison to a lifespan of 50 years. However, there is no consensus on the lifespans of buildings [22] and different values are used by the authors, e.g. 40 years [23], 50 years [38], 60 years [39] or 100 years [40]. The most commonly used value is 50 years, e.g. [18], [41], [42]. However, data on real building stocks show higher values [43], [44] with possibly decreasing values [45]. Increasing the lifespan of buildings may constitute one way to reduce their environmental impacts.

When comparing refurbishment (R) and demolition plus new building (D&N), the same lifespan is usually considered for both the refurbished and the new building, and a methodology to determine this value is often not considered, but a default value is chosen instead.

The appropriate evaluation of the lifespan is especially important when comparing R and D&N because the construction stage impacts play a major role. The main advantage of R compared to D&N is that R allows avoiding most construction stage impacts by means of using already existing elements. As a counterpart, the difference in the durability between the new and the refurbished building must be taken into account, to make a fair comparison. This second issue is often unaddressed in the literature. In this paper we claim the importance of this issue in the analysis and the results.

The main conclusions drawn are:

- Lifespan seems to be an important parameter that can affect results but there is no consensus on the value to be used nor is there a method for estimating it.

- As an applicable method to estimate lifespan does not exist, there is no quantitative data on the error that occurs in the results when default values are considered instead of specific data.

- The common practice in buildings LCA is to consider default values which, moreover, are not unanimously established. This strategy seems to be inadequate, especially in the comparisons between refurbishment and new construction due to the different ages and methods of construction.

- It is commonly accepted to take the value of the structure lifespan as the one for the complete building as the rest of the elements depend on it.

4.2 State of the art of durability of reinforced concrete structures

It is possible to define the durability of a building or a building component, as the ability to fulfil its function during the lifespan [46]. According to [46], the durability of a construction component depends on its vulnerability which, in turn, is a function of the constructive function of the element, of the external actions that act on it and of its quality. For this reason, in order to define this durability, it will be essential to analyse its vulnerability [46].

In the case of reinforced concrete structures, their constructive function is to maintain its resistance and stability and its aptitude to service, which implies to fulfil limits in the deformation, dynamic behaviour as well as being durable [47]. Durability of reinforced concrete is a function of its vulnerability, which depends on the construction characteristics of the element, on its quality, and on the external actions acting upon it [47].

Because of this, estimating the service life of a reinforced concrete structure requires the analysis of different items:

1. External actions and loads applied on the structure (physical, mechanical or chemical).

2. The properties (geometrical and physicochemical) of the specific structure, its quality (vulnerability).

3. The degradation phenomena that can affect a reinforced concrete structure, which depends on external actions and its own characteristics.

4. The kinematics of the degradation process, i.e., how the degradation phenomena can be modelled in order to predict its effects upon the structure with time.

4.2.1 *Properties of the structure. Assessment of existing reinforced concrete structures*

The quality of reinforced concrete is case dependent. Reinforced concrete is a composed material made from steel and concrete. In addition, concrete itself is also made of a mixture of different materials, mainly: cement, aggregates, water and additives. Depending on the characteristics of the components (and, of course, the execution) the properties of the concrete would be different.

4.2.1.1 Existing structures inspection techniques

When dealing with existing structures the quality and quantity of the available information differ considerably from one building to another. It is needed to know different parameters in order to assess its mechanical behaviour, state of conservation, vulnerability to degradation and development with time of degradation processes. Because of this, techniques to extract the required data from the structure are fundamental.

Usually, many techniques do exist to extract similar parameters but every technique has its own characteristics and its suitability can differ from one case study to another. In order to facilitate the selection of the most appropriate technique, a table is developed based on literature references, among others [48], classifying most of the available inspection techniques depending on the general information that they provide (group and subgroup) and also remarking main characteristics: the place where the technique must be done (in situ or laboratory), the specific information that provides and the type of information (quantitative or qualitative). Additionally, the techniques are evaluated from 1 to 10 according to the relevance of the provided information (qualitative and quantitative), applicability, disturbance to building (destructiveness) and occupants, complexity of execution and interpretation of results and availability. This table and the evaluation criteria are included in the appended **Table A1.**

4.2.1.2 Concrete properties depending on construction age

As stated above, the quality of concrete is case dependent and in the assessment of existing buildings, the parameters needed should be measured by experimental tests. However, when the objective is to perform an LCA sometimes it is not possible to make experimental testing. One possible alternative to estimate the characteristics is to extract them from the codes at the time when the structure is built.

To simplify this task the properties of concrete, according to codes and a summarising table adapted from [48] and modified according to data from the literature, is included (**Table A2**).

The main conclusion regarding the assessment of existing reinforced concrete structures is that there are a large number of reinforced concrete inspection techniques. Some parameters can be obtained through different techniques. A detailed analysis must be carried out to select those that are most suitable. It is desirable to combine techniques that provide precise quantitative data, which allow the instruments to be calibrated, with techniques that provide qualitative or less precise data but allow the inspection of larger extensions. Additionally, in accordance with the scope of this study, which is LCA and not structural intervention, cost-effectiveness and ease of application are fundamental issues.

When it is not possible to test the existing structure, historical standards can be used to estimate the needed parameters, due to the scope of this study. However, it must be noted that substantial differences may exist with the real structure, especially if it was built in ages when there was neither control of execution nor a complete knowledge of the technique.

4.2.2 Degradation phenomena of reinforced concrete

The first step in order to assess durability of concrete is to evaluate the degradation phenomena that can affect reinforced concrete structures. They are multiple and depend not only on the characteristics of the reinforced concrete but also on the environment in which it is placed (weather, physico-chemical conditions, use conditions etc.). The main degradation phenomena that can affect reinforced concrete are summarised in

Table 1.

Table 1. Main degradation phenomena that can affect reinforced concrete

Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
Chemical-external	Acid attack	Existence of nearby acids on the outside	Acid type	Spalled concrete, cracks		Low w/c ratio concrete and adequate concrete cover
Chemical-external	Aggressive water attack (low-salt water)	Concrete in touch with low minerals water.	Water aggressiveness measurement	Lixiviation of concrete components (calcium)		To protect surface in contact with no-portland cement
Chemical-internal	Alkali-Carbonate reaction	Certain components of carbonate stones react with concrete (impure dolomitic and clayed rocks)	Petrographic analysis	Concrete cracking and swelling	Cracks appearing on the surface (parallel, in the compression load direction) or in the form of localised craters, followed by disaggregation. It differs from alkali-silica reaction in the absence of silica gel in the cracks.	Do not use reactive aggregates
Chemical-internal	Alkali-Silica reaction	Aggregates containing silica may react in very alkaline environments to form non-expanding calcium-alkali-silica or alkaline-silica solids that expands	Petrographic analysis	Concrete cracking and swelling	Cracks appearing on the surface (parallel, in the compression load direction) or in the form of localised craters, followed by disaggregation. It differs from alkali-silica reaction in the absence of silica gel in the cracks	Do not use reactive aggregates or cements with less 0,6 alkali elements
Chemical-internal	Sulphate attack	Certain sulphates (sodium, potassium, calcium, or magnesium) that can be found in	To determine the existing of the chemical reactions	Crack, spalling, swelling of concrete	Polygonal or straight small cracks that increase. Besides, swelling and disaggregation of concrete in the	Use high quality cement with low w/c ratio. Use a

Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
		the soil or dissolved in nearby water and attack concrete. Two reactions: 1st the sulphate reacts with the calcium hydroxide in the concrete and forms calcium sulphate. 2nd it reacts with the hydrated calcium aluminate and forms calcium sulphoaluminate			affected area	concrete suitable to the severity of the environmen t
Chemical-external	Joint chemical attack	Mainly by substances dissolved in moving water, with pressure differences. It depends on many factors such as T, w/c ratio, permeability, consolidation, type of cement etc.	Identify chemical substances	Crack, spalling, swelling of concrete		Concretes with w/c ratio 0.4 and adequate concrete cover
Electro-chemical	Reinforcement corrosion (uniform)	Carbonation (and oxygen and humidity). Especially in cyclic wet and dry areas	Electroche mical methods to measure corrosion speed and in situ test	Corrosion, concrete cracking and spalling	Cracks parallel to reinforcement	Adequate concrete cover, type of concrete adapted to external conditions
Electro-chemical	Reinforcement corrosion (pitting)	Presence of depassivating ions (and oxygen and moisture) such as chlorides, sulphates or sulphides Especially in cyclic wet and dry areas	Electroche mical methods to measure corrosion speed and component s of concrete	Corrosion, concrete cracking and spalling	Cracks parallel to reinforcement	Adequate concrete cover, type of concrete adapted to external conditions
Mechanical	Overloads (lack of resistance due to excessive loads)	The original load state may have changed. The standard with which it was designed may not be suitable for current loads	No	Concrete cracking, spalling, strain		Reinforcem ent or repair of the structure according to the current request

Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
Mechanical	Accidental loads	Impacts, explosions, earthquakes	No	Crack and spalling of concrete		It cannot be prevented. Its impact can be reduced
Mechanical (design error)	Excessive stresses due to inadequate design	Excessive stresses due to inadequate design	No	Spalling due to excessive compression and stress cracks		Review design and structural assessment
Mechanical	Excessive stress concentration due to errors in the construction details design	Inadequate constructive details	No	Crack and spalling of concrete. Disaggregati on and material lost		Review details and design
Mechanical	Deformation in slabs	Lack of resistance due to different causes (calculation errors, execution errors, etc.)				
Mechanical	Foundation settlements or movements	Differential movement of structural elements or the structure as a whole	Tests by means of instrumenta tion	Cracks or loss of alignment of elements. Movement of non-structural elements		Geotechnic al solutions
Mechanical	Erosion or abrasion	Friction of the structural element	No	Removal of part of the material, surface wear		
Hygrother mic	Hydraulic plastic shrinkage	Evaporation of water from fresh concrete before setting	No	Surface cracks from stress excess if evaporation is faster than water rising to the surface	Usually random and diagonal pattern. They used to be separated from 0,3 to 1m when parallel. It does not have to follow the direction of the reinforcement although it can	It does not occur in existing structures but can occur in intervention in them

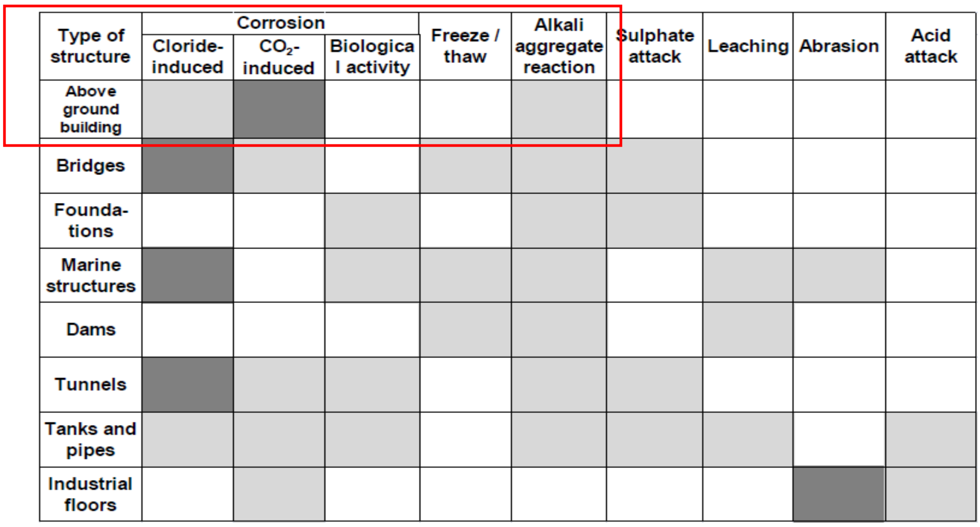
Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
					occur, being very probable a combination of plastic settlement and hydraulic retardation	
Hygrothermic	Plastic settlement	By segregation of the higher density solids that tend to fall and the water to rise to the surface, weakening the surface	No	Surface cracks	Cracks along the reinforcement position	
Hygrothermic	Dry concrete shrinkage (hydraulic shrinkage)	Long-term water loss by evaporation	No	Small cracks	Small orthogonal cracks. They usually appear at the top of the walls or in the slabs, in the areas of the vault	They are almost always just aesthetic defects. Covered with resins
Hygrothermic	Ice and thaw phases	Volumetric expansion of pore water in freezing cold climates	Yes	Varies from surface delamination to disintegration	Similar to the alkali-silica reaction	Replacement of damaged concrete with low w/c ratio and low air permeability, and drainage
Hygrothermic	Expansion and compression processes due to climatic conditions	Temperature changes in the outdoor climate	No	Cracks when the tensile strength of the concrete is exceeded		To execute expansion joints, add reinforcement
Hygrothermic	Internal expansion and compression processes	Internal temperature or humidity changes caused by cement hydration	No	Map cracking, when the tensile strength of the concrete is exceeded		It is not usual in existing concrete. In interventions measured as (lower cement content, execute the work in low temperatures, aggregates of low modulus of elasticity and temperature

Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
						coefficient
Hygrothermic	Fire	High temperatures due to fire	No	Loss of integrity, cracks and fissures		No
CONSTRUCTION PHASE						
Construction errors	Reduced mechanical resistance and durability	Addition of water		Indirect. It promotes the rest of the processes		To control the execution
Construction errors	Vulnerability to water injuries	Misalignment of elements and improper slopes	No	Water stagnation points		To control the execution
Construction errors	Reduced mechanical resistance and durability	Lack of consolidation (vibrating)	Yes, by analysing the occluded air	Surface holes, cold joints and honeycombing		To control the execution
Construction errors	Reduction of the mechanical resistance of the concrete and its durability	Improper curing	Yes, by analysing the characteristics of the concrete	Surface disintegration, cracks		To control the execution
Construction errors	Reduction of the mechanical resistance of the concrete and its durability	Moving before the concrete is fully consolidated	No	Separations, cracks and breaks		To control the execution
Construction errors	Excessive stress in concrete	Premature props removal	No	Cracks		To control the execution
Construction errors	Excessive stress in concrete	Settling of the structure or ground before the concrete reaches its full mechanical strength	No	Cracks		It is not always possible to prevent

Type	Phenomenon	Causes	Laboratory tests	Symptoms	Crack pattern	Preventive action
Construction errors	Impacts on the durability of concrete	Missing or badly arranged expansion joints	No	Cracks		Make sufficient and correctly placed joints

In order to size the problem, this thesis addresses only above ground structures. The foundation system is left out of the scope of this thesis. Among the great variety of degradation problems that can affect concrete (

Table 1) just corrosion due to carbonation is studied in this thesis to limit the problem and make the thesis viable. Alkali-Aggregate reaction (AAR) is slightly analysed in one of the papers, but just in a very simplified way. Corrosion due to carbonation is the most common degradation problem affecting reinforced concrete above ground building structures according to Budelmann [49], as can be shown in **Figure 3** extracted from [49].



Type of structure	Corrosion			Freeze / thaw	Alkali aggregate reaction	Sulphate attack	Leaching	Abrasion	Acid attack
	Cloride-induced	CO_2-induced	Biologica l activity						
Above ground building									
Bridges									
Founda-tions									
Marine structures									
Dams									
Tunnels									
Tanks and pipes									
Industrial floors									

Figure 3 *Most common degradation problems affecting reinforced concrete structures. Shading: commonly affected (dark grey), sometimes affected (light grey), uncommon (no shading) according to Budelmann [46].*

As a conclusion of the analysis exposed above it might be said that there are many degradation phenomena that can affect reinforced concrete. They affect the reinforcement or the concrete.

A distinction must be made between those that can affect new structures, existing structures or both. On the other hand, the diagnostic work is fundamental for which it is required on the one hand to be familiar with the symptoms of the degradation phenomena and on the other hand to carry out the appropriate tests (see appended **Table A1**). It also must be noted that usually many different degradation processes may occur at the same time and that many phenomena have very similar symptoms. However, some phenomena are more likely to occur than others. Therefore, and in order to limit the problem, this thesis only focuses on corrosion and some simplified references to the alkaline-aggregate reaction as they are the most common ones in above ground buildings structures (**Figure 3**).

4.2.3 Durability. Lifespan estimation. Modelling of the degradation processes with time.

Over the last decade, there have been extensive research and development activities in many countries regarding service life prediction (SLP) methods for building materials, products and components.

Estimating lifespan is a difficult and important task that has attracted attention for decades [50] because of the important implications related to it: economy, security, etc. However, predicting service life is not an easy task and many approaches to the problem of service life prediction methods for building materials, products and components can be found in the literature. We can group the different models in the following categories, according to [51]:

- **Factorial methods** (classical and probabilistic approach). They are one of the most extended methods in building components because of the ease of application. However, they are also questioned because of their simplicity [51].

- **Deterministic models** (regression analysis: simple nonlinear regression; multiple linear regression; and multiple nonlinear regression). Deterministic models use mathematical formulations trying to describe the relationship between the cause and effects of the degradation. They are very efficient when large and representative samples are available, although in general, they ignore the randomness associated to the degradation phenomenon and the errors associated to the predictions [52]. They are often used to describe some physico-chemical processes at laboratory level, as reinforced concrete corrosion, whose causes and consequences are well known, due to the knowledge of many examples. However, many other degradation phenomena as Alkali-Aggregate-Relations are almost unknown and widely accepted models do not exist yet.

- **Stochastic models**. Compared to the deterministic approach, stochastic models have a significant benefit in the sense that the degree of uncertainty associated with the considered phenomena can be quantified [53]. These models allow assessing: (i) the probability of each element being in a given degradation condition according to different criteria (such as its age, its characteristics and the environmental exposure conditions); (ii) the period of time with maximum probability of transition between a degradation condition and the next one (more severe); (iii) the probability of each case study reaching the end of its service life over a given period of time.

- **Computational methods** (artificial neural networks and fuzzy systems). Artificial neural networks aim to simulate and automate intelligent behaviour [13]. These methodologies can transform raw explanatory and relevant data into models easy to apply [14]. Fuzzy logic models are between numerical and symbolic models, closer to the way human beings actually rationalise [51].

To determine durability, as the ability of a construction component to fulfil its function [46], two main concepts or parameters must be known: which is what implies "to fulfil its function" and how this parameter can be evaluated. In the field of new reinforced concrete structures, both concepts are defined in structural codes. When dealing with existing structures, the problem is more complex due to the question of whether it is correct or not to apply codes intended for new structures to existing ones. In fact, structural codes allow applying other methodologies to asses existing structures.

In this case, the model used is the one prescribed in the codes for the design of reinforced concrete structures, based on the concept of limit states, which considers steel as an elasto-plastic material and concrete with a parabolic-rectangular strain-stress curve. This is considered as a semi-probabilistic method. The mechanical properties with time of the degraded structure are obtained by applying deterministic chemical models in the simplified model (paper 1) and stochastic chemical models in the improved version (paper 2).

4.3 State of the art of available techniques to extend reinforced concrete lifespan

In the field of reinforced concrete structures intervention many techniques do exist, that can be classified in different types, depending on the objective of the intervention:

- Protection. This is needed when the structure is not affected by degradation but is vulnerable to certain external actions that may cause future damage to it.

- Reparation. In this thesis, this concept is named as "refurbishment" as it is how life cycle analysis methodology name any kind of intervention made in the building during its service life. Reparation is needed when the structure is affected by degradation but can be intervened to stop this process or even return the structure to its initial, or at least a better, state.

- Strengthening. It is necessary when the bearing capacity of the structure is not considered adequate in terms of aptitude for service, stiffness or strength and stability.

- Substitution. It consists of adding a new structural element that replaces the structural function of the existing one, which may be eliminated or not.

A summary of most of available techniques is presented in appended **Tables A3.a, A3.b, A3.c** and **A3.d**. However, many other techniques or alternatives may exist. Data in the table are extracted from literature, among others [54]–[58]. In this table, techniques are classified depending on the general objectives of interventions, their specific objectives, the type of technique, the element that is treated (concrete or reinforcement), description, needed preparation of the structural element before applying the technique and main materials involved.

As conclusion of this analysis it might be said that there are many different techniques for intervening structures with the same purpose. It is necessary to have information to be able to select which of the possible techniques is more suitable in each case. Some data exist regarding price, possibility of execution, etc. but there is hardly any environmental data that could enrich the decision-making process.

4.4 Research results and contributions in appended papers

Results and contribution of this thesis are presented in this chapter. Main conclusions have been directly extracted from every specific paper.

In relation to the first general objective of this thesis which is to develop a methodology that allows estimation the lifespan of buildings, to be applied in the field of buildings LCA, the main research results and contributions can be found in papers 1 and 2:

- A model to estimate lifespan of reinforced concrete beams in LCA is developed, considering corrosion degradation problem and alkali-aggregate reaction (AAR) in a simplified way based on iterative structural calculations, in which the mechanical characteristics are updated in every step according to the cinematic model of the chemical process (paper 1).

- In paper 2, two improvements are made to the model proposed in paper 1. The first improvement consists of the introduction of the distributions and deviations of the input parameters, that allows to calculate deviation of the final result as well as the probability associated to the estimated lifespan obtained with the model. This is important due to the considerable uncertainty in the determination of this parameter. The second improvement deals with the definition of the admissible limit in the structural performance. In paper 1, the selection of this admissible limit is left entirely to the technician, whereas in paper 2, the use of the partial factor method and its adaptation to existing structures is proposed.

- In paper 2, the model is extended and applied to a whole building. Firstly, a simplification is made as just beams are analysed because they are more sensitive to rebar section losses than columns. Secondly, beams are classified depending on their exposure conditions, into: indoor, outdoor, below the roof or in contact with sanitary floor slab. Therefore, the degradation model is applied to four types of beams.

Specifically, the main conclusions are:

- It is possible to develop a model to estimate lifespan on a simplified way. However, broadly accepted and applicable equations that describe the chemical process and its cinematic only exist for corrosion. The rest of possible degradation phenomena are quite less characterised and some of them remain almost unknown.

- As knowledge of the chemistry inherent in the degradation processes and its evolution over time advances, the lifespan estimation model will become more accurate and will be able to consider a greater number of phenomena. However, it is first necessary to have equations that describe the evolution of mechanical properties over time caused by degradation processes other than corrosion, which currently do not exist.

In relation to the second general objective of this thesis which is to quantitatively evaluate the influence of the lifespan in the LCA results, main contributions and results can be found in papers 1 and 2:

- The influence of lifespan in LCA of reinforced concrete beams is evaluated in paper 1. To do this, four different scenarios of lifespan are defined and analysed, two of them include minor structural interventions, made at different stages, and the other two not.

- The hypothetical long term environmental differences of every scenario are evaluated (paper 1).

- The potential of repair and maintenance to extend the lifespan of a beam and its associated environmental benefits are evaluated for a case study (paper 1).

- Comparative LCAs are done between refurbishment and demolition plus new building, that consider the estimated lifespan obtained with the model (paper 2).

- Two thermal performance levels are evaluated: standard and passive, in both alternatives, the refurbished and the new building (paper 2).

- Comparisons are also made with other approaches to determine buildings lifespans based on default value and statistical data (paper 2).

Specifically, the main conclusions from paper 1 are:

1. The required interventions in building structures should be considered in LCA since, among other reasons, the embodied energy is not a constant value per year.

2. Demolishing and replacing reinforced concrete structures before exhausting their useful life leads to an increase in the embodied energy of 65% (scenario 1a: demolishing after 50 years) or 39% (scenario 1b: demolishing after 80 years), considering a period of 250 years. This percentage increases with longer periods of time.
3. Planning interventions with a long-term vision is crucial to select the most environmentally friendly strategy as exhausting the useful life of reinforced concrete structures can bring environmental advantages.
4. A beam subject to degradation cannot be refurbished indefinitely, according to the refurbishment operation considered in this paper. In spite of this, the impact of several repair interventions of a beam plus the final demolition and new construction, obtain better results than demolition and reconstruction before the end of its physical service life is reached. This is even though the time interval between refurbishment operations is shorter and shorter with time.
5. Repair interventions have a huge potential to extend the service life of a reinforced concrete beam.
6. Extending service life of structures also means extending the service life of many other components, which further increases its environmental benefits.
7. Selecting the minimum working design life in structural codes, as the service life value in LCA of buildings, can lead to significant variations in results. In this case study, the value prescribed in codes is 50 years, statistical data of demolition is 80 years, and calculated service life according to degradation models is 265 years if no intervention is done, i.e., more than 5 times the value of the codes.

Specifically, the main conclusions from paper 2 are:

1. Estimating the different lifespan of each specific building that is compared is fundamental in buildings LCA, especially when comparing refurbishment with demolition and new building, where the differences can be significant. In this case study the difference in the lifespan of the refurbished and the new building is up to 176 years.
2. Considering the same lifespan for both the refurbished and the new building, as it is done in common practice, can lead to important errors in the results. In this case study, the difference in the results obtained when a fixed 100

years value for both the refurbished and the new building is assumed, and results obtained when the lifespan is estimated using a durability-based approach is of 6.50%, 7.36%, -7.53% and -8.02% for the standard refurbishment (SR), passive refurbishment (PR), standard demolition and new building (SD&N) and passive demolition and new building (PD&N) alternatives. This implies that in the comparison of SR and SD&N alternatives a cumulative difference of 14.03% is obtained. In the comparison of PR and PD&N the difference is of 15.38%. It must be noted, that in this study a 100 years lifespan is considered as the "default value" alternative. If a 50 years lifespan for both the refurbished and the new building had been considered in the analysis, as it is often done in LCA, the difference in the results would be even greater.

3. Statistical studies of buildings lifespan provide more realistic results. In this case, 30 and 80 years for the refurbished and the new building compared to the estimated lifespan value of 34 and 210 years, for the refurbished and the new building. However, they reflect human behaviour regarding buildings lifespan, this is, that buildings tend to be demolished before they reach their physical end of life, but not their potential physical durability. In addition, although they can be accurate in general terms, they might not be accurate for the particular building that is being analysed.
4. Extending the service life of buildings is a good strategy towards sustainability. Lifespans of 210 years should be promoted in new buildings, particularly using LCA thinking in their design, by defining adaptable building structures allowing changing the use of buildings (flexibility between housing and tertiary uses, adaptability according to the changing need of spaces). This paper shows that reductions around 11% in CO_2-eq. annual emissions can be achieved with such a lifespan compared to a statistical value of 80 years. Therefore, increasing buildings lifespan is one of the important ways to progress towards sustainability.

The third general objective of this thesis, which is to environmentally evaluate different methods to extend buildings lifespans, is developed in papers 3 and 4. Paper 4 is an extension of the analysis made in paper 3. In paper 4, two more strengthening techniques are added to the analysis (resulting in a total of 4) and a simplified method for the structural assessment of reinforcements is also added. Main contributions of papers 3 and 4 are:

- Comparative LCA between four different strengthening techniques of reinforced concrete beams are done: 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).

- Environmental results considering nine different convectional beam cross sections are displayed: three flat beams (hxb:150x300, 200x400, 250x500), three square beams (hxb: 250x250, 300x300, 500x500) and three suspended beams (hxb: 400x200, 500x250, 600x300).

- LCA comparison between strengthening and demolition plus new construction is also analysed.

- A simplified model for structural assessment of reinforced concrete beams strengthen techniques is proposed.

Specifically, the main conclusions are:

1. The proposed simplified model is a suitable, low time-consuming and scientifically based option to obtain the data needed in a LCA of reinforced concrete beams strengthening.
2. 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.
3. 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 restored.
4. 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 kilogrammes 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.

5. 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.
6. In the case of RC, the construction process is the most contributing stage

5 FINAL CONCLUSIONS

As final conclusions the following can be remarked, directly related with the initial hypotheses of the thesis:

- *Hypothesis 1: Lifespan is a decisive factor in buildings LCA, which is a methodology to assess the environmental impact of the building.* Lifespan is fundamental in comparative LCAs of buildings, especially when comparing buildings built at different times, as it is in refurbishment vs. demolition and new construction. Differences in the lifespans between existing and new building can be up to 100 years. In common practice, the same lifespan is considered for the refurbished and the new building when both alternatives are compared. This is normally not correct and can significantly skew results. There is no consensus about the lifespan that should be considered in LCA, but the lifespan data often used are very conservative in the case of new concrete structures.

  The importance of considering the service life in a more accurate way in LCA is, although of complex estimation, fundamental. Otherwise, durable materials can result seriously punished. Reinforced concrete is a highly impacting material, above all due to the great amount of it that is required in a building structure. However, it is also a material with a long service life. Demolishing a structure (and therefore, a building) that can last 250 years after just 50 or 80 is a highly impacting action. Refurbishment can ensure this durability and even extend it.

- *Hypothesis 2: It is possible to estimate the lifespan of a specific building.* Applicable methods to estimate this parameter are needed. In this thesis one method has been developed, considering just the main degradation phenomena that can affect a building above air reinforced concrete structure. This estimation can be applied to buildings LCA. However, lifespan is a very complex problem and the proposed model just provides an estimation after making important simplifications (i.e. just one degradation phenomenom is introduced). . There is a need for further including other degradation phenomena in the model.

- *Hypothesis 3 and 4: The difference in the lifespans of existing and new buildings can modify the order of preference of solutions when comparing refurbishment with new building.*

Passive solutions for energy performance of buildings compensate standard ones, even if the lifespan of the building is moderately short. Although it may be a big difference in the lifespan of a new and an existing building, refurbishment always appears as the best option in the case studies analysed here when the same performance level is compared. However, demolition and building a new passive building obtains better results than standard refurbishment.

- *Hypothesis 5: It is possible to extend the lifespan of buildings and to evaluate the potential environmental benefits of this extension.* Extending the service life of buildings is a good strategy towards sustainability. Applying lifespan estimation methods in LCA allows quantifying this environmental benefit.

6 FUTURE RESEARCH WORK

This thesis has opened a research line but additional future research work is needed in order to obtain more accurate models. Additionally, more LCA studies taking into account the lifespan problem are required.

Specifically, in the future it would be advisable:

- To incorporate in the model to estimate lifespans more degradation phenomena describing their evolution and the relation between them. This must necessarily be accompanied by more research into concrete degradation phenomena that will enable applicable models to be obtained.

- To obtain degradation models which accurately describe behaviour of in situ structures in addition to a laboratory level.

- To further analyse probabilistic methods of structural assessment of existing structures and the definition of what is considered as "acceptable behaviour" o "lifespan limit".

- To apply this thesis procedure to the LCA of other real buildings, with in situ and laboratory test to extract the data needed in the model.

AFTERWORD

I submitted this thesis to Universidad de Zaragoza in March 2020.

I would like to finish this thesis expressing my gratitude to the people and institutions that have contributed to making it a reality.

First of all, I would like to thank my thesis supervisors, Belinda López and Luis Gracia, for all their efforts and dedication, both professionally and personally. They instilled in me the importance of research and structures theory for architecture and trusted in my research skills before I did. Also to my doctoral programme tutor, Ignacio Zabalza, for his invaluable and disinterested help.

To the GIA research group, for allowing me to be part of this interesting project from the beginning.

To Bruno Peuportier, for his warm welcome and diligent supervision of my work during the research stay. To Piotr Berkowsky, for his invaluable help in this process. To all my colleagues at Politechnika Wroclawska, MINES ParisTech and Colegio de España, for making the "abroad" in something very close.

To my colleagues PhD students from the Department of Mechanical Engineering and especially to Alberto and Javier, for accompanying me on this journey and sharing both moments of joy and moments of weakness.

To my family, especially to mi father, for teaching me that the path of research was possible from a very young age and for supporting me in all the decisions taken. To Alex, for listening to me, supporting me and trusting me even when I didn't do it myself.

REFERENCES

[1] B. Palacios-Munoz, B. López-Mesa, and L. Gracia-Villa, "Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact," *Int. J. Life Cycle Assess.*, vol. 24, no. 11, pp. 1913–1924, Nov. 2019.

[2] B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, and B. López-Mesa, "Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach," *Build. Environ.*, vol. 160, p. 106203, Aug. 2019.

[3] B. Palacios-Munoz, B. López-Mesa, and L. Gracia-Villa, "Structural design and comparative LCA of two strengthening techniques: Concrete beams under flexural loads," in *Construction pathology, Rehabilitation technology and heritage management (Digital Book of Asticles- REHABEND 2018, Euro-American Congress)*, 2018, pp. 1609–1617.

[4] B. Palacios-Munoz, L. Gracia-Villa, I. Zabalza-Bribián, and B. López-Mesa, "Simplified structural design and LCA of reinforced concrete beams strengthening techniques," *Eng. Struct.*, vol. 174, no. July, pp. 418–432, Nov. 2018.

[5] Ministry of Public Works and Transport, *Real Decreto Legislativo 7/2015, Texto Refundido de la Ley del Suelo*. Spain, 2015.

[6] COM(2003) 302, *COMMUNICATION FROM THE COMMISSION TO THE COUNCIL AND THE EUROPEAN PARLIAMENT Integrated Product Policy Building on Environmental Life-Cycle Thinking*, no. 302. pp. 1–12.

[7] M. of E. (Spain) MINETAD, "Plan Nacional de Acción de Eficiencia Energética 2017-2020," 2017.

[8] European Commission, *COM(2017) 56 REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT AND THE COUNCIL 2016 assessment of the progress made by Member States in 2014 towards the national energy efficiency targets for 2020 and towards the implementation of the Energy*

Efficienc. European Union, 2017.

[9] European Commission, *Commission Recommendation (EU) 2016/1318*, no. 1038. 2016, pp. 46–56.

[10] D. 2010/31/CE, *Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings*. 2010.

[11] European Parliament, *Directive 2012/27/EU*, vol. L315/1, no. October. 2012, pp. 1–56.

[12] European Commission, *DIRECTIVE (EU) 2018/844 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCILof 30 May 2018amending Directive 2010/31/EU on the energy performance of buildings and Directive 2012/27/EU on energy efficiency*. 2018.

[13] ISO, *ISO 14040:2006 Environmental management - Life cycle assessment principles and framework*. 2006.

[14] ISO 14044:2006, "ISO 14044:2006 Life cycle assessment — Requirements and guidelines," *International Organization for Standardization*, vol. 14044. p. 46, 2006.

[15] CEN European Comittee for Standarization, *EN 15643-1:2010 Sustainability of construction works - Sustainability assessment of buildings - Part 1: General framework*. European Union, 2010.

[16] N. P. M. Scholten and H. van Ewijk, "Environmental Performance Regulations in the Netherlands," *4th Int. Conf. Civ. Enginerring, Part I, Build. Renov.*, pp. 245–249, 2013.

[17] A. Vilches, A. Garcia-martinez, and B. Sanchez-monta, "Life cycle assessment (LCA) of building refurbishment : A literature review," vol. 135, pp. 286–301, 2017.

[18] I. Zabalza Bribián, A. Aranda Usón, and S. Scarpellini, "Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification," *Build. Environ.*, vol. 44, no. 12, pp. 2510–2520, 2009.

[19] S. V. Russell-Smith and M. D. Lepech, "Cradle-to-gate sustainable target value

design: Integrating life cycle assessment and construction management for buildings," *J. Clean. Prod.*, vol. 100, pp. 107–115, 2015.

[20] I. Zabalza Bribián, A. Valero, A. Aranda Usón, and E. Llera, "Methodological aspects and design implications to achieve life cycle low emission buildings. A case study: LCA of a new university building," *Strojarstvo*, 2013.

[21] O. Ortiz-Rodríguez, F. Castells, and G. Sonnemann, "Life cycle assessment of two dwellings: One in Spain, a developed country, and one in Colombia, a country under development," *Sci. Total Environ.*, vol. 408, no. 12, pp. 2435–2443, 2010.

[22] R. M. Cuéllar-Franca and A. Azapagic, "Environmental impacts of the UK residential sector: Life cycle assessment of houses," *Build. Environ.*, vol. 54, pp. 86–99, 2012.

[23] F. Nemry *et al.*, "Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs," *Energy Build.*, vol. 42, no. 7, pp. 976–984, 2010.

[24] A. Vilches, A. Garcia-Martinez, and B. Sanchez-Montañes, "Life cycle assessment (LCA) of building refurbishment: A literature review," *Energy Build.*, 2017.

[25] A. A. Famuyibo, A. Duffy, and P. Strachan, "Achieving a holistic view of the life cycle performance of existing dwellings," *Build. Environ.*, vol. 70, no. 2, pp. 90–101, 2013.

[26] H. Mohammadpourkarbasi and S. Sharples, "Eco-Retrofitting Very Old Dwellings□ : Current and Future Energy and Carbon Performance for Two Uk Cities," in *PLEA 2013: Sustainable Architecture for a Renewable Future*, 2013, no. September.

[27] B. Peuportier, "Assessment and design of a renovation project using life cycle analysis and Green Building Tool," in *Proceedings of the International Conference - The Challenge, the Knowledge, the Solutions*, 2002, pp. 352–357.

[28] G. Assefa and C. Ambler, "To demolish or not to demolish: Life cycle consideration of repurposing buildings," *Sustain. Cities Soc.*, vol. 28, pp. 146–

153, 2017.

[29] G. Ding, "Demolish or refurbish–Environmental benefits of housing conservation," *Australas. J. Constr. Econ. Build.*, vol. 13, no. 2, pp. 18–34, 2013.

[30] M. D. Alba-Rodríguez, A. Martínez-Rocamora, P. González-Vallejo, A. Ferreira-Sánchez, and M. Marrero, "Building rehabilitation versus demolition and new construction: Economic and environmental assessment," *Environ. Impact Assess. Rev.*, vol. 66, no. December 2016, pp. 115–126, 2017.

[31] Y. Schwartz, R. Raslan, and D. Mumovic, "The life cycle carbon footprint of refurbished and new buildings – A systematic review of case studies," *Renew. Sustain. Energy Rev.*, vol. 81, no. October 2017, pp. 231–241, 2018.

[32] W. Pan, K. Li, and Y. Teng, "Rethinking system boundaries of the life cycle carbon emissions of buildings," *Renew. Sustain. Energy Rev.*, vol. 90, no. March, pp. 379–390, 2018.

[33] H. Islam, M. Jollands, and S. Setunge, "Life cycle assessment and life cycle cost implication of residential buildings - A review," *Renew. Sustain. Energy Rev.*, vol. 42, pp. 129–140, 2015.

[34] R. Marsh, "Building lifespan□ : effect on the environmental impact of building components in a Danish perspective," *Archit. Eng. Des. Manag.*, vol. 13, no. 2, pp. 80–100, 2017.

[35] J. Palmeri, "A Life Cycle Approach to Prioritizing Methods of Preventing Waste from the Residential Construction Sector in the State of Oregon," State of Oregon, 2010.

[36] S. M. Strand and P. J. Hovde, "USE OF SERVICE LIFE DATA IN LCA OF BUILDING MATERIALS," in *8DBMC International Conference on Durability of Building Materials and Components*, 1999, pp. 1948–1958.

[37] A. Haapio, "Service Life of a Building in Environmental Assessment of Buildings," no. May, 2008.

[38] K. Adalberth, A. Almgren, and E. H. Petersen, "Life-Cycle Assessment of Four Multi-Family Buildings," *Int. J. Low Energy Sustain. Build.*, 2001.

[39] C. D. Frenette, C. Bulle, R. Beauregard, A. Salenikovich, and D. Derome, "Using life cycle assessment to derive an environmental index for light-frame wood wall assemblies," *Build. Environ.*, vol. 45, no. 10, pp. 2111–2122, 2010.

[40] U. Iyer-Raniga and J. P. C. Wong, "Evaluation of whole life cycle assessment for heritage buildings in Australia," *Build. Environ.*, vol. 47, no. 1, pp. 138–149, 2012.

[41] O. Ortiz, C. Bonnet, J. C. Bruno, and F. Castells, "Sustainability based on LCM of residential dwellings: A case study in Catalonia, Spain," *Build. Environ.*, 2009.

[42] K. Adalberth, "Energy use during the life cycle of single-unit dwellings: Examples," *Build. Environ.*, vol. 32, no. 4, pp. 321–329, Jul. 1997.

[43] I. M. Johnstone, "Energy and mass flows of housing: A model and example," *Build. Environ.*, vol. 36, no. 1, pp. 27–41, 2001.

[44] H. Bergsdal, H. Brattebø, R. A. Bohne, and D. B. Müller, "Dynamic material flow analysis for Norway's dwelling stock," *Build. Res. Inf.*, vol. 35, no. 5, pp. 557–570, 2007.

[45] M. Aksözen, U. Hassler, and N. Kohler, "Reconstitution of the dynamics of an urban building stock," *Build. Res. Inf.*, 2017.

[46] J. Monjo Carrió, "Durability vs Vulnerability," *Inf. la Construcción*, vol. 59, no. 507, pp. 43–58, Sep. 2007.

[47] Head of spanish State (Jefatura del Estado), *Ley 38/1999, de 5 de noviembre, de Ordenación de la Edificación*. Spain, 1999.

[48] I. V. de la E. IVE, *Guía de intervención en estructuras de hormigón en edificios existentes*, 2ª. Valencia: Generalitat Valenciana, 2010.

[49] H. Budelmann, A. Holst, and A. Wachsmann, "Durability related life-cycle assessment of concrete structures□ : Mechanisms , models , implementation," in *Life-Cycle and Sustainability of Civil Infrastructure Systems*, 2013, pp. 75–86.

[50] P. J. Hovde, "The Factor Method – a simple tool to service life estimation.," *10DBMC International Conference on Durability of Building Materials and*

Components\r. 2005.

[51] A. Silva, J. de Brito, and P. L. Gaspar, "Comparative analysis of service life prediction methods applied to rendered façades," *Mater. Struct.*, vol. 49, no. 11, pp. 4893–4910, 2016.

[52] S. Setunge and M. S. Hasan, "Concrete Bridge Deterioration Prediction using Markov Chain Approach," *Digit. Libr.*, 2011.

[53] U. J. Na, S.-J. Kwon, S. R. Chaudhuri, and M. Shinozuka, "Stochastic model for service life prediction of RC structures exposed to carbonation using random field simulation," *KSCE J. Civ. Eng.*, vol. 16, no. 1, pp. 133–143, Jan. 2012.

[54] IVE Instituto Valenciano de la Edificación, *Guía de intervención en estructuras de hormigón en edificios existentes*, Generalita. Valencia (Spain): Generalitat Valenciana, 2010.

[55] M. Kaminski and E. Kusa, "Strains in CFRP - strengthened reinforced concrete beams," in *Concrete Solutions, 5th International Conference on Concrete Repair*, 2014, pp. 297–304.

[56] G. Monti, "Modelling aspects and design issues for anchorages, shear strengthening and confinement," in *Technical report, CEB FIB Bulletin 35, Retrofitting of concrete structures by externally bonded FRPs*, Lausanne: International Federation for Structural Concrete (fib), 2006, p. 74.

[57] M. Raupach and T. Büttner, *Concrete Repair to EN 1504 Diagnosis, Design, Principles and Practice*, 1st ed. Boca Ratón, Florida, USA: CRC Press, 2014.

[58] A. M. Morsy, K. M. Helmy, N. H. El-Ashkar, and M. Nada, "Flexural strengthening for R.C. beams using CFRP sheets with different bonding schemes," in *Concrete Solutions, 5th International Conference on Concrete Repair*, 2014, pp. 313–320.

APPENDIX A1. Available reinforced concrete structures inspection techniques

As stated before, a state of the art about the most common available inspection techniques of reinforced concrete structures has been developed in this thesis and included in **table A1**. These techniques have been evaluated, from 1 to 10, according to different parameters: relevance of the information that provide (qualitative and quantitative), applicability, disturbance to building (destructiveness) and occupants, complexity of execution and interpretation of results and availability. The criterion followed to provide the rating is explained below.

QUALITATIVE RELEVANCE

Value	Relevance	Criteria
1	No relevance	Not knowing the parameter is not important as it usually does not influence the overall analysis
2	Very little relevance	The information provided is not very relevant for the analysis of the overall structural behaviour, since the error would be very limited if the parameter were not considered, within the range of precision of the study.
3	Little relevance	The information provided influences behaviour but not in a very relevant way, and its influence can be disregarded without too much error.
4	Moderate importance	It has an appreciable, though not decisive, influence, and if it is not known, it could be estimated by standard values from the literature without practically losing accuracy.
5	Standard relevance	It has an appreciable, though not decisive, influence, and if it is not known, it could be estimated by standard values from the literature, though losing some accuracy.
6	Quite relevance	It influences in a considerable way, without being one of the main factors, and in case it is not known it could be estimated by standard values of the bibliography although losing some accuracy.
7	Remarkable relevance	It has a considerable influence, without being one of the main factors, and if it is not known it could not be estimated by standard values from the literature, thus losing significant accuracy.
8	Relevant	It has a decisive influence on the solution, being one of the main factors, and in case it is not known it could be estimated by standard values from the literature although losing a significant accuracy.

9	Very relevant	It has a decisive influence on the solution, being one of the main factors, and in case it is not known it could not be estimated by standard values from the literature so the model would not have an acceptable precision being only indicative
10	Essential	The value is essential and cannot be obtained from the literature with acceptable accuracy, so not knowing it means not being able to perform applicable calculations.

QUANTITATIVE RELEVANCE

Value	Relevance	Criteria
1	Imprecise approximation	It gives only a general idea of the parameter, without precision, which cannot be used directly
2	local-little accuracy	It provides only an imprecise local result of the parameter
3	local-acceptable accuracy	It provides only a relatively accurate local result of the parameter
4	local- very accurate	It provides a very accurate local result of the parameter
5	superficial-little accuracy	It provides only an imprecise local surface result of the parameter
6	superficial-acceptable accuracy	It provides only a relatively accurate local surface result of the parameter
7	superficial- very accurate	It provides only a very accurate local surface result of the parameter
8	global-little accuracy	Gives an overall (or large parts of the building) low accurate result of the parameter (the area left unmeasured is minimal)
9	global-acceptable accuracy	Provides a relatively accurate overall result (or of large parts of the building) of the parameter (the area left unmeasured is minimal)
10	Perfectly quantified parameter	It gives a very precise overall result (or for large parts of the building) of the parameter (the area left unmeasured is minimal). The parameter is perfectly defined.

APPLICABILITY

Value	Applicability	Criteria
1	Almost inapplicable	It is a novel technique still in the research and development phase that can only be applied in very specific cases
2	Very low applicability	It is a relatively new technique that is still under development and can only be applied in very specific cases
3	Low applicability	It is a known and controlled technique but it can only be applied in very specific cases
4	Moderate applicability	It is a novel technique still in the research and development phase and can be applied in some cases (approx. 30 % to 60 %)
5	Standard applicability	It is a relatively new technique that is still under development and can be applied in some cases (approx. 30% to 60%)
6	Relatively applicable	It is a known and controlled technique, which can be applied in some cases (approx. 30% to 60%)
7	Quite applicable	It is a novel technique still in the research and development phase that can almost always be applied
8	High applicability	It is a relatively new technique that is still under development and can almost always be applied
9	Really high applicability	It is a known and controlled technique that can almost always be applied
10	Totally applicable	It is a well known and controlled technique, always applicable

INVASIVITY

Invasivity with building

Value	Invasivity	Criteria
1	Non-invasive	It does not produce any alteration in the building. There is not even physical contact with it.
2	Quite similar to non-invasive	The technique produces slight disturbances in the building during the test (such as vibrations) but once the building has been completed it experiences virtually no disturbance.
3	Minimally invasive	The realization of the test requires the fixation to the building of instruments or elements of scarce entity that originate a slight alteration of the same one as small holes, anchorages etc.
4	Low invasive	The test requires the removal only of the coating (if any), but not material of the to the structural elements
5	Moderate invasive	The test requires making small incisions or punctual openings that are easily repaired and of reduced dimensions, both in the coating material (if it exists) and in the structural

		elements.
6	Standard invasiveness	The test requires the removal of small samples, cores, micro-probs or similar from the entire section of the element
7	Quite invasive	The test requires the removal of specimens from the complete section of the major entity element (> 100 mm in diameter)
8	Invasive	The test requires the removal of specimens from the complete section of the element of sufficient entity (> 100 mm in diameter) and a high number of specimens must be removed from the average in order to obtain valid results.
9	Very invasive	The operation involves the extraction of some complete structural elements (as well as other constructional elements), but the building retains its entity and materiality
10	Totally invasive	The operation implies the extraction of complete structural elements (as well as other constructive elements), in such quantity and magnitude that the building loses part of its entity and materiality.

Invasivity with occupants

Value	Invasivity	Criteria
1	Non-invasive	It does not produce any disturbance to the occupants.
2	Quite similar to non-invasive	It does not disturb the occupants except for some occasional conversation or meeting.
3	Minimally invasive	It produces slight inconveniences to the occupants such as the need to enter the houses, minimum adaptation of the way of life (restrictions for example to the use of certain elements such as windows)... but without physical inconveniences such as noise, vibrations, dirt etc.
4	Low invasive	Causes slight discomfort to the physical occupants such as noise, vibrations, dirt etc. for a short period of time (no more than one hour)
5	Moderate invasive	Produces slight discomfort to the physical occupants such as noise, vibrations, dirt etc. for a period of time of moderate duration (no more than one day)
6	Standard invasiveness	It causes quite a lot of discomfort to the physical occupants such as a lot of noise, vibrations, dirt etc. for a short period of time (no more than one hour)
7	Quite invasive	It causes quite a lot of discomfort to the physical occupants such as a lot of noise, vibrations, dirt etc. for a period of time of moderate duration (no more than one day)

8	Invasive	It causes significant discomfort to the physical occupants such as a lot of noise, vibrations, dirt etc. for a long period of time (more than one day)
9	Very invasive	In order to carry out the test, it is necessary to vacate the building (or homes, offices, etc.) for a period of no more than one day
10	Totally invasive	In order to carry out the test, it is necessary to vacate the building (or homes, offices, etc.) for more than one day

COMPLEXITY

Value	Importance	Criteria
1	No complexity	Both the execution and the interpretation of results are easy, not even requiring qualified personnel to carry out tests
2	Very little complexity	Both the execution of the test and the interpretation of results are easy, but it requires slightly qualified personnel.
3	Little complexity	The execution of the test is easy but the interpretation of results is of medium difficulty, so it requires qualified personnel.
4	Moderate complexity	The interpretation of results is easy although the execution of the test is of medium difficulty, so it requires qualified personnel to do so.
5	Standard complexity	Both the execution of the test and the interpretation of results are of medium difficulty, so qualified personnel is required for this purpose.
6	Relatively complex	The execution of the test is easy although the interpretation of results is very difficult, so it requires highly qualified personnel to do so.
7	Quite complex	The execution of the test is of medium difficulty but the interpretation of results is of great difficulty, so it requires highly qualified personnel.
8	Complex	The interpretation of results is easy although the execution of the test is very difficult, so it requires highly qualified personnel to do so.
9	Very complex	The execution of the test is of great difficulty and the interpretation of results is of medium difficulty, so it requires highly qualified personnel to do so.
10	Extremely complex	Both the execution of the test and the interpretation of results are very difficult, so highly qualified personnel is required for this purpose.

Table A1_ Inspection techniques (English version/*Spanish version*)

Classification *Clasificación* / **Subgroup** *Subgrupo*	**Place of execution** *Lugar de realización*	**Technique name** *Nombre de la técnica*	**Resulting information** *Información que proporciona*	**Information type** *Tipo de info.*	**Qualitative relevance** *Relev. cualitativa*	**Quantitative relevance** *Relev. cuantitativa*	**Applicability** *Aplicabilidad*	**Invasivity** *Invasividad* **with build.** *con edif.*	**with ocupants** *ocupantes*	**Complexity** *Complejidad*
GEOMETRIC DEFINITION OF THE STRUCTURAL SYSTEM (INCLUDING HIDDEN ELEMENTS) AND ANALYSIS OF PRESENCE AND LOCATION OF REINFORCEMENT. HYPOTHESIS OF BOUNDARY CONDITIONS. *DEFINICIÓN GEOMÉTRICA DEL SISTEMA ESTRUCTURAL (INCLUSO ELEMENTOS OCULTOS) Y ANÁLISIS DE PRESENCIA Y LOCALIZACIÓN DE ARMADO. HIPÓTESIS DE CONDICIONES DE CONTORNO*										
Building geometry *Geometría del edificio*	In-situ + external data *in-situ + datos externos*	Analysis of the building's background *Estudio de la historia del edificio*	Analysis of the background of the building: construction period and construction technique, subsequent interventions, initial geometry and modifications, regulations applicable at the time of intervention, etc. Study of written, graphic, documentary and other types of documentation in any media. *Estudio del proceso evolutivo del edificio: época de construcción y técnica constructiva, intervenciones posteriores, geometría inicial y modificaciones, normativa de aplicación en el momento de intervención etc. Estudio de documentación escrita, gráfica, documental y de otros tipos en cualquier soporte.*	Quantitative *Cuantitativa*	8	8	10	1	2	5
	in situ *in situ*	Analysis and measurement of the building geometry by conventional methods (laser meters, etc.) *Estudio y medición de la geometría del edificio por métodos convencionales (medidores láser, etc.)*	Geometric definition by means of in situ measurements with conventional elements and initial mapping. *Aproximación geométrica mediante mediciones in situ con elementos convencionales y levantamiento inicial de planos.*	Quantitative *Cuantitativa*	10	9	10	1	3	5
	in situ *in situ*	Measurement with topographic elements *Medición con elementos topográficos*	Geometry of the building or element to be analysed. *Obtención de la geometría del edifico o elemento a analizar.*	Quantitative *Cuantitativa*	8	10	10	1	3	5

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
	in situ *in situ*	Photogrammetry (image analysis and convergent photogrammetry) *Fotogrametría (análisis de imágenes y fotogrametría convergente)*	Three-dimensional and two-dimensional models of the building's geometry with different levels of detail from which precise measurements and reconstructions are obtained *Obtener modelos tridimensionales y bidimensionales de la geometría del edificio con diferente nivel de detalle de los que se obtienen mediciones y reconstrucciones precisas*	Quantitative *Cuantitativa*	7	10	5	1	3	5
	in situ *in situ*	Laser and 3D scanner *Láser y escáner 3D*	Accurate geometry by creating precise 3D models *Obtener la geometría precisa pudiendo crear modelos precisos en 3D*	Quantitative *Cuantitativa*	7	10	7	1	3	5
	in situ *in situ*	Geodetic methods *Métodos geodésicos*	Measurement of geometry, inclinations, deformations, etc. *Medida de la geometría, inclinaciones, deformaciones, etc.*	Quantitative *Cuantitativa*	7	9	8	1	3	5
Soil and foundation characterization *Caracterización del terreno y la cimentación*	in situ *in situ*	Geotechnical study *Estudio geotécnico*	Ground characterization *Obtención del la caracterización del terreno.*	Quantitative *Cuantitativa*	8	4	10	2*	6	3
	in situ *in situ*	Test pits for foundation inspection *Calicatas para inspección de cimentación*	Geometry, morphology and typology of the foundation and its state. *Conocer la geometría, morfología y tipología de la cimentación y de su estado.*	Qualitative *Cualitativa*	8	7	9	7	8	5
	in situ *in situ*	Georadar (applied to foundations) *Georadar (aplicado a cimentaciones)*	Detection of hidden structural elements, section morphology, reinforcements, detection of the presence of humidity, detection of cracks, defects or holes, location of the position of large gaps and inclusions of different materials such as steel, wood, etc. *Investigación de elementos estructurales ocultos, morfología de la sección, armaduras, detección de presencia de humedad, detección*	Qualitative *Cualitativa*	7	6	7	2	3	7

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
			de fisuras, defectos o huecos, localizar la posición de grandes vacíos e inclusiones de materiales diferentes como acero, madera, etc.							
Morphology of structural elements (size, reinforcement, hidden elements) *Morfología de los elementos estructurales (dimensiones, armado, elementos ocultos)*	in situ *in situ*	Measurement by conventional methods of the sections of the structural elements *Medición por métodos convencionales de las secciones de los elementos estructurales*	Size and geometry of the structural elements *Dimensiones y geometría de los elementos estructurales.*	Quantitative *Cuantitativa*	10	6	9	4	4	2
	in situ *in situ*	Impact-eco test *Impacto- eco*	Measurement of concrete thickness of elements accessible on one side only, mapping of internal voids, acoustic behaviour of interfaces to determine the quality of the bond. *Medida del espesor del hormigón de elementos accesibles a una sola cara, mapeo de huecos internos, comportamiento acústico de interfases para determinar la calidad de la adherencia.*	Quantitative *Cuantitativa*	8	3	5	2	3	6
	in situ *in situ*	Electromagnetic waves test *Medidas por ondas electromagnéticas.*	Detail of reinforcement. Location of the reinforcement, determination of the number of reinforcements and estimation of the covering, known the diameter or vice versa. *Detalle de armado. Localización de la armaduras, determinación del nº de armaduras y estimación del recubrimiento conocido el diámetro o a la inversa.*	Quantitative *Cuantitativa*	9	7	8	2	3	5
	in situ *in situ*	Ultrasonic tests *Pruebas ultrasónicas*	Qualitative characterization of the element: type of section, thickness,	Qualitative *Cualitativa*	9	4	8	2	3	7

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
			presence of reinforcements, presence of holes, injuries, etc. *Caracterización cualitativa del elemento: tipo de sección, espesor, presencia de armaduras, presencia de huecos, lesiones etc.*							
Morphology of structural elements (size, reinforcement, hidden elements) *Morfología de los elementos estructurales (dimensiones, armado, elementos ocultos)*	in situ *in situ*	X-graphy *X-grafía*	It allows the detection, interpretation and evaluation of internal discontinuities such as cracks, porosity, metallic or non-metallic elements etc. Reinforcement detection *Permite la detección, interpretación y evaluación de discontinuidades internas tales como grietas, porosidad, elementos metálicos o no metálicos etc. Detección de armaduras*	Qualitative *Cualitativa*	9	5	7	2	3	5
	in situ *in situ*	Georadar (for walls) *Georadar (paramentos)*	Detection of hidden structural elements, section morphology, reinforcements, detection of the presence of humidity, detection of cracks, defects or holes, locate the position of large gaps and inclusions of different materials such as steel, wood, etc. *Investigación de elementos estructurales ocultos, morfología de la sección, armaduras, detección de presencia de humedad, detección de fisuras, defectos o huecos, localizar la posición de grandes vacíos e inclusiones de materiales diferentes como acero, madera, etc.*	Qualitative *Cualitativa*	7	6	7	2	3	7
	in situ *in situ*	Sonic and ultrasonic tomography *Tomografía sónica y ultrasónica*	Determine the wall section. Create a map of sound velocity distribution inside the element. Allows to zone the element from a quality point of view, detect the presence of voids and defects, and detect changes in the physical characteristics of the	Qualitative *Cualitativa*	9	6	7	2	3	7

Classification *Clasificación* / **Subgroup** *Subgrupo*	**Place of execution** *Lugar de realización*	**Technique name** *Nombre de la técnica*	**Resulting information** *Información que proporciona*	**Information type** *Tipo de info.*	**Qualitative relevance** *Relev. cualitativa*	**Quantitative relevance** *Relev. cuantitativa*	**Applicability** *Aplicabilidad*	**Invasivity** *Invasividad* **with build.** *con edif.*	**with ocupants** *ocupantes*	**Complexity** *Complejidad*
			materials. *Determinar la sección muraria. Crea un mapa de distribución de velocidades acústicas en el interior del elemento. Permite zonificar lel elemento desde un punto de vista de su calidad, detectar la presencia de vacíos y defectos, y detectar cambios en las características físicas de los materiales.*							
	in situ *in situ*	Gamma-ray tomography *Tomografía con rayos gamma*	Detection of reinforcement as well as defects, discontinuities, etc. *Detectar armaduras así como defectos, discontinuidades etc.*	Qualitative *Cualitativa*	9	7	7	2	3	5
	in situ *in situ*	Infrared Thermography *Termografía de infrarrojos*	Sirve para detectar anomalías de construcción, distintos tipos de materiales, presencia de agua o humedad, huecos...	Qualitative *Cualitativa*	5	9	8	1	2	6
OBTAINING THE PATTERN OF DAMAGE. CONTROL OF GEOMETRIC VARIATIONS AND CRACKS. CONTROL OF GROUND SETTLEMENT *OBTENCIÓN DEL PATRÓN DE LESIONES. CONTROL DE LAS VARIACIONES DE LA GEOMETRÍA Y LAS FISURAS. CONTROL DE ASIENTOS DEL TERRENO*										
External cracking and delamination *Cuadro fisurativo externo y desprendimiento de lajas*	in situ *in situ*	Infrared Thermography *Termografía de infrarrojos*	Detection of crack patterns (among other things) *Detecta patrones fisurativos (entre otras cosas).*	Qualitative *Cualitativa*						
	in situ *in situ*	Direct inspection and graphic representation *Inspección directa y representación gráfica*	Study of the cracking and delamination by direct inspection and graphic representation by conventional methods *Estudio del cuadro fisurativo por inspección directa y representación gráfica por métodos convencionales*	Qualitative *Cualitativa*	10	5*	10	5**	4**	7
	in situ *in situ*	Fisurometry with placement of measurement references *Fisurometría con colocación de*	Separation between the references by means of caliber, strip, thread count... *Obtener la lectura de la separación entre las*	Quantitative *Cuantitativa*	7	3	9	3	3	2

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad*		Complexity *Complejidad*
								with build. *con edif.*	with ocupants *ocupantes*	
		referencias de medida	*referencias mediante calibre, pie de rey, regleta, cuenta hilos...*							
External cracking and delamination *Cuadro fisurativo externo y desprendimiento de lajas*	in situ *in situ*	Extensómetros *Extensometers*	Measurement of the increased opening of cracks over time *Mide el incremento de apertura de grietas o fisuras en el tiempo*	Quantitative *Cuantitativa*	7	4	9	3	2	4
	in situ *in situ*	Strain gauges of various types *Galgas extensométricas de diversos tipos*	Strain registration *Registro de deformaciones*	Quantitative *Cuantitativa*	7	4	9	3	3	4
	in situ *in situ*	Static damage monitoring systems (installed in the building) *Sistemas de monitorización estática de lesiones (instalados en el edificio)*	Variation in time of certain physical parameters of non-instantaneous variation such as opening of cracks and fissures, seating, displacements, etc. They include several instruments (sensors, settlement, deformometers, etc.) *Miden la variación en el tiempo de determinados parámetros físicos de variación no instantánea como abertura de grietas y fisuras, asientos, desplazamientos, etc. Comprenden varios instrumentos (sensores, cédulas de asiento y nivelación, deformómetros etc.)*	Quantitative *Cuantitativa*	9	9	8	3	3	5
	in situ *in situ*	Dynamic damage monitoring systems (installed in the building) *Sistemas de monitorización dinámica de lesiones (instalados en el edificio)*	Response of the building to dynamic excitation over time and allow anomalies to be detected and numerical models to be calibrated. In addition, it can be used to verify the structural response before, during and after the intervention. *Miden la respuesta del edificio a una excitación dinámica en el tiempo y permite detectar anomalías y calibrar los modelos numéricos. Además, se puede utilizar para*	Quantitative *Cuantitativa*	9	9	8	3	3	9

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
			verificar la respuesta estructural antes, durante y después de la intervención.							
Movement and settlement *Desplazamientos y asentamientos*	in situ *in situ*	Leveling references *Referencias de nivelación*	Control of possible vertical movements of the structure. *Control de los posibles movimientos verticales que pueda sufrir la estructura.*	Quantitative *Cuantitativa*	9	6	9	3	3	4
	in situ *in situ*	Clinometers *Clinómetros*	They are used to record the inclination of structural elements (mainly walls and columns) *Se emplean para el registro de la inclinación de elementos estructurales (fundamentalmente muros y pilares)*	Quantitative *Cuantitativa*	8	6	8	3	3	4
	in situ *in situ*	Geodetic Methods *Métodos Geodésicos*	Measurement of structure or ground deformation using high precision geodetic techniques *Medida de deformaciones de la estructura o del terreno mediante técnicas geodésicas de alta precisión.*	Quantitative *Cuantitativa*	9	9	8	1	3	8
Carbonation *Carbonatación*	in situ *in situ*	Measurement with phenolphthalein in holes or samples *Medición mediante fenolftaleína en orificios o en muestras*	Concrete carbonation. Determination of the depth of the carbonation front. *Carbonatación del hormigón. Determinación de la profundidad del frente de carbonatación.*	Qualitative *Cualitativa*	7	4	9	3	2	3
Reinforcement corrosion *Corrosión de armaduras*	in situ *in situ*	Visual evaluation *Apreciación visual*	Importance of corrosion *Importancia de la corrosión*	Qualitative *Cualitativa*	9	2	9	5	4	3
	laboratory *laboratorio*	Gravimetric or weight loss measurement *Medida gravimétrica o de pérdida de peso*	Measurement of the speed of steel corrosion by comparing the weight of the current and original reinforcement *Medida de la velocidad de la corrosión del acero comparando el peso de la armadura actual y el original*	Quantitative *Cuantitativa*	9	3	9	5	4	5

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
Reinforcement corrosion *Corrosión de armaduras*	in situ *in situ*	Measurement of diameter loss *Medida de la pérdida de diámetro*	Measurement of the corrosion rate of steel *Medida de la velocidad de la corrosión del acero*	Quantitative *Cuantitativa*	9	4	9	6	4	3
	in situ *in situ*	Electrochemical techniques: polarization resistance method *Técnicas electroquímicas: método de la resistencia de polarización.*	Measuring the corrosion rate of steel *Medida de la velocidad de la corrosión del acero*	Quantitative *Cuantitativa*	9	4	8	5	4	5
	in situ *in situ*	Measurement of potentials in steel *Medición de potenciales en el acero*	Potential of the concrete reinforcement using electrodes to locate areas where the reinforcement is not passive and therefore susceptible to corrosion *Mide el potencial de la armadura del hormigón mediante electrodos para localizar áreas en las que la armadura no está pasiva y por ello, susceptible de corroerse.*	Quantitative *Cuantitativa*	8	4	5	5	4	5
	in situ *in situ*	Four-pronged method. Electrical resistivity of concrete *Método de las cuatro puntas. Resistividad eléctrica del hormigón*	Measures the electrical resistivity of the concrete, a factor in determining the importance of corrosion (estimated, as this is also influenced by other factors) Measurement of the electrical resistivity of the concrete *Mide la resistividad eléctrica del hormigón, factor para determinar la importancia de la corrosión (se estima, pues en ésta también influyen otros factores) Medición de la resistividad eléctrica del hormigón*	Quantitative *Cuantitativa*	5	3	5	2	4	5
	in situ *in situ*	Concrete electrical resistivity *Método del disco. Resistividad eléctrica del hormigón*	Electrical resistivity of the concrete, a factor in determining the importance of corrosion (it is estimated that this is also influenced by other factors) *Mide la resistividad eléctrica del hormigón, factor para determinar la importancia de la*	Quantitative *Cuantitativa*	5	3	5	5	4	5

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
Reinforcement corrosion *Corrosión de armaduras*			*corrosión (se estima, pues en ésta también influyen otros factores)*							
	in situ *in situ*	Half-Cell (measurement of the "eletrode" potential of the reinforcement) *Half-Cell (medida del potencial "eletrode" de la armadura)*	Probability of reinforcing steel corrosion *Mide la probabilidad de corrosión de las armaduras*	Qualitative *Cualitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	Medida de la resistencia de polarización *Measurement of polarisation resistance*	Corrosion rate by measuring the polarization resistance of the steel with which the corrosion current is obtained. *Mide el ratio de corrosión, mediante la medida de la resistencia a la polarización del acero con la que se obtiene la corriente de corrosión.*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd
	laboratory *laboratorio*	Electrical resistivity of concrete through different laboratory methods *Resistividad eléctrica del hormigón a través de distintos métodos de laboratorio*	Electrical resistivity of the concrete, a factor in determining the importance of corrosion (it is estimated that this is also influenced by other factors) *Mide la resistividad eléctrica del hormigón, factor para determinar la importancia de la corrosión (se estima, pues en ésta también influyen otros factores)*	Quantitative *Cuantitativa*	5	4	4	6	4	5
	in situ *in situ*	Magnetic field method for detecting electrical flows in reinforcement *Método del campo magnético para detectar flujos en la armadura*	It applies a "steady-state" magnetic field and measures the received flow with a field scanner, detecting disturbances due to anomalies such as deterioration, cracks or section losses *Aplica un campo magnético "steady-state" y mide con un escáner de campo el flujo recibido, detectando perturbaciones por anomalías como deterioros, fisuras o pérdidas*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
Reinforcement corrosion *Corrosión de armaduras*			*de sección.*							
	in situ *in situ*	Measurement by gauge or caliper of loss of diameter of the reinforcement *Medida mediante calibre o pie de rey de la pérdida de diámetro de la armadura*	Loss of section of steel reinforcement *Pérdida de sección de las armaduras de acero*	Quantitative *Cuantitativa*	9	4	9	5	4	2
Other damage *Otras lesiones*	in situ *in situ*	Georadar *Georadar*	Investigation of hidden structural elements, morphology of the section of composite walls, detection of the presence of moisture, detection of cracks, defects or gaps. *Investigación de elementos estructurales ocultos, morfología de la sección de muros compuestos, detección de presencia de humedad, detección de fisuras, defectos o huecos.*	Quantitative *Cuantitativa*	9	6	7	2	3	7
	in situ *in situ*	Ultrasonic test *Prueba ultrasónica*	Qualitative characterization of the wall: homogeneity, presence of holes, damage, etc. Determine the dynamic elastic module (perpendicular) *Caracterización cualitativa del paramento: homogeneidad, presencia de huecos, lesiones etc. Determinar el módulo elástico dinámico (perpendicular)*	Qualitative *Cualitativa*	9	4	8	2	3	7
	in situ *in situ*	Pulse-echo *Pulso-eco*	Measurement of concrete thickness and detection of defects. *Medida del espesor de homigón y detección de defectos.*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	Impact-echo *Impacto- eco*	Measurement of concrete thickness of elements accessible on one side only, mapping of internal voids, acoustic behaviour of interfaces to determine	Quantitative *Cuantitativa*	9	3	5	2	3	6

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
Other damage *Otras lesiones*			the quality of the bond. *Medida del espesor del hormigón de elementos accesibles a una sola cara, mapeo de huecos internos, comportamiento acústico de interfases para determinar la calidad de la adherencia.*							
	in situ *in situ*	Acoustic emissions *Emisiones acústicas*	Cracking pattern, displacement between concrete and reinforcement, adhesion failure between fibres and concrete, in fibre-reinforced concrete *Pueden determinar patrón fisurativo, desplazamiento entre hormigón y armadura, fallo de adherencia entre fibras y hormigón, en hormigón reforzado con fibras*	Qualitative *Cualitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	X-graphy *X-grafía*	Detection, interpretation and evaluation of internal discontinuities such as cracks, porosity, metallic or non-metallic elements etc. Reinforcement detection *Permite la detección, interpretación y evaluación de discontinuidades internas tales como grietas, porosidad, elementos metálicos o no metálicos etc. Detección de armaduras*	Qualitative *Cualitativa*	9	5	7	2	3	5
	in situ *in situ*	Sonic and radar tomography *Tomografía sónica y radar*	To determine the wall section. Create a map of sound velocity distribution inside the element. It allows to zone the element from a quality point of view, to detect the presence of voids and defects, and to detect changes in the physical characteristics of the materials. *Determinar la sección muraria. Crea un mapa de distribución de velocidades acústicas en el interior del elemento. Permite zonificar l elemento desde un punto de vista de su*	Qualitative *Cualitativa*	9	6	7	2	3	7

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
Other damage *Otras lesiones*			*calidad, detectar la presencia de vacíos y defectos, y detectar cambios en las características físicas de los materiales.*							
	in situ *in situ*	Gamma-ray tomography Tomografía con rayos gamma	Reinforcement as well as defects, discontinuities etc. *Detectar armaduras así como defectos, discontinuidades etc.*	Qualitative *Cualitativa*	9	7	7	2	3	5
Settlements *Asentamientos*	in situ *in situ*	Inclinometers (monitoring technique) *Inclinómetros (técnica de monitorización)*	Control of possible movements in the subsoil, information about deformations in depth in the ground. *Controlar los posibles movimientos en el subsuelo, conocer las deformaciones en profundidad en el terreno.*	Quantitative *Cuantitativa*	5	4	8	3	2	5
	in situ *in situ*	Piezometers *Piezómetros*	Piezometric water levels in soils and rocks. A temperature sensor can also be incorporated, allowing simultaneous measurement of temperature and real-time monitoring of interstitial pressures. *Mide los niveles piezométricos de agua en suelos y rocas. También se puede incorporar un sensor térmico, permitiendo así la medición simultánea de la temperatura y la monitorización en tiempo real, de las presiones intersticiales.*	Quantitative *Cuantitativa*	5	4	7	3	2	5
	in situ *in situ*	Seat cells *Células de asiento*	It measures the vertical displacement of the terrain (seats). *Mide el desplazamiento vertical del terreno (asientos).*	Quantitative *Cuantitativa*	9	4	9	3	2	5
OBTAINING THE STRESS STATE WITH IN-SITU MEASUREMENTS *OBTENCIÓN DEL ESTADO DE TENSIONES CON MEDIDAS IN-SITU*										

Classification *Clasificación* Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
	in situ *in situ*	Simple flat-jack *Gato-plano simple*	Local stress level associated with a given plane *Nivel tensional local asociado a un determinado plano*	Quantitative *Cuantitativa*	8	7*	5	5	4	3
	in situ *in situ*	Double flat-jack *Gato-plano doble*	Level of stress (if it is first used as a simple flat-jack), deformability of the element, and an indication of its resistance. Young's modulus ratio - Poisson's coefficient. *Determina el nivel de esfuerzo (si primero se utiliza como gato-plano simple), la deformabilidad del elemento así como una indicación de su resistencia. Relación módulo de Young - coeficiente de Poisson.*	Quantitative *Cuantitativa*	8	7	5**	5	4	3
	in situ *in situ*	Hole-drilling test	Quantification of actual operating voltages. Possibility of obtaining main voltages. Possibility of obtaining tensile states. *Cuantificar tensiones reales de servicio. Posibilidad de obtención de tensiones principales. Posibilidad de obtención de estados a tracción.*	Quantitative *Cuantitativa*	8	4	7	5	4	7
	in situ *in situ*	Inspección de las cargas a las que está sometida la estructura *Inspection of the loads to which the structure is subjected*	Inspection and diagnosis of the loads the structure is subjected to. *Inspección y diagnóstico de las cargas a las que está sometida la estructura.*	Qualitative *Cualitativa*	10	8	10	1	3	5

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
OBTAINING THE MECHANICAL CHARACTERISTICS (E,V, G, F_K…) *OBTENCIÓN DE LAS CARACTERÍSTICAS MECÁNICAS (E,V, G, F_K…)*										
Concrete characterization *Caracterización del hormigón*	in situ *in situ*	Visual assessment *Apreciación visual*	Tipo de hormigón *Type of concrete*	Qualitative *Cualitativa*	8	5	10	4	3	3
Concrete characterization *Caracterización del hormigón*	in situ *in situ*	Double flat-jack *Gato-plano doble*	Level of stress, deformability of the element, and an indication of its resistance. *Determina el nivel de esfuerzo, la deformabilidad del elemento así como una indicación de su resistencia.*	Quantitative *Cuantitativa*	8	7	5**	5	4	3
	in situ *in situ*	Dilatometric or pressure measurement techniques *Técnicas dilatométricas o presiométricas*	Estimation of the element's modulus of deformation *Estimar el módulo de deformación del elemento*	Quantitative *Cuantitativa*	8	3	2	5	4	7
	in situ *in situ*	Ultrasound testing *Prueba con ultrasonidos*	Qualitative characterization of the facing: study of uniformity, presence of defects (cokes, cracks, etc), estimation of qualitative changes of properties. Determination of the dynamic elastic module (perpendicular), estimation of the resistance of the concrete *Caracterización cualitativa del paramento: estudio de uniformidad, presencia de defectos (coqueras, fisuras, grietas etc), estimar cambios cualitativos de las propiedades. Determinar el módulo elástico dinámico (perpendicular), estimación de la resistencia del hormigón*	Qualitative *Cualitativa*	8	5	8	2	3	7

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad*: with build. *con edif.*	Invasivity *Invasividad*: with ocupants *ocupantes*	Complexity *Complejidad*
Concrete characterization *Caracterización del hormigón*	in situ *in situ*	Test based on rejection sclerometry. Schmidt's hammer, etc. *Prueba basada en esclerometría de rechazo. Martillo de schmidt, etc.*	Surface hardness of the concrete to estimate other mechanical characteristics such as the characteristic resistance. It is actually applicable to determine the uniformity of the surface, to detect areas of deteriorated or poor concrete, to estimate resistance in situ (after calibration with compression tests). *Determina la dureza superficial del hormigón para estimar otras características mecánicas como la resistencia característica. En realidad es aplicable para determinar la uniformidad de la superficie, detectar áreas de hormigón deteriorado o pobre, estimar in situ la resistencia (previa calibración con pruebas de compresión)*	Quantitative *Cuantitativa*	6	3	5	2	3	5
	in situ *in situ*	Test based on print sclerometry (Frank hammer type, William's gun, Einbeck Hammer pendulum) *Prueba basada en esclerometría de huella (tipo martillo Frank, pistola de williams, péndulo Hammer de Einbeck)*	Surface hardness of the concrete to estimate other mechanical characteristics. *Determina la dureza superficial del hormigón para estimar otras características mecánicas.*	Quantitative *Cuantitativa*	Ya no se usan	peste	peste	peste	peste	peste
	in situ *in situ*	Penetrometer test (Windsor sclerometer type) *Prueba penetrométrica (tipo esclerómetro Windsor)*	Estimation of the characteristics of the concrete from its resistance to perforation. It provides an order of magnitude *Estimar las características del hormigón a partir de la resistencia a la perforación del mismo. Aporta un orden de magnitud.*	Quantitative *Cuantitativa*	6	2	5	5	4	5

Classification *Clasificación* / **Subgroup** *Subgrupo*	**Place of execution** *Lugar de realización*	**Technique name** *Nombre de la técnica*	**Resulting information** *Información que proporciona*	**Information type** *Tipo de info.*	**Qualitative relevance** *Relev. cualitativa*	**Quantitative relevance** *Relev. cuantitativa*	**Applicability** *Aplicabilidad*	**Invasivity** *Invasividad* **with build.** *con edif.*	**with ocupants** *ocupantes*	**Complexity** *Complejidad*
Concrete characterization *Caracterización del hormigón*	in situ *in situ*	Pull-out test *Prueba de extracción*	Concrete strength from the pull-out resistance. A metal part is soaked when the concrete is poured, which is then pulled out once it has hardened. It is suitable for new construction. There are adaptations for existing structures, but they do not work so well. *Resistencia del hormigón a partir de la resistencia de arranque. Se embebe una pieza metálica al verter el hormigón, que posteriormente se arranca una vez endurecido. Vale para nueva construcción. Hay adaptaciones para estructuras existentes, pero no funcionan igual de bien*	Quantitative *Cuantitativa*	6	4	3	5	4	6
	in situ *in situ*	Pull-off test *Pull-off test*	Concrete strength from the pull-out resistance. A metal disc is attached to the surface. It is considered a relation between the resistance to the disc removal and a part of the concrete and the characteristic resistance. *Resistencia del hormigón a partir de la resistencia de arranque. Se adhiere un disco metálico a la superficie. Se considera una relación entre la resistencia al arranque del disco y una parte del hormigón y la resistencia característica.*	Quantitative *Cuantitativa*						
	in situ *in situ*	On-site load testing *Pruebas de carga in situ*	Different mechanical parameters depending on the test carried out, mainly resistance. *Obtener diversos parámetros mecánicos en función del ensayo realizado, fundamentalmente la resistencia.*	Qualitative *Cualitativa*	8	6	9	2	9	9
	laboratory *laboratorio*	Prueba de compresión simple en laboratorio	Ultimate load, modulus of elasticity and Poisson coefficient of concrete.	Quantitative *Cuantitativa*	9	6	6	7	7	4

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
		Simple compression test in the laboratory	*Obtención de carga de rotura, módulo de elasticidad y coeficiente de Poisson del hormigón.*							
	laboratory *laboratorio*	Concrete indirect tensile strength test, "Brazilian test" ASTM C-496, UNE 83.306 and ISO 4108 *Prueba de resistencia a tracción indirecta del hormigón, "ensayo brasileño" ASTM C-496, UNE 83.306 e ISO 4108)*	Tensile strength of concrete specimens. *Obtener la resistencia a tracción de las probetas de hormigón.*	Quantitative *Cuantitativa*	9	7	6	7	7	4
Concrete characterization *Caracterización del hormigón*	laboratory *laboratorio*	Flexo-tensile resistance test (UNE 83.305 and ISO 4013) *Prueba de resistencia a flexotracción (UNE 83.305 e ISO 4013)*	Flexo-tensile resistance of concrete. *Obtener resistencia a flexotracción del hormigón.*	Quantitative *Cuantitativa*	9	7	6	7	7	4
	laboratory *laboratorio*	Load testing with scale models *Pruebas de carga con modelos a escala*	Various mechanical parameters depending on the test performed (sandbag load tests, etc.). *Obtener diversos parámetros mecánicos en función del ensayo realizado (pruebas de carga con sacos de arena, etc.).*	Quantitative *Cuantitativa*	8	6	10	1	3	8
	laboratory *laboratorio*	Compression test on concrete micro specimens in beams or other elements *Prueba de compresión sobre microprobetas de hormigón en viguetas u otros elementos*	Estimation of the compressive strength of concrete in girders (indicated for those made of aluminous cement). *Estimar la resistencia a compresión del hormigón en viguetas (indicado para aquellas fabricadas con cemento aluminoso)*	Quantitative *Cuantitativa*	9	6	6	6	7	4
Steel characteristics *Características del acero*	laboratory *laboratorio*	Elastic limit of the steel (laboratory tensile test) by means of test tubes *Límite elástico del acero (prueba de tracción en laboratorio) mediante probetas*	Elastic limit of the steel, ultimate load, equivalent middle section. *Obtención del límite elástico del acero, carga de rotura, sección media equivalente.*	Quantitative *Cuantitativa*	9	7	6	6	6	4

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
	laboratory *laboratorio*	Equivalent mean section *Sección media equivalente*	Equivalent mean section *Obtención de la sección media equivalente*	Quantitative *Cuantitativa*	6	7	9	6	7	
	laboratory *laboratorio*	Corrugated characteristics *Características del corrugado*	Reinforcement corrugation geometric characteristics (if any) *Características geométricas del corrugado de la armadura (si lo hay)*	Quantitative *Cuantitativa*	4	7	9	6	6	
	laboratory *laboratorio*	Single folding *Doblado simple*	Detecting the presence or absence of screams on steel. *Detectar la presencia o ausencia de gritas en el acero.*	Qualitative *Cualitativa*	4	7	9	6	6	
Steel characteristics *Características del acero*	in situ *in situ*	On-site load testing *Pruebas de carga in situ*	Various mechanical parameters depending on the test performed, mainly resistance. *Obtener diversos parámetros mecánicos en función del ensayo realizado, fundamentalmente la resistencia.*	Qualitative *Cualitativa*	8	6	9	2	9	9
OBTENCIÓN DE CARACTERÍSTICAS FÍSICO-QUÍMICAS DE LOS MATERIALES										
Detection of aluminium cement (chemical) *Detección de cemento aluminoso (químicas)*	laboratory *laboratorio*	X-ray diffractometry *Difractometría de rayos X*	Microstructural characterization of the material: detection of aluminous cement, qualitative and semi-quantitative identification of the main crystalline phases (the type of salts present in the interior and on the surface). *Caracterización microestructural del material: Detección de cemento aluminoso, identificación cualitativa y semicuantitativa de las principales fases cristalinas (el tipo de sales presentes en el interior y superficie).*	Semi-quantitative *Semi-cuantitativa*	7	7	8	5	4	3
	laboratory *laboratorio*	Scanning Electron Microscopy (SEM) *Microscopia electrónica de barrido (SEM)*	Determining the microstructure, crystalline phases, impurities, salts, micro-cracking, bio-deterioration, porous system, effects of cleaning and consilidation treatments etc.	Qualitative *Cualitativa*	7	7	8	5	4	6

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
			Determinar la microestructura, fases cristalinas, impurezas, sales, microfisuración, biodeterioro, sistema poroso, efectos de tratamientos de limpieza y consilidación etc.							
Detection of aluminium cement (chemical) *Detección de cemento aluminoso (químicas)*	laboratory *laboratorio*	Barium chloride method (identification of sulphates) *Método del cloruro de bario (identificación de sulfatos)*	Some sulphates that are specific to Portland cement (and not to alumina) due to additions of thickening effect. *Detecta algunos sulfatos que son específicos del cemento Portland (y no del aluminoso) por adiciones de efecto espesante.*	Qualitative *Cualitativa*	7	5	8	5	4	6
	laboratory *laboratorio*	Oxin test *Test de la oxina*	Presence of large amounts of aluminates by adding oxine, hydrochloric acid and ammonium acetate. *Detecta la presencia de gran cantidad de aluminatos al añadir oxina, ácido clorhídrico y acetato de amonio.*	Qualitative *Cualitativa*	7	5	8	5	4	6
	laboratory *laboratorio*	X-ray fluorescence *Fluorescencia de rayos X*	Determination of constituent chemicals. *Determinación de elementos químicos constituyentes.*	Semi-quantitative *Semi-cuantitativo*	7	7	8	5	4	3
	laboratory *laboratorio*	Different methods for the determination of the aluminium oxide (Al203) content Standard ASTM C114-11b *Diversos métodos para determinación del contenido de óxido de aluminio (Al203). Norma ASTM C114-11b*	Content of aluminium oxide (Al203). *Determina el contenido de óxido de aluminio (Al203).*	Qualitative *Cualitativa*	7	5	8	5	4	6
Physical *Físicas*	laboratory *laboratorio*	Stereo-microscope observation *Observación al estereo-microscopio*	Characterization of the material: macroscopic determination of the morphological characteristics to define the degradation of the material, its causes and the presence of salts. *Caracterización del material: Determinación macroscópica de las características*	Qualitative *Cualitativa*	7	4	8	5	4	3

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	with ocupants *ocupantes*	Complexity *Complejidad*
			morfológicas para definir la degradación del mismo, sus causas y la presencia de sales.							
	laboratory *laboratorio*	Infrared spectro-photogrammetry *Espectro-fotogrametría infrarroja*	Detection of organic and inorganic substances. *Detección de sustancias orgánicas e inorgánicas.*	Qualitative *Cualitativa*	4	4	8	5	4	3
Physical *Físicas*	in situ *in situ*	Infrared Thermography *Termografía de infrarrojos*	Detection of construction anomalies, different types of materials, presence of water or humidity, holes... *Sirve para detectar anomalías de construcción, distintos tipos de materiales, presencia de agua o humedad, huecos...*	Qualitative *Cualitativa*	5	9	8	1	2	6
	in situ *in situ*	Georadar *Georadar*	Investigation of hidden structural elements, morphology of the section of composite walls, control of the effectiveness of injections, detection of the presence of humidity, detection of cracks, defects or gaps. *Investigación de elementos estructurales ocultos, morfología de la sección de muros compuestos, control de eficacia de inyecciones, detección de presencia de humedad, detección de fisuras, defectos o huecos.*	Qualitative *Cualitativa*	7	6	7	2	3	7
	in situ *in situ*	Ultrasonic testing *Prueba ultrasónica*	Qualitative characterization of the factory: type of section, presence of holes, injuries, changes of materials, etc. *Caracterización cualitativa de la fábrica: tipo de sección, presencia de huecos, lesiones, cambios de materiales, etc.*	Qualitative *Cualitativa*	8	4	8	2	3	7
	in situ *in situ*	Ultrasonic and radar tomography *Tomografía ultrasónica y radar*	Determining the wall section. It may provide information on variation in elastic characteristics or presence of lesions or discontinuity.	Qualitative *Cualitativa*	8	6	7	2	3	7

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
			Determinar la sección muraria. Puede proporcionar información de variación de características elásticas o presencia de lesiones o discontinuidad.							
	laboratory *laboratorio*	Measurement of the specific gravity *Medida del peso específico*	To determine the specific gravity of the material. *Determinar el peso específico del material.*	Quantitative *Cuantitativa*	4	4	9	5	4	2
Physical *Físicas*	laboratory *laboratorio*	Measurement of water absorption by immersion or capillary action *Medida de la absorción de agua por inmersión o por capilaridad*	Degree of water absorption of the sample by immersion or by capillary action. Important for assessing the durability of the material and the effects of surface treatment. *Mide el grado de absorción de agua de la muestra por inmersión o por capilaridad. Importante para valorar la durabilidad del material y los efectos del tratamiento superficial.*	Quantitative *Cuantitativa*	2	4	8	5	4	2
	in situ *in situ*	Capacitance instruments for measuring the moisture content of concrete *Instrumentos de capacitancia para medir contenido de humedad del hormigón*	Electrical constants directly related to the amount of moisture (dielectric constant). *Mide constantes eléctricas directamente relacionadas con la cantidad de humedad (constante dieléctrica).*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	Electrical resistance instruments for measuring the moisture content of concrete *Instrumentos de resistencia eléctrica para medir contenido de humedad del hormigón*	It measures the electrical resistance of the concrete, which decreases with increasing humidity. *Mide la resistencia eléctrica del hormigón, que decrece con el aumento de humedad.*	Qualitative *Cualitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	Standpipe Test (chimney method, Karsten's pipe test, Australian test) *Prueba del tubo vertical (método de la chimenea, prueba del tubo de Karsten, prueba australiana)*	Measurement of absorption. *Medida de la absorción.*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd

Classification *Clasificación* / Subgroup *Subgrupo*	Place of execution *Lugar de realización*	Technique name *Nombre de la técnica*	Resulting information *Información que proporciona*	Information type *Tipo de info.*	Qualitative relevance *Relev. cualitativa*	Quantitative relevance *Relev. cuantitativa*	Applicability *Aplicabilidad*	Invasivity *Invasividad* with build. *con edif.*	Invasivity *Invasividad* with ocupants *ocupantes*	Complexity *Complejidad*
Physical *Físicas*	laboratory *laboratorio*	Measuring the water absorption of concrete *Medida de la absorción de agua del hormigón*	Initial water absorption of the concrete. *Mide la absorción inicial de agua del hormigón.*	Quantitative *Cuantitativa*	1	4	8	5	4	2
	in situ *in situ*	Initial surface absortion test (ISAT) *Medida de la absorción de agua del hormigón*	Initial water absorption of the concrete. *Mide la absorción inicial de agua del hormigón.*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd
	in situ *in situ*	Autoclam Sorptivity Test *Prueba de sorptividad Autoclam*	Measures water absorption, air permeability and water permeability. *Mide absorción de agua, permeabilidad al aire y permeabilidad al agua.*	Quantitative *Cuantitativa*	nd	nd	nd	nd	nd	nd
	laboratory *laboratorio*	Mercury porosimetry *Porosimetría a mercurio*	Determining the area, the macro and mesopores volume and calculating material porosity distribution. *Determina el área, el volumen de macro y mesoporos y calcula la distribución de la porosidad del material.*	Quantitative *Cuantitativa*	5	4	7	5	4	5
	laboratory *laboratorio*	Ice and thaw tests *Pruebas de hielo y deshielo*	Estimation of the lifespan of new materials subject to aggressive agents. *Busca estimar el tiempo de vida útil de materiales nuevos sujetos a agentes agresivos.*	Quantitative *Cuantitativa*	1	4	8	5	4	4
	laboratory *laboratorio*	Salt crystallization tests *Pruebas de cristalización salina*	Estimation of the lifespan of new materials subject to aggressive agents. *Busca estimar el tiempo de vida útil de materiales nuevos sujetos a agentes agresivos.*	Quantitative *Cuantitativa*	1	4	8	5	4	4
OBTAINING ENVIRONMENTAL CONDITIONS / *OBTENCIÓN DE CONDICIONES AMBIENTALES*										
	in situ *in situ*	Thermal sensors *Sondas térmicas*	Temperature variations. *Mide variaciones de temperatura.*	Quantitative *Cuantitativa*	4	9	10	3	3	2
	in situ *in situ*	Hygrometer *Higrómetro*	Moisture content. *Mide el contenido de humedad.*	Quantitative *Cuantitativa*	2	9	10	3	3	2
	in situ *in situ*	*Anemometer* *Anemómetro*	Instantaneous wind speed. *Mide la velocidad instantánea del viento.*	Quantitative *Cuantitativa*	2	9	10	3	3	2

APPENDIX A2.Characteristics of concrete according to codes

Table A2. Characteristics of concrete according to codes (adapted from [46])

Year	Compulsory	Yield strength and ultimate strength of reinforcement	Usual diameters [mm]	Type of bars	Concrete compressive strength	Dosage	Concrete cover
1941	Yes	Elastic limit of concrete > 11.78 MPa ->117.68 MPa Elastic limit of concrete > 15.69 MPa -> 137.29 MPa	5,6,7,8,10,12,14,16,18, 20,25,30	In buildings, hooked smooth steel but corrugated bars do exist already	Ultimate strength: - ordinary cement -> 12 MPa - high resistance -> 16 Mpa. Admissible stress: Columns: - concrete 12 MPa -> 3.5 MPa - concrete 16 MPa -> 5.5 MPa Elements under flexural loads: - concrete 12 MPa -> 4.0 MPa - concrete 16 MPa -> 5.0 MPa	Conc. 12 Mpa -> 300 kg/cm³ Conc. 16 Mpa -> 350 kg/cm³ Conc. 20 Mpa -> 400 kg/cm³ (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1944	No (just in public building)	Ultimate strength: ordinary steel (construction) -> 360 special steel -> 500 Apparent ultimate strength: ordinary steel (construction) -> 240 MPa special steel -> 360 MPa Admissible strength: ordinary steel (construction) -> 120 special steel: concrete (12 MPa) -> 130 MPa concrete (16 MPa) -> 170 MPa concrete (20 MPa) -> 180 MPa	5,6,7,8,10,12,14,16,18, 20,25,30	In buildings, hooked smooth steel but corrugated bars do exist already	Admissible strength depending on ultimate strength: - concrete 12 MPa -> 4.0 MPa - concrete 16 MPa -> 5.3 MPa - concrete 20 MPa -> 6.6 MPa	Conc. 12 Mpa -> 300 kg/cm³ Conc. 16 Mpa -> 350 kg/cm³ Conc. 20 Mpa -> 400 kg/cm³ (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1961 (Inst. Torroja HA-61)	No	Yield strength limit depends on rebar diameter, for smooth or corrugated bars. Ultimate strength of smooth ordinary steel -> 287.5 MPa	6,8,10,12,16,18 (jus for smooth),20,25,30,35	Smooth or corrugated. Corrugated steel was common	Characteristic compressive strength: - With ordinary steel -> 13 MPa - With corrugated steel -> 17 MPa	Conc. 12 Mpa -> 300 kg/cm³ Conc. 16 Mpa -> 350 kg/cm³ Conc. 20 Mpa -> 400 kg/cm³ (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1968. EH-68	Yes	Yield stress: - smooth steel bars: diameter < 16 mm -> 240 MPa diameter > 16 mm -> 230 MPa - high adherence -> 360 MPa Ultimate strength: - smooth bars 370-450 - high adherence diameter < 16 -> 1.15*240 MPa diameter > 16 -> 1.15*230 MPa	Ordinary steel: 6,8,10,12,16,18 (just for smooth),20,25,30,35	Smooth or corrugated. Corrugated steel was common	Characteristic compressive strength: - Without reinforcement -> 6 Mpa - Reinforced -> 12 Mpa	Conc. 12 Mpa -> 300 kg/cm³ Conc. 16 Mpa -> 350 kg/cm³ Conc. 20 Mpa -> 400 kg/cm³ (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements

1973 EH-73	Yes	Yield strength: - smooth steel bars > 220 MPa - corrugated -> 420-600 MPa Ultimate strength: - smooth bars -> 340-500 MPa - corrugated -> 500-720 MPa	Ordinary steel: 6,8,10,12,16,18 (just for smooth),20,25,30,35	Corrugated		Characteristic compressive strength: - Without reinforcement -> 5 MPa - Reinforced -> 12.5 MPa	Conc. 12 Mpa -> 300 kg/cm^3 Conc. 16 Mpa -> 350 kg/cm^3 Conc. 20 Mpa -> 400 kg/cm^3 (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1980	Yes	Yield strength: - smooth steel bars >220 MPa - corrugated -> 410-610 MPa Ultimate strength: - smooth bars -> 340-500 MPa - corrugated -> 450-710 MPa Electro-welded: AEH-500T -> 560 MPa AEH-600T -> 670 MPa	Ordinary steel: 6,8,10,12,16,18 (just for smooth),20,25,30,35	Corrugated		Characteristic compressive strength: - With or without reinforcement -> 12.5 MPa - Concrete with corrugated steel: AE-215L -> 12.5 MPa AEH-400 -> 15 MPa AEH-500 -> 17.5 MPa AEH-600 -> 20.0 MPa	Conc. 12 Mpa -> 300 kg/cm^3 Conc. 16 Mpa -> 350 kg/cm^3 Conc. 20 Mpa -> 400 kg/cm^3 (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1982	Yes	Similar to 1980	Similar to 1980	Corrugated		Similar to 1980	Conc. 12 Mpa -> 300 kg/cm^3 Conc. 16 Mpa -> 350 kg/cm^3 Conc. 20 Mpa -> 400 kg/cm^3 (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1988	Yes	Similar to 1980	Similar to 1980	Corrugated		Similar to 1980	Conc. 12 Mpa -> 300 kg/cm^3 Conc. 16 Mpa -> 350 kg/cm^3 Conc. 20 Mpa -> 400 kg/cm^3 (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	1 cm in beams and ribs 1.5 cm rest of elements 2 cm in outdoor elements
1991	Yes (pre-stressed concrete)	Yield strength: - smooth steel bars >220 MPa - corrugated -> 410-610 MPa Electro-welded: AEH-500T -> 510 MPa AEH-600T -> 610 MPa Ultimate strength: - smooth bars -> 340-500 MPa - corrugated -> 450-670 MPa Electro-welded: AEH-500T -> 560 MPa AEH-600T -> 660 MPa	Similar to 1980	Corrugated		Similar to 1980	Conc. 12 Mpa -> 300 kg/cm^3 Conc. 16 Mpa -> 350 kg/cm^3 Conc. 20 Mpa -> 400 kg/cm^3 (ing civil) Water/cement ratio 0,30 Sand/gravel relation 1:2.	In main reinforcements at least equal to the diameter of that bar and 0.8 the size of the aggregate. Environment I Structures inside buildings or external means of low humidity (not exceeding 60% relative humidity over 90 days a year) -> 20 mm. Environment II Normal (non-aggressive) or contact with normal water or ordinary ground ->.30 mm. Environment III Structures in aggressive industrial or marine atmosphere, or in contact with aggressive soils or saline or slightly acidic water -> 40 mm. These values can be reduced by

								5 mm if the concrete is between 25 and 40 N/mm2
1993	Yes	A distinction is made between passive and active reinforcement. Here, data for passive ones are included. Yield strength: - smooth steel bars ->215 MPa - corrugated -> 400-600 MPa Electro-welded: AEH-500T -> 500 MPa AEH-600T -> 600 MPa Ultimate strength: - smooth bars -> 330-490 MPa - electro-welded -> 550-660 MPa	4- 5- 6- 8- 10- 12- 16- 20- 25- 32- 40 - 50	Corrugated		Characteristic compressive strength with or without reinforcement -> 25 MPa	It depends on the type of exposure. The maximum allowed is 0.65	In main reinforcements at least equal to the diameter of that bar and 0.8 the size of the aggregate. Environment I Structures inside buildings or external means of low humidity (not exceeding 60% relative humidity over 90 days a year) -> 20 mm. Environment II Normal (non-aggressive) or contact with normal water or ordinary ground ->.30 mm. Environment III Structures in aggressive industrial or marine atmosphere, or in contact with aggressive soils or saline or slightly acidic water -> 40 mm. These values can be reduced by 5 mm if the concrete is between 25 and 40 N/mm2

APPENDIX A3. Available intervention techniques of reinforced concrete structures. Protection, repair, strengthening and substitution techniques

Table A3.a Available intervention techniques of reinforced concrete structures. PROTECTION TECHNIQUES (English version/*Spanish version*)

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Reduction or prevention against penetration of adverse agents *Reducción o prevención contra la penetración de agentes adversos*	Hydrophobic impregnation *Impregnación hidrófoba*	Surface treatment *Tratamiento superficial*	Treatment of concrete to produce a water-repellent surface. The interior surface of the pores and capillaries is coated but not filled. No film is formed on the surface of the concrete and its appearance is somewhat or not at all modified. *Tratamiento del hormigón destinado a producir una superficie repelente al agua. La superficie interior de los poros y capilares queda revestida pero no rellena. No se forma película en la superficie del hormigón y su aspecto se ve modificado algo o nada.*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Products based on organic silicon solutions (siliconates, silanes, siloxanes and silicon resins). *Productos basados en soluciones orgánicas de silicio (siliconatos, silanos, siloxanos y resinas de silicio).*
	Sealant impregnation *Impregnación selladora*	Surface treatment *Tratamiento superficial*	Treatment aimed at reducing surface porosity and reinforcing the surface. It forms a discontinuous film (from 10 to 100 microns) that partially fills pores and capillaries. *Tratamiento destinado a reducir la porosidad superficial y a reforzar la superficie. Forma una película discontinua (de 10 a 100 micrómetros) que rellena parcialmente poros y capilares.*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Polymers (acrylics), epoxies, inorganic substances (partner crystals or potassium silicate, fluorine compounds), drying vegetable oils (linseed oil). *Polímeros (acrílicos), epoxis, sustancias inorgánicas (cristales de socio o silicato potásico, compuestos de flúor), aceites vegetales secantes (aceite de linaza).*
	Coating with or without bridging capability (with bridging in active cracks, without bridging in passive cracks) *Revestimiento con o sin capacidad de puenteo (con puenteo en fisuras activas, sin puenteo en pasivas)*	Surface treatment *Tratamiento superficial*	Treatment designed to produce a continuous protective layer on the surface of the concrete that prevents contact between the concrete and aggressive agents. They are best suited to surfaces that are not subject to significant wear. *Tratamiento destinado a producir una capa protectora continua en la superficie del hormigón que evite el contacto entre este y los agentes agresivos. Se adaptan mejor a superficies que no están sujetas a desgaste significativo.*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Aqueous dispersion polymers (thermoplastic polymers and copolymers), solution polymers (acrylics, acrylic-styrene copolymers and chlorinated rubber), reactive polymers in solution or emulsion (epoxy and polyurethane components, or polyurethane prepolymers), 100 % reactive polymers in solids (epoxy, polyurethane, vinyl, acrylics, chlorinated rubber, butadiene-styrene, cement and bitumen). *Polímeros en dispersión acuosa (polímeros y copolímeros termoplásticos), polímeros en solución (acrílicos, copolímeros acrílico-estireno y caucho clorado), polímeros reactivos en solución o en emulsión (componentes epoxi y poliuretano, o prepolímeros de poliuretano), polímeros reactivos 100 %en sólidos (epoxi, poliuretano, vinilo, acrílicos, caucho tratado con cloro, butadieno-estireno, cemento y betunes).*
	Inyección de fisuras *Crack injection*	Tratamiento de fisuras *Crack treatment*	Pumping in cracks and capillaries of injection material to all the sealing structure, protect it and/or repair it by returning the monolithic and initial impermeability of the structure, joining the surfaces of the internal faces. *Bombeo en fisuras y capilares de material de inyección*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	The base material is usually hydraulic, polymeric or mixed mortar/concrete (in the case of resins, it is usually solvent-free epoxy). *El material base suele ser morteros/hormigones hidráulicos, poliméricos o mixtos (en el caso de resinas, normalmente son epoxídicas sin disolventes).*

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Reduction or prevention against penetration of adverse agents *Reducción o prevención contra la penetración de agentes adversos*			*para todar a la estructura de estanqueidad, protegerla y/o repararla devolviendo el monolitismo y la impermeabilidad inicial de la estructura, uniendo las superficies de las caras internas de l as fisuras y soldándolas. Se utiliza en fisuras pasivas con anchos superiores a los especificados en la EHE, aunque excepcionalmente se pueden inyectar fisuras de hasta 0,05 mm con epoxi.*				
	Crack sealing (profiling and sealing) *Sellado de fisuras (perfilado y sellado)*	Crack treatment *Tratamiento de fisuras*	It consists of hermetically sealing to achieve watertightness. This is achieved by enlarging the fissure in order to create joints that are sealed with material to absorb all movements. It is usually used in concrete in contact with water or hydrostatic pressure. It is used in active fissures with widths greater than the regulated in codes. It can be applied when an immediate repair is required and a structural one is not necessary. *Consiste en cerrar herméticamente para conseguir estanqueidad. Se consigue agrandando la fisura con el objeto de crear unas juntas que se sellan con material para absorber todos los movimientos. Se usa habitualmente en hormigón en contacto con agua o presión hidrostática. Se utiliza en fisuras activas de anchos superiores a la EHE. Se puede aplicar cuando se requiere una reparación inmediata y no es necesario una estructural.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Plastic materials (mastic type, they are mastics based on rubber-butyl and bituminous), elastomeric sealants (elastic, polyurethane type), thermoplastic sealants (polysulphide/polyurethane, based on acrylic polymers in dispersion), solid materials (they are diverse, such as chloroprene rubber, rubber and hydrophilic material, etc) Avoid cementitious mortars. It must be able to withstand cyclical deformation and not be brittle. An adhesion switch can be placed to avoid stress concentration. It is usually a polyethylene band. *Materiales plásticos (tipo mastic, son masillas a base de caucho-butilo y bituminosas), sellantes elastoméricos (elásticos, tipo poliuretano), sellantes termoplásticos (polisulfuro/poliuretano, basadas en polímeros acrílicos en dispersión), mat. Sólidos (son diversos, como caucho de cloropreno, caucho y material hidrófilo, etc). Evitar morteros cementicios. Debe ser capaz de soportar deformaciones cíclicas y no ser frágil. Se puede colocar un interruptor de la adherencia para evitar concentración de tensiones. Suele ser una banda de polietileno.*
	Sobrecapas *Overlays*	Crack treatment *Tratamiento de fisuras*	Treatment designed to produce a continuous protective layer on the surface of the concrete that prevents contact between the concrete and aggressive agents by adding an additional layer of a certain material. Valid for fine, inactive cracks, or active cracks if they are placed together over active cracks. *Tratamiento destinado a producir una capa protectora continua en la superficie del hormigón que evite el contacto entre este y los agentes agresivos mediante la adición de una capa adicional de un determinado material. Válido para fisuras finas inactivas, o activas si se disponen juntas sobre las fisuras activas.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	For example, Portland cement, polymer-modified concrete, silica vapor concrete. Suitable polymers: styrene butadiene, acrylic latex. Resin should be at least 15% by weight of the cement, but 20% is adequate. *Por ejemplo, cemento Portland, hormigón modificado con polímero, hormigón con vapor de sílice. Polímeros adecuados: estireno butadieno, látex acrílicos. La resina debe ser al menos el 15% en peso del cemento, pero lo adecuado es un 20%.*
	Ocratization *Ocratización*	Crack treatment	It is used to treat cracks that do not present movement, stabilising them by means of a	Concrete *Hormigón*		Preparation of the substrate (concrete):	Tetrafluorsilicate in gaseous or liquid form (sodium potassium fluorosilicate).

Specific objetive *Objetivo específico*	Name *Nombre*	Type *Tipo*	Description *Descripción*	Intervened element *Elemento intervenido*	Regulation *Normativa*	Previous actions *Preparación necesaria*	Needed materials *Materiales empleados*
Reduction or prevention against penetration of adverse agents *Reducción o prevención contra la penetración de agentes adversos*		*Tratamiento de fisuras*	superficial sealing, achieving watertightness. It is used in passive fissures with a width of less than 0.2 mm. F_4Si is introduced as a gas under pressure that reacts with the lime released in the hydration of the Portland. Another more modern and simplified technique is carried out by painting the crack with liquid glass. *Sirve para tratar fisuras que no presentan movimientos, estabilizándolas mediante un sellado superficial, consiguiendo estanqueidad. Se utiliza en fisuras pasivas de ancho menor a 0,2 mm. Se introduce F4Si gaseoso a presión que reacciona con la cal liberada en la hidratación del portland. Otra técnica más moderna y simplificada se realiza pintando la fisura con vidrio líquido.*			cleaning *Preparación del sustrato (hormigón): limpieza*	*Tetrafluorsilice en estado gaseoso o vidrio líquido (fluorsilicato de sodio y potasio).*
	Healing *Cicatrización*	Crack treatment *Tratamiento de fisuras*	Natural crack repair process. In dead or passive fissures. The crack must be continuously saturated with standing water for about 90 days. It is produced by carbonation of the cement by the action of CO2 from the air and water. CO3Ca crystals are formed that close the crack. *Proceso de reparación natural de la fisura. En fisuras muertas o pasivas. La fisura debe estar continuamente saturada de agua estancada durante unos 90 días. Se produce por carbonatación del cemento por la acción del CO_2 del aire y el agua. Se forman cristales CO_3Ca que cierran la fisura.*	Concrete *Hormigón*		Crack water saturation *Saturación de agua de la fisura*	Water *Agua*
Moisture control within a specified value range *Control de la humedad dentro de un intervalo de valores especificado*	Hydrophobic impregnation *Impregnación hidrófoba*	Surface treatment *Tratamiento superficial*	Treatment of concrete to produce a water-repellent surface. The interior surface of the pores and capillaries is coated but not filled. No film is formed on the surface of the concrete and its appearance is somewhat or not at all modified. *Tratamiento del hormigón destinado a producir una superficie repelente al agua. La superficie interior de los poros y capilares queda revestida pero no rellena. No se forma película en la superficie del hormigón y su aspecto se ve modificado algo o nada.*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Products based on organic silicon solutions (siliconates, silanes, siloxanes and silicon resins). *Productos basados en soluciones orgánicas de silicio (siliconatos, silanos, siloxanos y resinas de silicio).*
	Coating *Revestimiento*	Surface treatment *Tratamiento superficial*	Treatment designed to produce a continuous protective layer on the surface of the concrete that prevents contact between the concrete and aggressive agents. *Tratamiento destinado a producir una capa protectora continua en la superficie del hormigón que evite el contacto entre este y los agentes agresivos .*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning *Preparación del sustrato (hormigón): limpieza*	Aqueous dispersion polymers (thermoplastic polymers and copolymers), solution polymers (acrylics, acrylic-styrene copolymers and chlorinated rubber), reactive polymers in solution or emulsion (epoxy and polyurethane components, or polyurethane prepolymers), 100 % reactive polymers in solids (epoxy, polyurethane, vinyl, acrylics, chlorinated

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Moisture control within a specified value range *Control de la humedad dentro de un intervalo de valores especificado*							rubber, butadiene-styrene, cement and bitumen). *Polímeros en dispersión acuosa (polímeros y copolímeros termoplásticos), polímeros en solución (acrílicos, copolímeros acrílico-estireno y caucho clorado), polímeros reactivos en solución o en emulsión (componentes epoxi y poliuretano, o prepolímeros de poliuretano), polímeros reactivos 100 %en sólidos (epoxi, poliuretano, vinilo, acrílicos, caucho tratado con cloro, butadieno-estireno, cemento y betunes).*
	Electrochemical treatment *Tratamiento electroquímico*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete *Hormigón*			Aqueous dispersion polymers (thermoplastic polymers and copolymers), solution polymers (acrylics, acrylic-styrene copolymers and chlorinated rubber), reactive polymers in solution or emulsion (epoxy and polyurethane components, or polyurethane prepolymers), 100 % reactive polymers in solids (epoxy, polyurethane, vinyl, acrylics, chlorinated rubber, butadiene-styrene, cement and bitumen). *Polímeros en dispersión acuosa (polímeros y copolímeros termoplásticos), polímeros en solución (acrílicos, copolímeros acrílico-estireno y caucho clorado), polímeros reactivos en solución o en emulsión (componentes epoxi y poliuretano, o prepolímeros de poliuretano), polímeros reactivos 100 %en sólidos (epoxi, poliuretano, vinilo, acrílicos, caucho tratado con cloro, butadieno-estireno, cemento y betunes).*
Increased resistance to physical attack *Incremento de la resistencia al ataque físico*	Impregnation (hydrophobic or sealant) *Impregnación (hidrófoba o selladora)*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete *Hormigón*	UNE 1504-2:2005 *UNE-EN 1504-2:2005.*	Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza.*	Idem *Ídem*
	Coating *Revestimiento*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	Idem + repair and reinforcement materials. *Ídem + materiales de reparación y refuerzo.*
Increased resistance to physical attack	Crack sealing *Sellado de fisuras*	Surface treatment *Tratamiento*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection.	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning.	Idem *Ídem*

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Incremento de la resistencia al ataque físico		*superficial*	*Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*			*Preparación del sustrato (hormigón): limpieza.*	
Increased resistance to chemical attack *Incremento de la resistencia al ataque químico*	Coating *Revestimiento*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	Idem *Ídem*
	Crack sealing *Sellado de fisuras*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza.*	Idem *Ídem*
Limitation of oxygen content. Creating conditions so that potentially cathodic areas of the armature make an anodic reaction impossible *Limitación del contenido de oxígeno. Creación de condiciones para que las áreas potencialmente catódicas de la armadura hagan imposible alcanzar una reacción anódica*	Concrete or reinforcement coating *Revestimiento del hormigón o de la armadura*	Surface treatment *Tratamiento superficial*	Coatings containing electrochemically active pigments, capable of providing localized cathodic protection. *Revestimientos que contienen pigmentos electroquímicamente activos, capaces de proporcionar una protección catódica localizada.*	Concrete and reinforcement *Hormigón y armaduras*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	
	Corrosion inhibitor impregnation *Impregnación de inhibidores de corrosión*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Preventive treatment against corrosion. The inhibiting liquid penetrates by diffusion, reaching the reinforcement and forming a protective film. They provide an anodic (inhibits the ionization of the steel) and cathodic (obstructs the oxygen available on the surface of the steel) protection. *Tratamiento preventivo contra la corrosión. El líquido inhibidor penetra por difusión llegando hasta las armaduras y formando una película protectora. Otorgan una protección anódica (inhibe la ionización del acero) y catódica (obstruye el oxígeno disponible en la superficie del acero).*	Reinforcement *Armadura*		Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza*	

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Control of anodic areas to prevent corrosion reaction *Control de áreas anódicas para impedir reacción de corrosión*	Anodic protection by painting the frame *Protección anódica mediante pintado de la armadura*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Treatment similar to cathodic protection, which consists of coating the metal with a thin layer of oxide so that it does not corrode. There are metals such as aluminum that in contact with air are capable of spontaneously generating this oxide layer, and therefore, become resistant to corrosion. The oxide layer must be adherent and very firm, otherwise it would be useless. *Tratamiento similar a la protección catódica, que consiste en recubrir el metal con una fina capa de óxido para que no se corroa. Existen metales como el Aluminio que al contacto con el aire son capaces de generar espontáneamente esta capa de óxido, y por ello, hacerse resistentes a la corrosión. La capa de óxido ha de ser adherente y muy firme, de lo contrario no serviría de nada.*	Reinforcement *Armadura*		Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza.*	
	Barrier coatings *Revestimientos barrera*	Surface treatment on the frame *Tratamiento superficial en la armadura*	Coatings that isolate the reinforcement from the interstitial water of the cement-based matrix. *Revestimientos que aíslan la armadura del agua intersticial de la matriz a base de cemento.*	Reinforcement *Armadura*		Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza.*	
	Corrosion inhibitor impregnation *Impregnación de inhibidores de corrosión*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Idem. *Ídem.*	Reinforcement *Armadura*		Preparación del sustrato (hormigón): limpieza *Preparation of the substrate (concrete): cleaning*	
Control of cathode areas *Control de las áreas catódicas*	Cathodic protection *Protección catódica*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Electrochemical treatment on the reinforcement based on the change of the potential of the steel towards more negative values, to make the metal work like a cathode, reducing the corrosion current to insignificant values and thus be protected from corrosion. *Tratamiento electroquímico sobre la armadura basado en el cambio de potencial del acero hacia valores más negativos, para hacer trabajar al metal como un cátodo, reduciendo la corriente de corrosión a valores insignificantes y así quedar protegida de la corrosión.*	Reinforcement *Armadura*		*UNE-EN 12696:2001*	

Table A3.b Available intervention techniques of reinforced concrete structures. REPAIR TECHNIQUES (English version/*Spanish version*)

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Restoration of the concrete to its original form and function Partial replacement or partial addition of material. *Restauración del hormigón a la forma y función original. Sustitución parcial o añadido parcial de material..*	Concrete replacement (patching) by hand mortar application, concrete filling, concrete or mortar spraying. *Reemplazo del hormigón (parcheo) mediante aplicación de mortero a mano, relleno con hormigón, proyección de hormigón o mortero.*	Patching of concrete *Parcheo del hormigón*	Restoration of the physical and chemical properties of only the damaged part, after removal of the damaged part. When only repair is necessary, it is simply replaced with traditional or special mortar, adhesive and the new concrete or other material, protecting the reinforcements if they exist. *Restauración de las propiedades físicas y químicas sólo de la parte dañada, previa retirada de la parte deteriorada. Cuando sólo es necesario reparación, simplemente se reemplaza con mortero tradicional o especial, adhesivo y el nuevo hormigón u otro material, protegiendo las armaduras si existen.*	Reinforcement *Armadura*	Quality control UNE 1504-10 *Control de calidad UNE-EN 1504-10*	Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete (+ prEN 13670-1, prEN 14487-1, prEN 14487-2). *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón (+ prEN 13670-1, prEN 14487-1, prEN 14487-2).*	
Restoration of concrete bearing capacity. *Restauración de la capacidad portante del hormigón.*	Crack injection *Inyección de fisuras*	Crack treatment *Tratamiento de fisuras*	Idem. *Ídem.*	Concrete *Hormigón*	UNE-EN 1504-5:2005	Preparación del sustrato (hormigón): limpieza. *Preparation of the substrate (concrete): cleaning.*	Ídem
	Crack stitching *Cosido de fisuras*	Crack treatment *Tratamiento de fisuras*	Specific closing of the crack without making it watertight, restoring part of the tensile strength of the concrete. It is used when it is necessary to restore tensile strength in important cracks. *Cierre puntual de la fisura sin hacerla estanca, restituyendo parte de la resistencia a tracción del hormigón. Se utiliza cuando es necesario restablecer resistencia a la tracción en fisuras importantes.*	Concrete *Hormigón*			Steel staples (and mortar coating) or epoxy resin-based carbon fiber composite staples. *Grapas de acero (y recubrimiento con mortero) o grapas composite a base de fibra de carbono colocado con resina epoxi.*
	Drilling and sealing *Perforación y obturación*	Crack treatment *Tratamiento de fisuras*	This technique is used only when the crack is reasonably straight (retaining walls). It consists of drilling down the entire length of the crack (typical hole diameter 50 to 75 mm) and filling it with mortar (or pre-cast concrete) to form a wedge or plug (after cleaning and waterproofing the hole). *Esta técnica se emplea sólo cuando la fisura sea razonablemente recta (muros de contención). Consiste en perforar hacia abajo en toda la longitud de la fisura (orificio típico entre 50 y 75 mm de diámetro) y llenarla con mortero (u hormigón premoldeado) para formar una cuña o tapón. (previa limpieza e impermeabilización del orificio).*	Concrete *Hormigón*		Between the drilling phase and the filling, cleaning and waterproofing of the hole. *Entre la fase de perforación y el relleno, limpieza e impermeabilización del orificio.*	Precast concrete or mortar placed in bitumen. If the essential thing is to achieve impermeability and not load resistance, do not use mortar but a resilient material with a low modulus of elasticity. If the sealing effect is essential, the resilient material can be placed in a second hole, filling the first one with mortar. *Tapón de hormigón premoldeado o mortero colocado en bitumen. Si lo esencial es conseguir impermeabilidad y no la resistencia de cargas, no utilizar mortero sino un material resiliente de bajo módulo de elasticidad. Si el efecto obturador es esencial, el material resiliente se puede colocar en un segundo orificio, llenando con mortero el primero.*

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Recovery or conservation of reinforcement passivation *Recuperación o conservación del pasivado de la armadura*	Increase of the reinforcement cover *Incremento del recubrimiento de la armadura*	Concrete cover increase *Incremento de recubrimiento*	Arrangement of an additional layer of concrete on one or more of the faces that delimit the structural element. *Disposición de una capa adicional de hormigón sobre uno o más de los paramentos que delimitan el elemento estructural.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	
	Replacement of contaminated or carbonated concrete *Reemplazo del hormigón contaminado o carbonatado*	Concrete patching *Parcheo del hormigón*	Similar to the concrete patching technique. *Igual que en el parcheo*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	
	Electrochemical realkalisation *Realcalinización electroquímica*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Electrochemical treatment that consists of applying an electrical current that produces OH- in the reinforcements by electrolysis, with the fundamental objective of increasing the pH of the concrete that surrounds the reinforcement (a device similar to cathodic protection). *Tratamiento electroquímico que consiste en aplicar una corriente eléctrica que produzca OH- en las armaduras por electrolisis, con el objetivo fundamental de incrementar el pH del hormigón que envuelve a la armadura (dispositivo similar a la protección catódica).*	Reinforcement *Armadura*		prEN 14038-1:2000-09	
	Diffusion realkalisation (application of CO2 absorbing layer) *Realcalinización por difusión (aplicación de capa absorbente de CO2)*	Surface treatment *Tratamiento superficial*	Application of a CO2-absorbing layer to increase the pH of the concrete. *Aplicación de una capa absorbente de CO2 para incrementar el pH del hormigón.*	Concrete *Hormigón*		Preparation of the substrate (concrete): cleaning, grinding, lifting of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	
	Chloride extraction by absorption (application of a chloride absorbing layer)	Surface treatment *Tratamiento superficial*	Application of a chloride absorbing layer. *Aplicación de una capa absorbente de cloruros.*	Concrete *Hormigón*			

Specific objetive *Objetivo específico*	Name *Nombre*	Type *Tipo*	Description *Descripción*	Intervened element *Elemento intervenido*	Regulation *Normativa*	Previous actions *Preparación necesaria*	Needed materials *Materiales empleados*
Recovery or conservation of reinforcement passivation *Recuperación o conservación del pasivado de la armadura*	*Extracción de cloruros por absorción (aplicación de capa absorbente de cloruros)*						
	Corrosion inhibitor impregnation *Impregnación de inhibidores de corrosión*	Surface treatment on the reinforcement *Tratamiento superficial en la armadura*	Idem. *Ídem.*	Reinforcement *Armadura*		Preparation of the substrate (concrete): cleaning. *Preparación del sustrato (hormigón): limpieza.*	
Restoration of the load-bearing capacity of the reinforcement *Restauración de la capacidad portante de la armadura*	Replacement of embedded or external structural steel bars *Reposición de barras de acero estructural embebidas o exteriores*	Addition of reinforcement *Añadido de armadura*	When there is loss of section of the reinforcements due to corrosion. *Cuando existe pérdida de sección de las armaduras por corrosión .*	Reinforcement *Armadura*		Preparation of the reinforcement: cleaning / If defects in corrosion of the reinforcement: raised. *Preparación del refuerzo: limpieza/ Si defectos en corrosión del refuerzo: levantado.*	

Table A3.c Available intervention techniques of reinforced concrete structures. STRENGTHENING TECHNIQUES (English version/*Spanish version*)

Specific objetive *Objetivo específico*	Name *Nombre*	Type *Tipo*	Description *Descripción*	Intervened element *Elemento intervenido*	Regulation *Normativa*	Previous actions *Preparación necesaria*	Needed materials *Materiales empleados*
Increasing the load-bearing capacity of a concrete structure element *Incremento de la capacidad portante de un elemento de la estructura de hormigón*	Reinforced oncrete section increase *Recrecido de hormigón*	Concrete and reinforcement addition *Añadido de hormigón*	Arrangement of an additional layer of concrete on one or more of the faces that delimit the structural element to be reinforced. Columns, beams and even slabs are strengthened, working by compression, shear, bending and torsion. When an element has a bearing capacity lower than the specified one or when, due to reform or change of use, it must be subjected to a load higher than the original one. *Disposición de una capa adicional de hormigón sobre uno o más de los paramentos que delimitan el elemento estructural a reforzar. Se refuerzan pilares, vigas e incluso forjados, trabajando a compresión, flexión cortante y torsión. Cuando un elemento tiene una capacidad portante inferior a la especificada o cuando por reforma o cambio de uso deba estar sometido a una carga superior a la original.*	Hormigón y armadura	DB CTE-Anejo D, EHE-08, facultativo: CEB nº 162…	Preparation of the substrate (concrete): cleaning and removal of the concrete *Preparación del sustrato (hormigón): limpieza y levantamiento del hormigón.*	Traditional or shotcrete (gutter), steel connectors, additional reinforcement. Sometimes an adhesive bonding product is needed such as grouts, cement-based fluid mortars, epoxy resins, latex emulsions etc. *Hormigón tradicional o hormigón proyectado (gutina), conectores de acero, armadura adicional. A veces es necesario un producto de unión adhesivo como lechadas, morteros fluidos de base cementicia, resinas epoxi, emulsiones látex etc.*
	Addition of embedded or external structural steel bars	Addition of reinforcement *Añadido de*	Patching operation plus addition of conventional reinforcement (steel bars through the crack). Transverse holes are	Concrete and reinforcement *Armadura y hormigón*		Preparation of the reinforcement: cleaning / If there are	

Increasing the load-bearing capacity of a concrete structure element *Incremento de la capacidad portante de un elemento de la estructura de hormigón*	*Adición de barras de acero estructural embebidas o exteriores*	*armadura*	drilled at about 90° to the direction of the crack. They are filled with epoxy resin and conventional reinforcing bars are placed inside. *Operación de parcheo más añadido de armaduras convencionales (barras de acero atravesado la fisura). Se realizan orificios tranversales a unos 90° respecto a la dirección de la fisura. Se rellenan con resina epoxídica y se colocan en su interior barras de armadura convencional.*				corrosion defects in the reinforcement: removal. *Preparación del refuerzo: limpieza/ Si existen defectos de corrosión en el refuerzo: levantado.*	
	Steel sheets attached with epoxy resin *Planchas de acero adheridas con resina epoxi*	Adding new elements *Añadido de elementos nuevos*	The method consists of reinforcement to increase the load-bearing capacity by means of steel plates bonded with epoxy resins, which make it possible to increase the rigidity of the part, reduce cracking and deformation for service loads and increase the ultimate bending capacity in a non-excessive manner. *El método consiste en el refuerzo para incrementar la capacidad portante mediante planchas de acero adheridas con resinas epoxi, que permiten incrementar la rigidez de la pieza, reducir la fisuración y la deformación para cargas de servicio además de aumentar de forma no excesiva la capacidad última a flexión.*		Concrete and reinforcement *Armadura y hormigón*		Preparation of the substrate (concrete): cleaning (sandblasting advisable, if not possible fine grain bush hammering and brushing of hard wire), grinding, lifting of the concrete *Preparación del sustrato (hormigón): limpieza (aconsejable chorro de arena, si no se puede abujardado de grano fino y cepillado de alambre duro), picado, levantamiento del hormigón*	
	Steel sheets attached with mechanical anchorages *Planchas de acero adheridas con tacos*	Adding new elements *Añadido de elementos nuevos*	It is similar to the previous one when it is not possible to use epoxy resins. Here the steel sheets are attached with special mechanical anchorages for concrete. *Es similar al anterior cuando no es posible utilizar resinas epoxi. Aquí las planchas de acero se sujetan con tacos especiales para hormigón.*		Concrete and reinforcement *Armadura y hormigón*		Preparation of the substrate (concrete): cleaning, grinding, removal of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	
	Epoxy resin bonded composite strips os laminates *Bandas de materiales compuestos adheridas con resina epoxi*	Adding new elements *Añadido de elementos nuevos*	The basic objective is to increase or restore the bearing capacity of a concrete structure element by adding external elements called composites, with high mechanical performance and resistance, as well as being easy to apply due to the light weight and flexibility of the sheets. *El objetivo básico es el incremento o restauración de la capacidad portante de un elemento de la estructura de hormigón por añadido de elementos exteriores denominados composites, de altas prestaciones mecánicas y resistentes, además de ser de fácil aplicación por el ligerísimo peso y flexibilidad de las láminas.*		Concrete and reinforcement *Armadura y hormigón*			In addition to epoxy resin, there are different materials: carbon (the most used), glass fibre (E glass fibres, S glass fibres and AR glass fibres) and aramid fibres. *Además de la resina epoxi, hay distintos materiales: de carbono (el más utilizado), fibra de vidrio (fibras de vidrio E, fibras de vidrio S y fibras de vidrio AR) y fibras de aramida.*

Increasing the load-bearing capacity of a concrete structure element *Incremento de la capacidad portante de un elemento de la estructura de hormigón*	Bonding of metal profiles *Adhesión de perfiles metálicos*	Adding new elements *Añadido de elementos nuevos*	Place metal profiles attached to a structural element. Normally, to guarantee the transmission of loads of the affected element, the space between them is retaken with controlled expansion mortar. Depending on the state of the structural element, profiles can be added to reinforce it or to replace it. *Colocar perfiles metálicos adosados a un elemento estructural. Normalmente, para garantizar la transmisión de cargas del elemento afectado, se recurre al retacado del espacio entre ambos con mortero de expansión controlada. Dependiendo del estado en el que se encuentra el elemento estructural, se puede plantear la adhesión de perfiles para reforzarlo o para sustituirlo.*	Concrete and reinforcement *Armadura y hormigón*	Preparation of the substrate (concrete): cleaning, grinding, removal of the concrete. *Preparación del sustrato (hormigón): limpieza, picado, levantamiento del hormigón.*	The material should have a very low viscosity (exposed according to ASTM C 881 type IV requirements). Epoxy materials plus conventional reinforcing steel. *El material debería tener una viscosidad muy baja (exposídico según requisitos ASTM C 881 tipo IV). Materiales epoxídicos más acero de armar convencional.*
	Pre-stressed (post-stressed) *Pretensado (post-tensado)*	Modification of reinforcement *Modificación de armadura*	This technique uses pre-stressing bars or wires to apply a compressive load. *Esta técnica emplea barras o cables de pretensado para aplicar una fuerza de compresión.*	Reinforcement *Armadura*		Steel. In certain systems, it is necessary to seal the cracks with epoxy. *Acero. En determinados sistemas, es necesario sellar las fisuras con epoxi.*
	Sistemas DIT, en forjados	Adding new elements *Añadido de elementos nuevos*	Systems based on the addition of metal profiles other than conventional structural steel profiles, looking for lighter sections or materials and a fast and functional assembly as well as compatibility with the service of the structure. *Sistemas que se basan en el añadido de perfiles metálicos distintos a los perfiles de acero estructural convencional, buscando secciones o materiales más ligeros y un montaje rápido y funcional así como compatiblidad con el servicio de la estructura.*	Concrete and reinforcement *Armadura y hormigón*	Preparation of the substrate (concrete): cleaning and removal of the concrete. *Preparación del sustrato (hormigón): limpieza y levantamiento del hormigón.*	Steel profile and filler material (mainly epoxy resin and mortar). *Perfil de acero y material de relleno (fundamentalmente resina epoxi y mortero).*

Table A3.d Available intervention techniques of reinforced concrete structures. SUBSTITUTION TECHNIQUES (English version/*Spanish version*)

Specific objetive *Objetivo específico*	**Name** *Nombre*	**Type** *Tipo*	**Description** *Descripción*	**Intervened element** *Elemento intervenido*	**Regulation** *Normativa*	**Previous actions** *Preparación necesaria*	**Needed materials** *Materiales empleados*
Increase or restoration of bearing capacity by functional replacement *Incremento o restauración de la capacidad portante por sustitución funcional del mismo*	Bonding of profiles without removing the existing structural element *Adhesión de perfiles sin eliminación del elemento estructural existente*	Adding new elements *Añadido de elementos nuevos*	Placement of profiles or elements that, without removing the existing ones, absorb the loads to be supported, without really replacing the original part but its function. In this way, the new part would take on all the load in the event of the failure of the old part. *Colocación de perfiles o elementos que, sin suprimir los existentes, absorban las cargas a soportar, sin sustituir realmente a la pieza original sino su función. De esta forma la nueva pieza tomaría toda la carga ante un eventual fallo de la antigua pieza.*	Concrete and reinforcement *Armadura y hormigón*	*CTE DB-SE-A o EHA*		
Increasing or restoring carrying capacity by physical replacement *Incremento o restauración de la capacidad portante por sustitución física del mismo*	Removal and replacement of an existing structural element *Eliminación y reemplazo de un elemento estructural existente*	Replacement of existing elements *Sustitución elementos existentes*	Physical replacement of one structural element by another. Due to the high impact involved, this action should only be applied when no other action is possible. *Sustitución física de un elemento estructural por otro. Debido a las altas repercusiones que comporta, esta actuación sólo debe aplicarse cuando no sea posible otra actuación.*	Concrete and reinforcement *Armadura y hormigón*	Depending on the regulation of the structural type of steel, concrete or other. *Dependiendo del tipo estructural normativa de acero, hormigón u otra.*		

APPENDIX A4. Papers.

PAPER 1

B. Palacios-Munoz, B. López-Mesa, and L. Gracia-Villa, "Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact," *Int. J. Life Cycle Assess.*, vol. 24, no. 11, pp. 1913–1924, Nov. 2019 https://doi.org/10.1007/s11367-019-01622-w

The International Journal of Life Cycle Assessment (2019) 24:1913–1924
https://doi.org/10.1007/s11367-019-01622-w

BUILDING COMPONENTS AND BUILDINGS

Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact

Beatriz Palacios-Munoz[1] · Belinda López-Mesa[2] · Luis Gracia-Villa[1]

Received: 7 August 2018 / Accepted: 2 April 2019 / Published online: 25 April 2019
© Springer-Verlag GmbH Germany, part of Springer Nature 2019

Abstract

Purpose Service life strongly affects results of building LCA and is considered equivalent to that of its structure. Quantitatively obtaining this parameter is a complex task that remains unsolved in the literature. This paper provides a methodology to estimate the service life of a building and quantitative data related to the environmental impact of demolition plus new construction and refurbishment, considering the potential service life and the ability of refurbishment to extend it.

Methods This paper focuses on reinforced concrete structures, specifically on beams, as service life of buildings is taken as that of its structure. Firstly, a methodology to estimate the service-life value to conduct the LCA is provided. The applied methodology is based on the definition of different scenarios that include four different approaches to reinforced concrete beam interventions in the long term. The methodology can be extended to a complete building structure. Secondly, LCA of demolition plus new construction and refurbishment in different scenarios are carried out. Finally, the complete methodology is applied to a case study.

Results and discussion Concrete structures have a potential service life much longer than the minimum value prescribed in the codes, in this case study, more than five times. Reinforced concrete is subject to degradation and aging with time and several models existing to assess the effects. In addition, a structure can be refurbished, which strongly affects its service life. These different strategies when applied to a case study result in differences of up to 65% in non-renewable primary energy consumption in a 250-year period. Embodied energy and CO_2 per year of buildings which are not constant values. The appropriate strategy for a specific case study must be taken into account to select the value of service life in LCA.

Conclusions Reinforced concrete is a highly impacting material, but also a material with a long potential service life. This durability is not considered in the LCA if the service life value is restricted to the minimum one prescribed in the codes. Demolishing a structure (and therefore, a building) that can last 250 years after just 50 or 80 is a highly impacting action. Refurbishment can ensure this durability and even extend it.

Keywords Buildings · Energy consumption · Life cycle assessment · Refurbishment · Reinforced concrete · Service life

1 Introduction

Buildings are responsible for nearly 40% of final energy consumption and about 35–50% of CO_2 emissions of EU (Vilches et al. 2017). This makes the building sector, in general, and the renovation activity, in particular, one of the most important ones in the European Strategy for Energy and Climate Change.

Building lifespan is a major factor in LCA (Pan et al. 2018) since results are normalized on an annualized basis for comparison between construction and operational phases (Marsh 2017). This means that the environmental impact associated with building materials has to be distributed along the service life of the building (König and De Cristofaro 2012). Selecting

Responsible editor: Holger Wallbaum

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s11367-019-01622-w) contains supplementary material, which is available to authorized users.

✉ Luis Gracia-Villa
lugravi@unizar.es

[1] School of Engineering and Architecture, Department of Mechanical Engineering, University of Zaragoza, María de Luna 3 C.P, 50018 Zaragoza, Spain

[2] School of Engineering and Architecture, Department of Architecture, University of Zaragoza, María de Luna 3 C.P, 50018 Zaragoza, Spain

different service-life values can lead to significant differences in the results. Some studies can be found in the literature by Hoxha et al. (2016), Strand and Hovde (1999), Carlisle and Friedlander (2016), and Marsh (2017) regarding this matter.

Service life is also significant when comparing refurbishment with demolition and new building. In spite of its critical role in LCA, there is no consensus in the literature regarding how to address this issue. Marsh (2017), after reviewing over 100 peer-reviewed scientific articles, concludes that there is no methodological documentation regarding the selection of building lifespan. This is also stated by other authors such as Strand and Hovde (1999) and Palmeri (2010). Building lifespan is considered equivalent to that of its structure because when the structure is no longer useful other components have to be demolished, even though they have not reached the end of their own service life.

Extending the service life of a building (and its structure) might lead to significant environmental benefits. Maintenance and refurbishment can extend the service life, but this is not environmentally free, as energy and materials are required. In this paper, the term refurbishment is used to refer to corrective maintenance (Motawa and Almarshad 2013) because this is the terminology used in the LCA standards.

Several papers can be found in the literature, regarding the comparison between demolition plus reconstruction and refurbishment (Itard and Klunder 2007; Power 2008; Goldstein et al. 2013; Schwartz et al. 2018). However, most of the authors focus on the operational and embodied energy but they almost never include durability aspects. Ferreira et al. (2015) state that more work needs to be done to mathematically demonstrate the environmental gain of refurbishment when compared with demolition and new construction. After an exhaustive literature review, they find that studies generally claim that refurbishment seems to be environmentally more positive than new construction. This is because the environmental cost of demolition and the huge embodied energy of the new construction cannot be compensated with the savings in the operational stage of a new building compared with the impacts of the refurbished building. However, in these studies, an assumption is made that, in our opinion, condition the results. The implicit assumption made is that the existing building (that means, its structure) is going to last the same as the new building when in reality, the new building has the potential of a larger service life. We believe that the potential durability of the existing building and the new one must be considered for a fair environmental comparison.

Aligned with the approach of assuming the service life of the building as that of its structure, this paper focuses on reinforced concrete structures, since this technology dominates in the quantity of embodied energy (Palacios-Munoz et al. 2018). Reinforced concrete (RC) is subject to aging and some factors can cause material degradation. Durability of concrete can be defined as its ability to resist weathering action, chemical attack, abrasion, or any other processes of deterioration to remain its original form, quality, and serviceability when exposed to its intended service environment (Kumar Mehta and Monteiro 2014). Determining the service life of a structure is a really complex matter as it involves many factors, with interactions among them. These factors have to do not only with the environment in which the structure is situated but also with its characteristics (materials, quality of the construction process, etc.), the user, accidents, etc. There are different approaches to address this problem in the literature: (a) the codes approach, consisting in the prescription of a minimum value of service life that must be reached, (b) statistical approaches that consider not only physical reasons to define the service life of a building but also other factors (economic, subjective, etc.), and (c) modeling the degradation to mathematically estimate the service life of the structure.

1.1 The codes approach

The codes usually address this problem by determining a minimum service life depending on the type of building and provide prescriptive requirements that ensure its compliance under normal conditions.

1.2 Statistical approaches

Buildings and therefore, their structure, are often substituted by a new one before their physical end of life is reached. According to Marteinsson (2005), the main cause of substitution is the subjective perception (44%), followed by change in use (26%). In fact, deterioration was the cause of only 17% of the buildings. In fact, statistical studies reveal that a building built in Spain is demolished after 80 years on average (Rincón et al. 2013) while its expected physical service life may be considerably longer, as this paper reveals later.

1.3 Models of deterioration

The possible external actions to which a building is exposed are multiple. They are often classified as physical, mechanical, and chemical ones (Monjo Carrió 2007). Environmental factors can cause abundant degradation phenomena in the reinforced concrete (corrosion, alkali-aggregate reaction, erosion, leaching, chemical attack, etc.), and often several of them occur simultaneously. According to Budelmann et al. (2013), the main concrete damage mechanisms in aboveground RC structures are: (i) corrosion (induced by chloride or CO_2) and (ii) alkali-aggregate reaction (AAR). This paper focuses on corrosion induced by CO_2 and AAR.

1.4 Models for corrosion induced by CO_2

Reinforcement corrosion is a major cause for degradation of existing RC structures (Ta et al. 2016). It leads to several damage types that influence the structure physical lifespan (Pedrosa and Andrade 2017). The corrosion phenomena are considered a two-stage process: (i) corrosion initiation stage and (ii) corrosion propagation stage (Tuutti 1982).

The carbonation of cementitious materials is driven by carbon dioxide (CO_2) in the air. The depth of the carbonated cement concrete front increases with time. When it reaches the reinforced layer, corrosion is likely to occur because steel bars are not passivated anymore (Ta et al. 2016). Steel bars are passivated when they have a very thin (~few nm) protective coating (a passive film) which limits the metal loss from the steel surface due to corrosion (Gonzalez et al. 1980). This coating is created at the pH levels typical of sound concrete. The time when corrosion is likely to start is called initiation time, t_i. This t_i depends on a wide range of parameters (humidity, temperature, concrete cover, porosity, etc.). The combination of concrete quality and concrete cover thickness is apparently the most important parameter that controls the rate of carbonation ingress (Tang et al. 2015).

1.5 Models for AAR

The alkali-aggregate reaction (AAR) is the chemical reaction of alkali in concrete and alkaline mineral in aggregate to form the hygroscopic gel that absorbs water causing the expansion of AAR and creates the cracking in concrete (Nik Azizan et al. 2017). Although the AAR is known since the 1940's (Vernonelli 1978), the availability of models in the literature is much lower compared with corrosion. In addition, available models are very difficult to apply, with complex mathematical developments.

Regarding mechanical properties of concrete affected by AAR, most of the experimental campaigns focus on the compressive strength, but results are contradictory, with no clear trend (Esposito et al. 2016). On the other hand, elastic modulus was always found to be sensitive to the reaction (Esposito et al. 2016), e.g., in the studies of Multon et al. (2005), Giannini and Folliard (2012), Sanchez et al. (2014), and Nik Azizan et al. (2017). Some authors (Nik Azizan et al. 2017; Esposito et al. 2016) provide semi-empirical equations to estimate the value of the elastic modulus with time.

In accordance with the importance of durability in LCA of structures and the different approaches to do it previously presented, the objective of this paper is to quantitatively analyze the environmental impact of different refurbishment and demolition plus reconstruction strategies of building structures, depending on when the structure is demolished. Specifically, this paper focuses on beams, which are rigid members or structures supported at the edges, subject to bending stresses from a direction perpendicular to its length. This paper adopts a multidisciplinary approach to provide quantitative data. The results will be useful in the decision-making process towards more sustainable strategies in intervention projects.

2 Methods

The applied methodology consists of calculating the non-renewable primary energy consumption (MJ-Eq.) and kilograms of CO_2 equivalent (kgCO_2-Eq.) emissions of a beam of specific characteristics for a certain period of time. The methodology followed can be summarized as follows.

Firstly, four scenarios are defined with the aim to compare the environmental impacts of demolishing an existing beam plus building a new beam with those of refurbishment of the existing beam (section 2.1). Secondly, it is necessary to determine when the different interventions could be undertaken (section 2.2). Thirdly, the environmental impact associated with every intervention is calculated according to the LCA methodology (section 2.3). Finally, the environmental impact of every scenario in the long term is calculated by taking into account the associated impacts of every intervention at the moment when it is done. The time lapse analyzed is 250 years. In addition, the study is extended up to 600 years with the aim to analyze the potential of concrete structures durability and its influence in LCA.

2.1 Defining the scenarios

As already exposed, buildings are subject to a natural process of aging and degradation due to, among others, environmental factors. Additionally, buildings are usually demolished before the end of their service life due to other reasons (Marteinsson 2005). Therefore, maintaining a building beam for a long period of time can be done either by demolishing the beam and constructing another one every certain period of time or by intervening in the beam with refurbishment until it has to be demolished and a new one built. These strategies lead us to define and analyze four different scenarios:

(i) Scenario 1: The beam is not subject to structural refurbishment during its service life. It can be divided in two:

  a) Scenario 1a: The beam is replaced by a new one when the building reaches the working life prescribed in the codes.
  b) Scenario 1b: The beam is replaced by a new one due to non-physical reasons before it reaches the end of its useful life.

(ii) Scenario 2: The beam is subject to minor structural interventions. It can be divided in two:

a) Scenario 2a. The beam is intervened when the admissible structural safety factor is reached. Finally, the beam is demolished and replaced by a new one when no more interventions are possible.
b) Scenario 2b. The beam is intervened when cracking in the concrete cover occurs. It is finally demolished and replaced by a new one when no more interventions are possible.

2.2 Determining the time when an intervention is done in every scenario

2.2.1 Type of intervention

In this paper, two different types of interventions have been considered: demolition plus new construction (DC), and refurbishment (R). In the case of DC, the existing beam is demolished and a new one under similar loads is built. This new beam is built with materials of modern properties that meet the nowadays standards.

The refurbishment operation (R) that is considered in this paper is among the most widely accepted to solve the corrosion problem. This is to eliminate the deteriorated concrete and corrosion products, to protect the rebars, and to replace the eliminated concrete by a new one. Although the paper also considers degradation due to AAR, a widely accepted solution with a consensus on its effectiveness and its application in residential building has not been found. Because of this, the AAR problem is not considered to be solved and degradation will continue until the beam is finally replaced.

It must be noted that the proposed refurbishment operation, does not improve the mechanical behavior of the beam as the loss section of rebars is not restituted, but stops the degradation phenomenon for a certain period of time.

2.2.2 Calculating the time to intervention

In scenario 1a, minimum design working life prescribed in Eurocode 0 (Union 2002), is used depending on the type of building. A design working life of 50 years must be ensured for building structures and other common structures.

In scenario 1b, the time when DC occurs is obtained from statistical data to take into account that often buildings are substituted before the physical end of life is reached. To approximately define this time, data from Rincón et al. (2013) are used. Rincón et al. (2013) obtain statistical data of when buildings in Spain are demolished, depending on their construction period.

In scenarios 2a and 2b, two steps must be taken to estimate the time when an intervention is done: firstly, degradation with time is obtained using structural degradation models from the literature; and secondly, the limit of acceptable degradation must be chosen. The detailed process can be found in the Electronic Supplementary Material, Annex B.

2.3 Calculating the non-renewable primary energy consumption and emissions of kilograms of CO_2 equivalent associated with every possible intervention

Environmental impact associated with both proposed interventions (demolition plus new building and refurbishment) are obtained applying the LCA methodology. These interventions are evaluated according to the Cumulative Energy Demand (CED) v.1.08 methodology (in MJ-Eq or kWh-Eq) and the Global Warming Potential (GWP) indicator based on 2007 IPCC v1.02 methodology, by means of using the software tool SimaPro v7.3. These indicators are chosen because they are among the most widely used in building LCAs (Vilches et al. 2017), as in studies of Famuyibo et al. (2013) and Mohammadpourkarbasi and Sharples (2013).

2.3.1 Goal and scope of the LCA

The objective of the performed LCAs is to obtain the non-renewable primary energy consumption (MJ-Eq) and kilograms of CO_2 equivalent (kgCO_2-Eq.) of two different alternatives. One consists of demolishing an existing beam and building a new one that fulfills the regulation requirements. The other consists of refurbishing the existing one to solve a corrosion problem.

2.3.2 Functional unit

The functional unit used is a beam with a performance above the "acceptable" limits. It must be noted that the performance level of the replaced and the refurbished beam is not the same, as the SSF is higher in the new beam than in the refurbished one. However, solutions are considered comparable as long as both are technically acceptable, as argued in the study of López-Mesa et al. (2009).

2.3.3 Boundaries of the system

Regarding the system boundaries, according to the EN 15643-2 (EN 2012) standard, in a LCA applied to buildings, we must take into account those associated to product stage, construction process stage, use stage, and end-of-life stage. In this case, the impact associated with the use stage is considered to be zero, as no operational energy or water is consumed.

(i) *Product stage.* The product stage includes all the impacts associated with the product manufacturing, from the raw material to the factory gate.

(ii) *Construction process stage.* It comprises energy and equivalent CO_2 emissions associated with transport from the factory gate to the building site and construction operation on-site.

(iii) *End-of-life stage.* A simplified end-of-life scenario with no recycling and disposal to landfill is considered in the general analysis but a sensitivity analysis considering recycling is performed as well. Disposal to landfill is often the real case in current practice in Spain (Bizcocho Tocón 2014). To model this landfill scenario, data from Ecoinvent v.2.2 database (Frischknecht et al. 2004) are used. The transportation distance that is considered is 30 km. No additional waste treatment operation is considered.

The European directive D2008/98/EC (European Parliament and the Council of the European Union 2008) imposes to recycle 70% of building-related waste. A sensitivity analysis is done considering that 70% of concrete is recycled and that concrete is made from recycled aggregates. Energy is consumed in the recycling process. To model recycled concrete, the aggregates that needed to produce the concrete are substituted by the energy needed in the recycling process. According to Gao et al. (2001), there is a need of 84.62 MJ per ton of final recycled aggregate. This energy is modeled as produced from diesel, burnt in a building machine. On the other hand, at the end of life stage, 70% of concrete is avoided from the landfill and transported to a recycling plant instead of to landfill. The considered transportation distance to the recycling plant is 36 km.

Because of that in the sensitivity analysis two alternatives are considered to model the recycling scenario. In the first alternative, the concrete is considered to be produced from raw materials, but 70% is recycled at the end of life stage. Here, the impacts associated with the end-of-life stage change because the landfill is 70% reduced. No treatment is considered in this assumption, as is considered to be computed in the new aggregate production from recycled concrete, out of the limits of the studied system.

In the second alternative, concrete is supposed to be produced from reduced aggregates. Here the aggregates from raw materials are avoided.

2.3.4 LCI data

In both the interventions (demolition plus new building or refurbishment) analyzed in the paper, unit embodied values are obtained taking Ecoinvent 2.2 database as a source. 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 construction work inputs are based on BEDEC data base (Institut de Tecnología de la Construcció de Catalunya 2017) and authors' knowledge and experience. The impact assessment methodologies CED and GWP are applied to respectively obtain non-renewable primary energy and CO_2 equivalent emissions.

The LCI inputs for the LCA of demolition, new beam construction, and refurbishment operation are summarized in Table 1. The detailed information can be found in Table A1 in Annex A (Electronic Supplementary Material).

3 Results

The results are obtained by applying the proposed methodology to a case study.

3.1 Case study

The case study consists of a hypothetic RC beam of a social housing building placed in Zaragoza (Spain) and built in 1956. This building is chosen since social housing built after the Civil War represents a widely spread building typology in Spain (Kurtz et al. 2015). The beam has 6.00 m of span and cross section of 400-mm width × 600-mm height, with a concrete cover of 40 mm. Tensile and compressive rebars area is 2945.24 mm^2 and 157.08 mm^2, respectively. The beam is subject to simple bending with a required moment of 140 kN m. Characteristic compressive strength of concrete is $f_{cd} = 11.77$ MPa, which is a concrete commonly used around 1960 in Spain (Torroja 1961). The new beam that replaces the existing one has a cross section of 300-mm width × 350-mm height, with a concrete cover of 50 mm. Tensile rebars section is 1256.64 mm^2 and compressive one, 157.08 mm^2. The properties of existing and new materials (when a new beam is built) are shown in Table 2.

Regarding the model for corrosion induced by CO_2, Table 3 shows the values that are considered for the required parameters of the meta-model proposed in (Ta et al. 2016).

The beam is supposed to be in an exposure class XC4 among those defined in Eurocode (European Union 2004). According to the table, the value of $I_{corr} = 0.431034$ $\mu A/year$ is used.

In the case of AAR, a hypothetic expansion of concrete is equal to $\varepsilon_{AAR}(\%) = 0.002 \times t$, with t the years from construction, is supposed. In practice, this parameter has to be measured at different periods of time.

3.2 Mechanical behavior with time

According to the degradation models, the mechanical properties of the beam are obtained after a period of 100, 200, 400, and 600 years from construction. The safety factors of the

Table 1 LCI inputs and outputs of demolition, new beam construction, and refurbishment

Stage/process	Description
Beam demolition	
Demolition	
	Portable diesel compressor and pneumatic hammer
	Oxi-cutting machine
	Loader
End-of-life	
	Transportation to landfill
	Disposal to landfill
New beam construction	
Product stage	
Material cradle to gate	Concrete
	Reinforcing steel and wire
	Plastic spacers to ensure concrete cover
Construction process stage	
Transport gate to site	Transport of concrete to building site (including energy consumed in the continuous mixing of concrete during transport)
	Transportation of rebars to the building site
	Transportation of spacers to the building site
Construction works	Formwork
	Shoring up
	Concrete pump
End-of-life stage	
Landfill	Transportation to landfill
	Disposal to landfill
Refurbishment operation	
Product stage	
Material of reinforcement Cradle-to-gate	Silica sand (for sandblasting)
	Epoxy resin (to protect rebars and junction between new and old concrete)
	Mortar (adhesive and cement mortar)
	Glass fiber
Construction process stage	
Transport gate to site	Transportation of compressor
	Transportation of products (supposed 15 km)
Construction works	Concrete cutting
	Compressor for inner rebar sandblasting (cleaning)
	Shoring
	Formwork
End-of-life stage	
Landfill	Transportation to landfill
	Disposal to landfill

beam after 100, 200, 400, and 600 years, without considering any structural refurbishment, are 1.272, 1.229, 1.144, and 1.106, respectively.

Figure 1 shows the bending moment-axial force diagram of the beam after a period of 100, 200, 400, and 600 years. As can be seen, near 400 years, the beam stops fulfilling the current safety factors.

3.3 Time for intervention and impacts

Results of LCA of the analyzed interventions (demolition, new beam construction, and refurbishment) are summarized in Table 4.

In scenario 1a, service life is 50 years, which is the design working life in codes (Union 2002). In scenario 1b, a statistical

Table 2 Material properties

Material	Existing				New			
	f_d (MPa)	γ	E_c (MPa)	f_{ctm} (MPa)	f_d (MPa)	γ	E_c (MPa)	f_{ctm} (MPa)
Concrete	11.77 (2)	1.5	22,983 (1)	1.50 (1)	25	1.5	30,000 (1)	2.20 (1)
Inner rebars	117.68 (2)	1.15	180,000 (2)	–	500	1.15	200,000	–

(1) Equation in Eurocode 2 (European Union 2004)

(2) Usual materials in Spain in 1956, according to Torroja (1961)

Table 3 Parameters for corrosion meta-model proposed by Ta et al. (2016)

Parameter	Value	Unit
Cement type	Portland (CEM I)	–
Cement compressive strength (f_{cem})	15.6	N/mm^2
Cement content	350	kg/m^3
Sand content	600	kg/m^3
Gravel content	1200	kg/m^3
Maximum aggregate size	38.1	mm
Fly ash content	0	g/m^3
w/c ratio	0.35	–
Initial curing period	7	days
Relative external humidity	66	%
Temperature	303.15	k
CO_2 concentration in air	0.00082	kg/m^3

value for service life is chosen according to Rincón et al. (2013). In a study by Rincón et al. (2013), a building built in 1956 in Spain and therefore, its beams, will last for 30 more years. After demolition, if trends continue being the same, the new constructed beam will last for 80 years from construction.

In scenario 2a, refurbishment interventions are supposed to be undertaken when SSF decreases 2% from previous one, and end-of-life is reached when the structural safety factor (SSF) is equal to 1.20 (minimum value would be 1). At year 430, the beam cannot be further repaired and must be substituted. In scenario 2b, refurbishment intervention is carried out when cracking of the concrete cover occurs. By doing these reparations, the beam does not need to be substituted at least for 600 years.

For a period of time of 250 years, the type of intervention or interventions that are needed (depending on the scenario) and the time, in years from construction, when such interventions are carried out in the different scenarios are summarized in Table 5.

Degradation phenomena can cause a decrease in the structural safety factor (SSF) of a reinforced concrete element, due to their influence in different geometric and mechanical properties. Refurbishment can decelerate the degradation process. Figure 2 shows the variation of the SSF due to degradation phenomena in the case study if no refurbishment is done and if it is done according to scenarios 2a and 2b.

To take into account the service life of the building and the influence that interventions have on it, methodology proposed in the previous section has been applied. In Fig. 3, the total cost of MJ-Eq. depending on building age is represented for a 250-year period, according to the different scenarios of intervention.

In the case of kilograms of CO_2 equivalent (kgCO_2-Eq.) emissions, the trend is similar and is shown in Fig. 4.

As can be seen in Figs. 3 and 4, the selection of the best intervention strategy is strongly dependent on time. A bigger time lapse of 600 years is analyzed, and results are shown in Fig. 5.

Table 6 summarizes the reduction in the impact results obtained in the refurbishment scenario 2b compared with those of the new building scenarios 1a and 1b, both for landfill and recycling.

4 Discussion

It is widely accepted that extending the life span of buildings, and in particular, its structure, can have significant

Fig. 1 Bending moment-axial force at time equal to 100, 200, 400, and 600 years

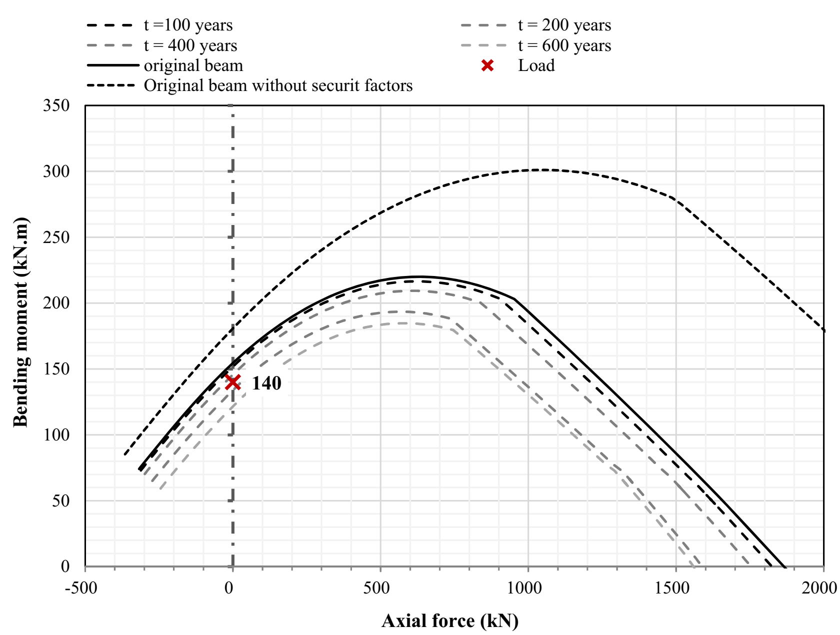


Table 4 Non-renewable primary energy consumption and equivalent CO_2 kg of analyzed interventions

Intervention	Landfill		70% recycling	
	MJ-Eq. (non-renewable)	kgCO_2-Eq.	MJ-Eq. (non-renewable)	kgCO_2-Eq.
Original beam construction	3571.99	399.84	3571.99	399.84
New beam construction	3640.46	301.43	3658.95	304.99
Demolition of the original beam	1200.51	53.95	721.70	37.45
Demolition of the new beam	525.69	23.62	286.49	14.63
Refurbishment (1)	998.27	53.43	997.46	53.40

(1) The damage has been considered to affect a length of 1 m

environmental benefits but no quantitative data do exist in the matter. This paper proposes and applies a methodology to evaluate this environmental benefit. The results support this assertion quantifying this environmental benefit.

One of the relevant issues shown in this study is the ability of refurbishment to extend the service life of the beam. Figure 2 shows the decrease of the structural safety factor (SSF) with time when no refurbishment is done and according to scenarios 2a and 2b. If we identify the limit of the service life as a minimum acceptable value of the SSF, here 1.20, refurbishment can nearly duplicate (scenario 2a) the service life or can extend it more than 10 times (scenario 2b). Additionally, Fig. 2 shows that the refurbishment operation that has been considered in this paper, can slow down the degradation process, but cannot avoid a final demolition. Additionally, refurbishment has to be made more and more frequently with time. For example, in scenario 2a, the time interval between successive interventions is 115, 112, 109 and 94 years for the first, second, third and fourth interventions, respectively. The fourth intervention consists in demolition and new building, as the SSF of the beam reaches the acceptable limit of 1.20.

In Fig. 3, the cumulative non-renewable primary energy is presented for a time period of 250 years. As can be seen, the cumulative energy cost is much higher when the building is replaced before it reaches the end of its useful life. The embodied energy of all the refurbishment operations, even if they have to be carried out frequently, does not overcome the cost of demolition and reconstruction, in this case study. If we compare a beam that is demolished before its physical service life is reached, according to the usual attitude (scenario 1b), with a beam that is not demolished but refurbished when it is required (scenario 2b) the non-renewable energy consumption in the scenario that includes refurbishment (2b) is 60% of that with no refurbishment (1b), after 250 years. In the comparison with the scenario 1a, where the beam is replaced when service life prescribed in codes is reached, the embodied energy of scenario 2b is just 30% of that of 1a. This implies a difference in non-renewable primary energy consumption of 5014.04 MJ-Eq and 17,512.5 MJ-Eq., respectively, just for a single beam, in 250 years.

If we consider a longer term, results in Fig. 5 reflect a similar trend, even though a repaired beam needs to be finally replaced when no more interventions are possible. In this case study, this is needed after 430 years, which explains the increase in the graph for scenario 2a due to the impacts associated with demolition and new construction. After 600 years, the non-renewable primary energy consumption of scenario 2b is 41% and 25% of that of scenarios 1b and 1a, respectively.

In the case of CO_2 emissions, as can be seen in Fig. 4, differences follow a similar trend. In a period of time of

Table 5 Building age at the moment of intervention and type of intervention in the different scenarios in a period of 250 years

Scenario	1st		2nd		3rd		4th		5th	
	Time	Type	Time	Type	Time	Type	Time	Type	Time	Type
1a	50.0	DC	100.0	DC	150.0	DC	200.0	DC	250.0	DC
1b	92.0(1)	DC	172.0	DC	–	–	–	–	–	–
2a	115.0	R	227.0	R	–	–	–	–	–	–
2b	58.9	R	117.8	R	235.5	R	–	–	–	–

DC, demolition plus new construction; *R*, refurbishment

(1) Age of the building plus expected service life

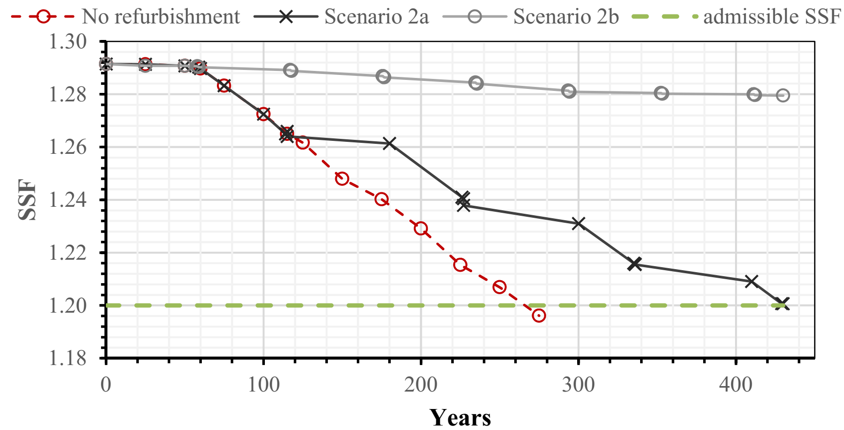


Fig. 2 SSF with time according to different scenarios

250 years, emissions of scenario 2b are 57% and 30% of that of scenario 1b and 1a, respectively. That means a difference between scenario 2b and 1b of 466.77 kgCO_2-Eq., and between 2b and 1a of 1441.91 kgCO_2-Eq. Analyzing a longer period of 600 years, CO_2 emissions in scenario 2b are 31% and 22% of that of 1b and 1a, respectively. It can be seen that the environmental benefits of refurbishment are significant.

It must be noted that taking the value of service life prescribed in codes, which is the usual practice, can lead to significant discrepancies with the value obtained both statistically and with physical degradation according to models. In this specific case study, the value of design working life in codes is 50 years, according to statistical data is 80 years, and the value obtained by applying degradation models without considering any intervention is 265 years.

The results of life span are case dependent. They depend on the capacity of the beam and the supported loads, the acceptable limit of the structural behavior, the quality of the concrete, and the exposure class. The quality of concrete influences both the capacity of the beam (i.e., compressive strength) and its durability, being the concrete cover and the water/cement ratio among the most influencing parameters. The acceptable limit of the structural behavior must be chosen by the technician based, among others, on the quality of the building work, the available information, and the reliability level that is assumed. This is beyond the scope of this study but further information can be found in the literature (International Federation for Structural Concrete (fib) 2016). In this simplified study, the exposure class and therefore, the corrosion rate (Table B1, Electronic Supplementary Material) depends on the element that is considered (i.e., if it is protected from the rain or not).

Additionally, as can be seen in Table 6, the environmental benefit of refurbishment compared with demolition plus new building is reduced when the recycling scenario is considered. This is because recycling reduces the impacts associated with demolition plus new building, whereas the impacts of refurbishment remain nearly constant (see Table 4). However, the difference between the reductions with and without recycling concrete is not high enough so as to significantly change the general results. This is because even if recycling allows avoiding landfill impacts, energy is consumed in the concrete recycling process since the old concrete needs to be crushed. In fact, as shown in Table 4 and aligned with the literature (Gao et al. 2001), the energy intensity of recycled concrete is higher than that for virgin material. In a future

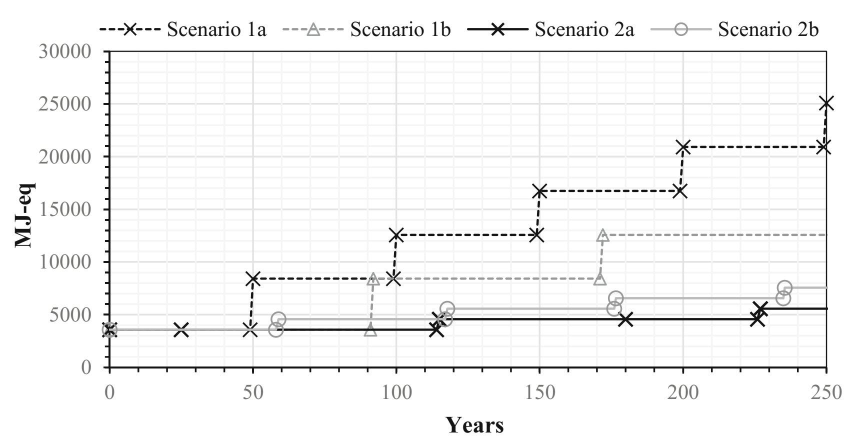


Fig. 3 Total MJ-Eq. depending on time for a 250-year period

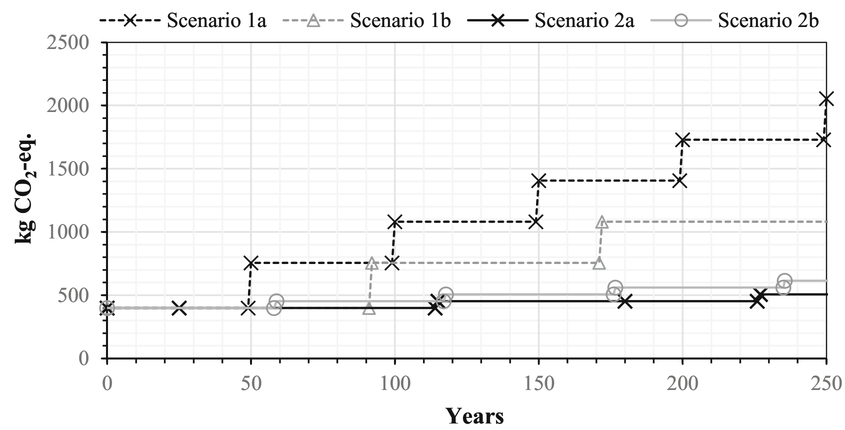


Fig. 4 Total kgCO_2-Eq. depending on time for a 250-year period

scenario this could change, i.e., if the required energy is produced from renewable sources or the recycling process is improved.

4.1 Limits of the study

Despite the relevant conclusions of this paper, some limits must be noted.

According to the proposed model the life span of the evaluated concrete, beam is at least 265 years even when no refurbishment is applied to it. This value can be considered optimistic since degradation is not the main cause of demolishing structures as it mostly depends on people behavior. On the other hand, not all the degradation processes have been accounted for in the present study, just the most common ones, and this represents therefore a limit of the study. However, the data obtained provides important information on the potential durability of concrete structures when they are evaluated considering just their physical properties.

Relating to degradation models, there is a need of further research to develop more accurate models, especially, but not only, for other than corrosion phenomena. Although some research has been produced relating to the interaction between different phenomena (among others, RILEM 2013 and Zhang et al. 2017), this issue and its consequences on a structural level are almost unknown.

On the other hand, among the several possible techniques for corrosion reparation, just one of them is analyzed in this paper.

It must also be remarked that static life cycle inventory data have been used to represent scenarios in the distant future. The impacts of interventions in the future are likely to be different from those considered today, both in the case of new construction and refurbishment. In addition, when a time lapse of 600 years is analyzed, the scenario 2b considers that the structure is in maintenance during the whole period and in scenario 2a for 430 years. This is not likely to occur in reality. However, this theoretical scenario clearly illustrates the potential of maintenance in reinforced concrete durability and its environmental benefits.

5 Conclusions

In this paper, four different strategies towards beam intervention are analyzed. The potential of repair and maintenance to

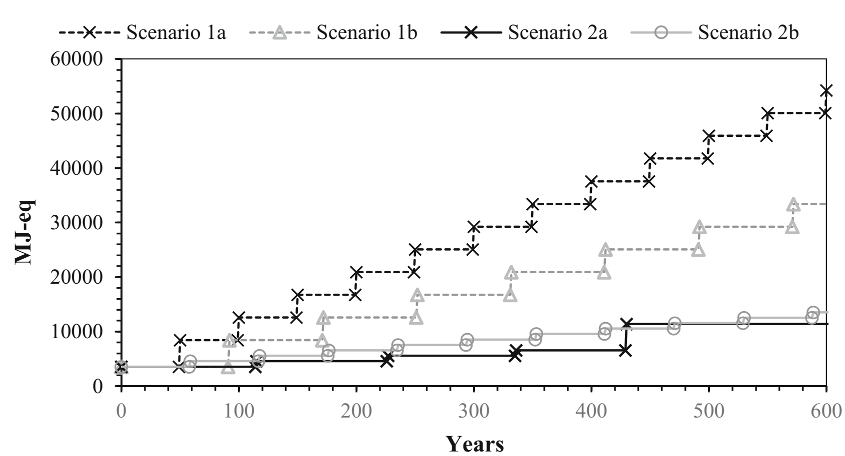


Fig. 5 Total MJ-Eq. depending on time for a 600-year period

Table 6 Reduction in the impacts in scenario 2b (refurbishment) compared with 1a and 1b (demolition + new building)

End-of-life scenario	Reduction in 2b compared with 1a		Reduction of 2b compared with 1b	
	MJ-eq. (non-ren.)	$kgCO_2$-Eq.	MJ-Eq (non-ren.)	$kgCO_2$-Eq.
Landfill	69.8%	70.1%	39.8%	43.2%
70% recycled/30% landfilled	68.1%	69.6%	36.4%	42.2%

extent the service life and its associated environmental benefits in terms of non-renewable primary energy consumption and kilograms of CO_2 equivalent have been quantified for a case study. The main conclusions of this paper can be summarized as follows:

1. Demolishing and replacing reinforced concrete structures before exhausting their useful life leads to an increase in the embodied energy of 70% (scenario 1a: demolishing after 50 years) or 40% (scenario 1b: demolishing after 80 years), considering a period of 250 years. This percentage increases with longer periods of time.
2. Planning interventions with a long-term vision is crucial to select the most environmentally friendly strategy as exhausting the useful life of reinforced concrete structures and the interventions made is a fundamental factor.
3. A beam subject to degradation cannot be refurbished indefinitely, according to the refurbishment operation considered in this paper. In spite of this, the impact of several repair interventions of a beam plus the final demolition and new construction, obtain better results than demolition and reconstruction before the end of its physical service life is reached. This is even though the time interval between refurbishment operations is shorter and shorter with time.
4. Repair interventions have a huge potential to extend the service life of a reinforced concrete beam.
5. Extending service life of structures also means extending the service life of many other components, which further increases its environmental benefits.
6. Selecting the minimum working design life in structural codes, as the service life value in LCA of buildings, can lead to significant variations in results. In this case study, the value prescribed in codes is 50 years, statistical data of demolition is 80 years, and calculated service life according to degradation models is 265 years, if any intervention is done: more than 5 times the minimum value of the codes.

The importance of considering the service life in a more accurate way in LCA is, although of complex estimation, fundamental. Otherwise, durable materials can result seriously undervalued. Reinforced concrete is a highly impacting material, above all due to the great amount of it that is required in a building structure. However, it is also a material with a long service life. The evaluation made in this paper can be considered optimistic because not all the degradation processes have been accounted for, but just the most common ones. However, the conclusions show that demolishing a structure with a potential life span of 250 years after just 80 years because of non-technical reason is a highly impacting action. Refurbishment can ensure this durability and even extend it.

Funding information This work was supported by the Spanish Ministry of Education, Culture and Sports, through a FPU research grant (grant FPU15/01069) and Gobierno de Aragón (Research Group GIA T37_17R) cofunded by FEDER 2014-2020 "Construyendo Europa desde Aragón".

References

Bizcocho Tocón N (2014) Aplicación del análisis de ciclo de vida a la gestión de los residuos de construcción. University of Sevilla

Budelmann H, Holst A, Wachsmann A (2013) Durability related life-cycle assessment of concrete structures: mechanisms, models , implementation. In: Strauss F, B (eds) Life-cycle and sustainability of civil infrastructure systems. Taylor and Francis Group, pp 75–86

Carlisle S, Friedlander E (2016) The influence of durability and recycling on life cycle impacts of window frame assemblies. Int J Life Cycle Assess 21:1645–1657

EN (2012) EN 15643-2:2011 - Sustainability of construction works - assessment of buildings - part 2 : framework for the assessment of environmental performance. Int Stand:1–36

Esposito R, Anaç C, Hendriks MAN, Çopuroğlu O (2016) Influence of the alkali-silica reaction on the mechanical degradation of concrete. J Mater Civ Eng 28:04016007. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001486

European Parliament and the Council of the European Union (2008) Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain directives

European Union (2004) EN-1992-1-1: eurocode 2: design of concrete structures - part 1–1 : general rules and rules for buildings. The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC

Famuyibo AA, Duffy A, Strachan P (2013) Achieving a holistic view of the life cycle performance of existing dwellings. Build Environ 70:90–101

Ferreira J, Duarte Pinheiro M, De Brito J (2015) Economic and environmental savings of structural buildings refurbishment with demolition and reconstruction - a Portuguese benchmarking. J Build Eng 3:114–126

Frischknecht R, Jungbluth N, Althaus H-J et al (2004) Overview and Methodology, ecoinvent report No. 1. Dübendorf, Switzerland

Gao W, Ariyama T, Ojima T, Meier A (2001) Energy impacts of recycling disassembly material in residential buildings. Energy Build 33:553–562
Giannini ER, Folliard KJ (2012) Stiffness damage and mechanical testing of core specimens for the evaluation of structures affected by ASR. 14th ICAAR
Goldstein BP, Herbøl M, Figueroa MJ (2013) Gaps in tools assessing the energy implications of renovation versus rebuilding decisions. Curr Opin Environ Sustain 5:244–250
Gonzalez JA, Algaba JS, Andrade C (1980) Corrosion of reinforcing bars in carbonated concrete. Br Corros J 15:135–139
Hoxha E, Bazzana M, Habert G et al (2016) Influence of service life on building LCA. In: Quattrone M et al (eds) XIII international conference on durability of building materials and components (XIII DBMC). RILEM Publications, São Paulo
Institut de Tecnología de la Construcció de Catalunya (2017) BEDEC - Banco de datos de elementos constructivos
International Federation for Structural Concrete (fib) (2016) Bulletin no. 80. Partial factor methods for existing concrete structures. Recommendation
Itard L, Klunder G (2007) Comparing environmental impacts of renovated housing stock with new construction. Build Res Inf 35:252–267
König H, De Cristofaro ML (2012) Benchmarks for life cycle costs and life cycle assessment of residential buildings. Build Res Inf 40:558–580
Kumar Mehta P, Monteiro PJM (2014) Concrete: microstructure, properties, and materials, Fourth edn. McGraw-Hill Education
Kurtz F, Monzón M, López-Mesa B (2015) Energy and acoustics related obsolescence of social housing of Spain’s post- war in less favoured urban areas The case of Zaragoza. Inf la Construcción 67:m021. https://doi.org/10.3989/ic.14.062
López-Mesa B, Pitarch Á, Tomás A, Gallego T (2009) Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Build Environ 44:699–712
Marsh R (2017) Building lifespan : effect on the environmental impact of building components in a Danish perspective. Archit Eng Des Manag 13:80–100
Marteinsson B (2005) Service life estimation in the design of buildings. University of Gävle
Mohammadpourkarbasi H, Sharples S (2013) Eco-retrofitting very old dwellings : current and future energy and carbon performance for two UK cities. In: PLEA 2013: Sustainable architecture for a renewable future. Munich (Germany)
Monjo Carrió J (2007) Durability vs vulnerability. Inf Constr 59:43–58. https://doi.org/10.3989/ic.2007.v59.i507.531
Motawa I, Almarshad A (2013) A knowledge-based BIM system for building maintenance. Autom Constr 29:173–182
Multon S, Seignol JF, Toutlemonde F (2005) Structural behavior of concrete beams affected by alkali-silica reaction. ACI Mater J 102:67–76
Nik Azizan NZ, Mandal A, Majid TA et al (2017) Numerical prediction of stress and displacement of ageing concrete dam due to alkali-aggregate and thermal chemical reaction. Struct Eng Mech 64:793–802
Palacios-Munoz B, Gracia-Villa L, Zabalza Bribián I, López-Mesa B (2018) Simplified structural design and LCA of reinforced concrete beams strengthening techniques. In press Eng Struct 174:418–432
Palmeri J (2010) A life cycle approach to prioritizing methods of preventing waste from the residential construction sector in the state of Oregon. State of Oregon
Pan W, Li K, Teng Y (2018) Rethinking system boundaries of the life cycle carbon emissions of buildings. Renew Sust Energ Rev 90:379–390
Pedrosa F, Andrade C (2017) Corrosion induced cracking: effect of different corrosion rates on crack width evolution. Constr Build Mater 133:525–533
Power A (2008) Does demolition or refurbishment of old and inefficient homes help to increase our environmental, social and economic viability? Energy Policy 36:4487–4501
RILEM (2013) Report rep043. Publications on durability of reinforced concrete structures under combined mechanical loads and environmental actions: an annotated bibliography. Aedificatio Publishers, Beijing
Rincón L, Pérez G, Cabeza LF (2013) Service life of the dwelling stock in Spain. Int J Life Cycle Assess 18:919–925
Sanchez LFM, Fournier B, Jolin M, Bastien J (2014) Evaluation of the stiffness damage test (SDT) as a tool for assessing damage in concrete due to ASR: test loading and output responses for concretes incorporating fine or coarse reactive aggregates. Cem Concr Res 56:213–229
Schwartz Y, Raslan R, Mumovic D (2018) The life cycle carbon footprint of refurbished and new buildings – a systematic review of case studies. Renew Sust Energ Rev 81:231–241
Strand SM, Hovde PJ (1999) Use of service life data in LCA of building materials. In: 8DBMC International Conference on durability of building materials and components. pp 1948–1958
Ta VL, Bonnet S, Senga Kiesse T, Ventura A (2016) A new meta-model to calculate carbonation front depth within concrete structures. Constr Build Mater 129:172–181
Tang SW, Yao Y, Andrade C, Li ZJ (2015) Recent durability studies on concrete structure. Cem Concr Res 78:143–154
Torroja IE (1961) Instrucción H.A. 61 Especial para estructuras de hormigón armado
Tuutti K (1982) Corrosion of steel in concrete. Swedish Cem Concr Res Inst 469. https://doi.org/10.4324/9780203414606_chapter_2
Union E (2002) Eurocode 0 - basis of structural design. En 3:89–13. https://doi.org/10.1680/cien.144.6.8.40609
Vernonelli DJK (1978) Durabilidad de los hormigones: reacción árido-álcalis. Mater Constr 28:33
Vilches A, Garcia-Martinez A, Sanchez-Montañes B (2017) Life cycle assessment (LCA) of building refurbishment: a literature review. Energy Build 135:286–301
Zhang P, Cong Y, Vogel M, Liu Z, Müller HS, Zhu Y, Zhao T (2017) Steel reinforcement corrosion in concrete under combined actions: the role of freeze-thaw cycles, chloride ingress, and surface impregnation. Constr Build Mater 148:113–121

Publisher’s note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

PAPER 2

B. Palacios-Munoz, B. Peuportier, L. Gracia-Villa, and B. López-Mesa, "Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach," *Build. Environ.*, vol. 160, p. 106203, Aug. 2019. https://doi.org/10.1016/j.buildenv.2019.106203

Building and Environment 160 (2019) 106203

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Sustainability assessment of refurbishment vs. new constructions by means of LCA and durability-based estimations of buildings lifespans: A new approach

Beatriz Palacios-Munoz[a], Bruno Peuportier[b], Luis Gracia-Villa[a], Belinda 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] MINES ParisTech, CES- Centre D'efficacité Energétique des Systèmes, 5 Rue Léon Blum, 91120, Palaiseau, France
[c] University of Zaragoza, School of Engineering and Architecture, Department of Architecture, María de Luna 3, C.P. 50018, Zaragoza, Spain

ARTICLE INFO

Keywords:
Life cycle assessment
Lifespan
Reinforced concrete
Energy consumption
Refurbishment
New construction

ABSTRACT

A common practice in Life Cycle Assessment (LCA) of buildings is to consider a default value for their lifespans. However, statistical data show longer lifespans and it is proved that the higher they are the lower the environmental impacts. Therefore, the common practice of considering a default value for lifespans in buildings LCA involves a high risk of programmed obsolescence in the building sector. This paper addresses a new approach to estimate buildings lifespans based on their structures durability. We use a comparative case study of refurbishment vs. new construction to illustrate its use. The lifespans of the refurbished and the new buildings are estimated by applying degradation models of reinforced concrete structures. Two thermal performance levels are evaluated: standard and passive, in both alternatives, the refurbished and the new building. Comparisons are also made with other approaches to determine buildings lifespans based on default value and statistical data. Results show that a new building can have a lifespan more than six times longer than a refurbished one. A strong dependence of LCA results on the lifespan is revealed. Its value can alter the order of preference of the solutions when comparing alternatives and therefore default value approaches are unadvisable. There is in our case study a 11% potential of environmental improvement for new buildings behaviour by changing current practices and extending buildings' lifespan up to their physical limit.

1. Introduction

One of the European Union's (EU) fundamental objectives is sustainable development [1]. The contribution of buildings in environmental impacts is high. On the one hand, they account for nearly 40% of energy consumption in European Union. This is why buildings are central to the EU's energy efficiency policy [2]. On the other hand, they consume a large number of natural resources (materials, water, etc.) and represent an important source of harmful emissions to the environment. Life Cycle Assessment (LCA) provides the best framework for assessing the potential environmental impacts of products, according to the European Commission [1]. In this article, the need for more consistent data and for consensus on LCA methodologies is highlighted.

One question recently posed in the field of buildings LCA is whether or not it is more sustainable to refurbish than to rebuild [3]. Most of the literature on LCA focuses on new construction [4–8], whereas refurbishment is dealt with at a lower extent [9–12]. The comparison between the refurbishment of an existing building versus its demolition and new construction is a matter more recently studied [13–16]. The results of such a comparison depend on the building techniques but also on the level of performance achieved after the refurbishment and the new construction, as well as on the quality and lifespan of the building elements.

The studies found in the literature often address the influence of the construction stage and the performance of the buildings, but that of the lifespan is seldom studied.

Lifespan is a major factor in the LCA [17] and the results are strongly dependent on it [18]. However, there is no consensus on the lifespan of buildings [7] and different values are used by the authors, e.g. 40 years [8], 50 years [20], 60 years [21] or 100 years [22]. The most commonly used value is 50 years, e.g. Refs. [4,23,24]. This is because in the building sector most LCA practitioners do not estimate buildings lifespans but just apply a default value taken from structural

* Corresponding author.
E-mail addresses: bpalacios@unizar.es (B. Palacios-Munoz), bruno.peuportier@mines-paristech.fr (B. Peuportier), lugravi@unizar.es (L. Gracia-Villa), belinda@unizar.es (B. López-Mesa).

https://doi.org/10.1016/j.buildenv.2019.106203
Received 10 April 2019; Received in revised form 31 May 2019; Accepted 9 June 2019
Available online 10 June 2019
0360-1323/ © 2019 Elsevier Ltd. All rights reserved.

calculation codes. There is in such a case a high risk of programmed obsolescence in the building sector.

To overcome this problem, the literature has provided statistical analysis of buildings lifespans, e.g. Refs. [19,25–27], showing longer service lives than that of 50 years. The literature also shows that the higher the lifespan of buildings the lower the environmental impacts [19]. Marsh [19] states that on average, a building lifespan of 80 years reduces environmental impact by 29%, 100 years by 38%, and 120 years by 44%, in comparison to a lifespan of 50 years.

In real practice, physical degradation is not the main cause of building demolition, but the subjective perception (44%), followed by change in use (26%), according to Ref. [28]. Deterioration was the cause of only 17% of the projects [28]. This implies that buildings are demolished before they reach their physical end of life, and this represents a non-sustainable human behaviour. There is room for a more sustainable performance in the construction sector by modifying human behaviour regarding buildings service life. The question is to what extent it is better to refurbish and extend a building's service life.

This paper proposes a new approach to the problem of estimation of buildings lifespans to explore this problem, going a step forward, by means of a method that uses knowledge regarding the physicochemical durability of buildings, i.e. by means of degradation models. The paper compares the results of LCA of refurbishment (R) vs. demolition plus new building (D&N) using different approaches to determine the buildings lifespans: a) using a default value, b) using statistical data, and c) using durability-based estimations (our new approach). This study will be helpful to explore the durability of buildings and the room for improvement regarding sustainability if buildings lifespans were extended up to the end of their capacity.

A building is made of different elements such as walls, ceilings, windows, etc. which have different lifespans. When a LCA of a whole building is performed, a lifespan value for the complete building should be introduced. The general accepted criterion is to take the value of the structure lifespan as the one for the complete building [29] as all the other elements depend on its stability.

To evaluate the structure lifespan, and therefore that of the building, the methodology proposed by Ref. [30] for reinforced concrete (RC) structures is applied here. This methodology is based on the degradation models of this type of structures.

A building structure is exposed to multiple external actions often classified as physical, mechanical and chemical [31]. Environmental factors can cause several degradation phenomena in the reinforced concrete (corrosion, alkali-aggregate reaction, erosion, leaching, chemical attack, etc.), and they can occur simultaneously. The degree of knowledge about the different phenomena is diverse. According to Budelmann [32], the main concrete damage mechanisms in above ground RC structures are: (i) corrosion (induced by chloride or CO_2) and (ii) alkali aggregate reaction (AAR). In this paper, only the corrosion induced by CO_2 is considered among the wide amount of degradation phenomena.

Reinforcement corrosion is a major cause for degradation of existing RC structures [33]. It leads to several damage types that influence the structure physical lifespan, among others, the reduction of rebar section, the bonding loss between steel and concrete and the cracking of concrete cover due to the increase in volume of the oxides with respect to the original volume of the parent steel [34]. The corrosion phenomena is considered as a two-stage process: (i) corrosion initiation stage; and (ii) corrosion propagation stage [35].

The carbonation of cementitious materials is driven by carbon dioxide (CO_2) in the air. The depth of the carbonated cement concrete front increases with time. When it reaches the reinforced layer, corrosion is likely to occur because steel bars are not passivated any more [33]. The time when corrosion is likely to start is called initiation time, t_i. This t_i depends on a wide range of parameters: humidity, temperature, concrete cover, porosity, etc. The combination of concrete quality and concrete cover thickness is apparently the most important parameter that controls the rate of carbonation ingress [36].

The objective of this paper is to evaluate the influence of lifespan in the comparative LCA of a complete building considering R and D&N scenarios. To address this question, both alternatives are compared in a case study considering two energy performance levels (standard and passive) because the energy performance can be improved thanks to R and D&N, and considering three different approaches to determine the buildings lifespans: default value; statistical; and durability-based.

2. Material and methods

In this paper, a comparison between R and D&N is performed in a case study considering a concrete building, different lifespans and two energy performance levels. One is the standard performance corresponding to the coming Spanish regulation [37] and the other corresponds to a very low energy consumption performance [36]. In the case of the standard performance, the project of the future Spanish regulation is taken as a reference as it sets the requirements of a nearly zero energy consumption building. We name this level as standard (S). In the very low energy consumption case, the *Passive House* standard [38] limit for heating and cooling demand is used, i.e. less than 15 kWh/m^2. We name this level as passive (P). The lifespans of the refurbished and the new buildings are estimated adapting the methodology proposed by Ref. [30] for reinforced concrete structures. Specifically, the following steps are taken.

(i) First of all, the case study is defined, including the selection of the existing building, the refurbishment and the new construction characteristics (section 2.1). The selected refurbishment corresponds to techniques currently applied in residential buildings in Spain. The difference between the two refurbishment options is just the insulation thickness and window types to obtain different performance levels. The rest of the needed materials and processes are similar to avoid disturbances in the results comparison.

In the case of the new building, the same volume, living area and architectural configuration as the original ones are considered. Current building solutions and techniques in Spain are considered to define the building characteristics. The difference between the solutions with standard and passive performance is the insulation thickness and the windows characteristics.

(ii) Thermal behaviour is analysed to evaluate the use stage impacts of each solution. Thermal dynamic simulations using COMFIE Software [39] are carried out to obtain the heating and cooling need of the original building, the two refurbishment alternatives and the two new building alternatives. The operational conditions defined in the Spanish regulation [37] are considered to calculate energy needs: indoor temperature in summer and winter, ventilation, internal gains, etc.

To obtain the consumption, systems are included in a simplified way by considering the efficiency of the reference systems provided in the regulation. The same systems are considered for the refurbished and the new building and both in the standard and passive performance. This decision is taken in order not to disturb results because of systems, as every system could be implemented in all the solutions.

(iii) The lifespan of the existing building (and therefore, the refurbished one) and of the new building are estimated (section 2.2).
(iv) LCAs of the different options are performed taking into account the predicted lifespan (section 2.3).

2.1. Case study

2.1.1. Original building

The case study consists of a residential block built in 1956 in Zaragoza (Spain). The building has eight floors and two dwellings per floor, even in the ground level. The heated and cooled surface is 1257 m^2.

The structure is made of reinforced concrete. The slabs also include ceramic elements to lighten them. The external walls consist of two layers of bricks without air gap between them and a ceramic tile cladding on one of the façades and mortar plaster on the others, without insulation layer. The building has a tile roof without thermal insulation and the windows are of wood frame with single glazing.

The yearly heating and cooling need of the original building are 74 kW h/m^2 and 26 kW h/m^2, respectively.

The structure consists of three multi-storey frames with a span between them of 4.10 m and a span between beams of 4.00 m. All the beams are considered to be of the same cross section of 400 mm width - 600 mm height, with a concrete cover of 40 mm. Tensile and compressive rebars areas are 2592 mm^2 and 157 mm^2, respectively. The beams are considered to be under simple bending with a maximum supported moment of 140 kN m. The material properties used for the estimations are those of commonly used materials in the 60's in Spain, which were obtained from the codes of that time and are shown in Table 1.

2.1.2. Refurbishment

The refurbishment operation consists of adding exterior thermal insulation in the façade and in the roof. The ground floor in contact with the sanitary chamber is also insulated. The windows are replaced for new ones with better thermal characteristics. Some materials must be demolished or replaced during refurbishment. The difference between the option that just fulfils the regulation and the option that fulfils the very low consumption standard is the insulation thickness as well as the type of windows.

In the case of the standard energy refurbishment (SR) that fulfils the regulation, the thickness of the glass wool that is added in the façade, roof and ground floor is 10 cm. The windows are of wood frame with double glazing 6/16/6 with argon (U = 1.85 W/m^2.K). In the case of the passive energy refurbishment (PR), the thickness of the glass wool added in the façade, roof and ground floor is 18 cm, 19 cm and 10 cm, respectively. The windows are of wood frame with triple low emissivity glazing with argon (U = 1.09 W/m^2.K).

The heating and cooling demand of SR are 30 kWh/m^2 and 7 kWh/m^2, respectively. The heating and cooling demand of PR are 15 kWh/m^2 and 13 kWh/m^2, respectively. The cooling load would be much lower considering that people open their windows at night in summer, compared to the operational conditions of the regulation considered here (corresponding to the Spanish regulation).

The heating system is a natural gas boiler, with an efficiency equal to 0.92, and an electric heat pump for the cooling, with EER (Energy efficiency ratio) equal to 2.00. Hot water is produced by solar thermal energy (60%) and natural gas boiler (40%). As previously exposed, those are the efficiency values of the reference systems in the Spanish regulation.

The structure of the original building is maintained, and no structural intervention is considered.

2.1.3. New building

For the new building the same volume, living area and distribution is considered in order to be able to compare solutions. As the building is protected by a heritage regulation, the same architectural configuration must be ensured.

The new building structure is also of reinforced concrete. The slabs additionally include polystyrene pieces to lighten them and they are finished with ceramic tiles laid on mortar. The external walls are made of concrete blocks with external insulation of glass wool covered with mortar. The internal layer is finished with gypsum. The building has a traditional tile roof insulated with glass wool.

The internal walls of the building are made of concrete blocks with glass wool and gypsum.

As in the case of the refurbishment, the difference between the demolition plus standard new building (SD&N) and the demolition plus passive new building (PD&N), are the insulation layer thickness and the windows. In the case of SD&N, the thicknesses of the glass wool in the façade, roof and ground floor are 17 cm, 20 cm and 10 cm, respectively. The windows are of wood frame with double glazing 6/16/6 with argon (U = 1.85 W/m^2.K). In the case of the PD&N, the thicknesses of the glass wool in the façade, roof and ground floor is 22 cm, 23 cm and 11 cm, respectively. The windows are of wood frame with triple low emissivity glazing with argon (U = 1.09 W/m^2.K).

The heating and cooling demand of the new building according to the regulation are 27 kWh/m^2 and 6 kWh/m^2, respectively. In the passive building the heating and cooling demand are 15 kWh/m^2 and 12 kWh/m^2, respectively.

The considered heating and cooling systems are similar to those of the refurbished building (natural gas boiler with 0.92 efficiency, and heat pump with EER of 2.00). Hot water is produced by solar thermal energy (60%) and natural gas boiler (40%).

The considered structure is similar to that of the original building. To simplify, all the beams in the new building are considered to be of the same cross section of 300 mm width - 350 mm height, with a concrete cover of 30 mm. Tensile and compressive rebar areas are 1257 mm^2 and 157 mm^2, respectively. It is supposed that all the beams need to support the same load (maximum bending moment of 140 kN m). Material properties fulfil structural regulation requirements [42] and are showed in Table 1.

2.2. Determining the lifespan using the durability-based approach

As already exposed, the considered building lifespan is that of its structure. In this paper, we consider the degradation phenomenon of corrosion due to carbonation since it is the most frequent one.

The methodology followed is the one defined in Ref. [30], for this type of degradation.

The applied method is based on iterative structural calculations, in which the mechanical characteristics are updated in every step according to the degradation model. In this case, the iteratively updated parameter is the rebar section that decreases as the corrosion increases. It must be noted that corrosion can also lead to other mechanical effects

Table 1
Material properties of original and new building structure.

Material	Existing				New			
	f_d [MPa]	γ	E_c [MPa]	f_{ctm} [MPa]	f_d [MPa]	γ	E_c [MPa]	f_{ctm} [MPa]
Concrete	11.77[b]	1.5	22,983[a]	1.50[a]	25	1.5	30,000[a]	2.20[a]
Inner rebars	117.68[b]	1.15	180,000[b]	–	500	1.15	200,000	–

[a] Equation in Eurocode 2 [40].
[b] Usual materials in Spain in 1956, according to Ref. [41].

that influence the lifespan, such as the bonding loss between steel and concrete, and the cracking of concrete cover due to the increase in volume of the oxides with respect to the original volume of the parent steel [34]. However, these effects are not considered here due to the scope of this paper which is just to provide a rough value that can be used in LCA.

Corrosion is a localized phenomenon and occurs in specific structural elements (i.e. a beam or a column). To extend the method to a whole building some simplifications have been made in order to narrow the problem. On the one hand, the different structural elements of the building are exposed to environments with different levels of aggressiveness (interior, exterior, etc.) and corrosion damage might not be the same for all of them. This study focuses just on beams because they are more sensitive to rebar section losses than columns. Beams are classified, depending on their exposure conditions, into: indoor, outdoor, below the roof or in contact with sanitary floor slab. Therefore, the degradation model is applied to four types of beams.

The shortest value that is obtained is considered as the building lifespan. This can lead to a lower value than the potential one, but it remains on the security side. This same hypothesis is used for both R and D&N.

Two improvements are made to the methodology proposed by Ref. [30]. The first of them is explained next. To model the initiation time of corrosion, the model proposed in the fib Model Code (MC2010) [43] is applied, instead of the model proposed by V.-L. Ta et al. [33] which was used in Ref. [30]. This is because the model proposed in MC2010 provides statistical data of the distributions and deviations of the input parameters. This allows to calculate the deviation of the final result as well as the probability associated to a certain data of lifespan which is important due to the considerable uncertainty in the determination of this parameter.

To estimate the lifespan of a structural element like a beam or a column, affected by corrosion, different steps must be taken.

(i) First, the time when corrosion is likely to start (initiation time, t_i) must be obtained. To do this the model in the MC2010 is applied.
(ii) Secondly, the propagation of corrosion with time, this is, the loss of reinforcement bars section with time, must be calculated. This phenomenon depends on the corrosion rate, v_{corr}. This value must be measured and is not constant with time. However, when no data are available, it can be approximated by the values from Table 2 adapted from Ref. [44] depending on the Eurocode 2 [40] exposure classes. The standard deviation of this parameter is taken from Ref. [45] to make an estimation.

Usually, the design value of the beam's capacity is bigger than the required capacity. This is because reinforcing bars diameters are standardised and a combination of them must be chosen to, at least, overcome the required capacity. In the corrosion process the diameter of the reinforcing bars decreases with time. The admissible limit is set at the moment when the design value of the resistance of the beam is strictly equal to the supported bending moment.

Table 2
Representative values for Vcorr for the Eurocode 2 exposure classes [44].

(iii) Thirdly, an admissible limit in the structural performance must be defined. This is the second improvement we have made to the method proposed by Ref. [30]. In Ref. [30], the authors leave the selection of the admissible limit entirely to the technician, whereas we propose the use of the partial factor method and its adaptation to existing structures [46]. Next, we explain this method.

Exposure class	V_{corr} [μm/year]
XC1	0
XC2	4
XC3	2
XC4	5

The design of structures according to Eurocodes is based on the concept of limit states and their verification by the partial factor method [46]. In the structural assessment process there are uncertainties related to the determination of the loads, material properties, geometry, etc. To obtain the design value, different partial safety factors are introduced that need to be applied to materials properties and loads to ensure a certain reliability level. These factors are defined in the regulation in the case of new structures. For concrete and steel, they are 1.5 and 1.15, respectively.

When existing structures are assessed, the uncertainty regarding the available information is different. Therefore, to ensure the same reliability level than in new structures, the value of the partial factors are different. The same target reliability index (β = 3.8) has been assumed for both existing and new buildings. Assuming that the tests of material properties yield to coefficients of variation $V_c = 0.15$ and $V_s = 0.05$ [46] and the variability of geometrical uncertainties is insignificant, material factors for concrete and steel are 1.353 and 1.097, respectively.

(iv) Finally, iterative calculation must be done considering in every step the appropriate diameter of the rebar, according to degradation models. To do this, as already explained, t_i and v_{corr} are needed. Those are not deterministic values but can be described by means of a normal distribution defined by a mean value and a standard deviation. To assess the mean and standard deviation of the final result from the structural calculation, the structural model is approximated to a quadratic Taylor series.

The time when the admissible limit is reached is taken as the lifespan value of the analysed building. The lifespan of R is the difference between the lifespan of the existing building and the time when the refurbishment is done. This is because the refurbishment that is considered in this paper does not improve the structure but just the building's thermal performance.

2.3. LCA

LCA methodology is applied to evaluate four solutions: SR, PR, SD&N, and PD&N. The alternatives are evaluated according to the Global Warming Potential (GWP) indicator, based on 2007 IPCC v1.02 methodology, and using the Ecoinvent (v2.2) database [47] adapted to the Spanish electric mix of 2017, with the software tool EQUER [48]. This indicator is chosen because it is among the most widely used [9], as in Refs. [10,11].

The functional unit of these LCAs is housing 80 adults in a collective apartment building of 1257 m^2 living area, maintaining the architectural configuration of a 60 years old existing building, ensuring at least the fulfilment of the current energy demand regulation, during the lifespan of the building. The reference flow corresponds to 1 m^2 and 1 year.

The system boundaries include product stage, use stage and end-of life stage. Construction stage impacts as construction machinery are out of the boundaries of this system. Product stage includes raw materials extraction, transportation, manufacture of construction materials and transportation. Use stage includes the energy used for heating and domestic hot water, taking into account the thermal solar system. No cooling or mechanical ventilation energy consumption has been considered. Use stage also includes maintenance and renovation of elements according to the hypothesis exposed below. In the end-of-life stage materials that are considered to be recyclable are computed as end-of-life stage impact equal to zero but avoided impacts are out of the system boundaries. In relation to the cutting rules, the main materials are computed until the level of the painting. Materials and quantities that are taken into account in every solution are displayed in Appendix A, Table A1, A2, A3, A4 and A5.

The reference study period corresponds to the period from the renovation or construction work until the end of life of the structure. In every alternative (SR, PR, SD&N, PD&N) the estimated lifespan is considered.

The common hypotheses in the LCA include:

(i) No transport of occupants and no household waste is included in the studied system.
(ii) Water consumption (per person and day): Hot water 40 l, Cold water 100 l and mains water efficiency: 80%.
(iii) Constant electric mix (22% nuclear, 33% renewable, 17% carbon and 28% gas); grid losses 9%.
(iv) Surplus of materials during construction: 5%.
(v) Transport distance for materials: Production site to construction site, 100 km; site to recycling, 100 km; site to inert landfill and to incineration, 20 km.
(vi) Service life of windows and doors, 30 years; equipment, 20 years; coating, 10 years.

Building materials quantities are derived from the geometry and composition of walls, floors and roof. Equipment is also considered (boiler, cooling system and solar thermal panels). Besides, the following building services materials are added, including plumbing (sanitary equipment, drinking water and wastewater system), electrical and telecommunication services. We proceeded by considering fixed ratios of these elements per m^2 of floor (Table 3).

In relation to the end of life stage, reinforced concrete and metals are considered to be recyclable in order to follow the European Waste Directive 2008/98/CE [49] that imposes to recycle 70% of building related waste. Although they are not being totally recycled in Spain nowadays [50], we make the assumption that in the future, when the demolition stage takes place, this will have changed according to this regulation. Wood and plastics are considered to be incinerated, and the rest of materials landfilled.

3. Results and discussion

3.1. Dependence of the kg CO2-eq./m^2 year indicator on lifespan

Prior to estimating the lifespan, we have made a theoretical study of the impacts of five solutions along a time period of 150 years considering an existing building of 50 years old. In Fig. 1 the kg CO_2-eq./m^2 of the different solutions are plotted.

As can be seen in Fig. 1, depending on the year of analysis, the best solution would be different. For example, after a time lapse of 50 years since the intervention both types of R obtain better results than D&N. In contrast, if a time lapse of 150 years is considered, SR has equivalent impact to PD&N. This type of analysis has the implicit assumption that R and D&N have the same lifespan. This is usual practice in comparative LCA of R and D&N. However, this is not likely to happen.

The total amount of kg CO_2-eq./m^2 depends on the number of years considered. For this reason, the results are usually annualised and

Table 3
Materials ratios considered plumbing and electricity.

Element	Unit	Ratio per m^2
Copper	kg	4,36E-01
Steel	kg	1,31 E+00
PVC	kg	2,72E-01
Ceramic	kg	2,50 E+00
Polyethylene	kg	6,50E-01
3-conductor cable	m	6,25 E+00

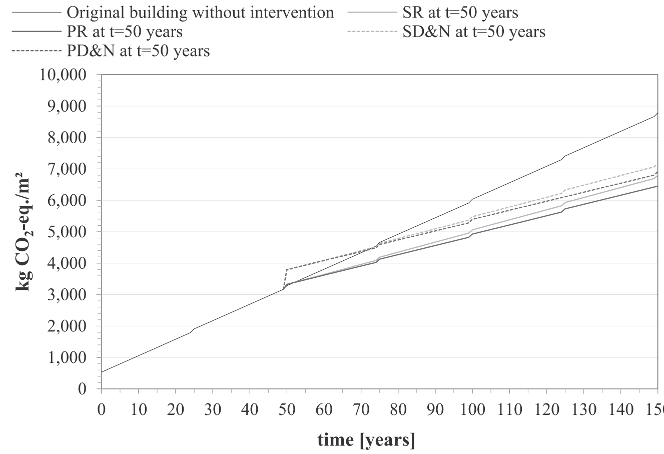


Fig. 1. kg CO2-eq./m^2 of the original building and different intervention alternatives at t = 50 years: SR, PR, SD&N and PD&N.

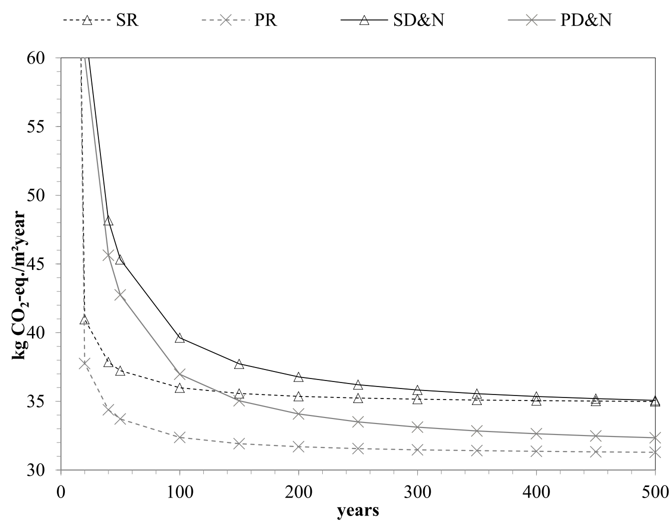


Fig. 2. GWP indicator (kg CO2-eq./m^2 year) depending on the analysed years.

transformed into kg CO_2-eq./m^2·year. This allows to compare different stages and different buildings. However, this does not correct the problem of different lifespans. Even if the results are annualised, the value of this indicator is still strongly dependent on time, as can be seen in Fig. 2. When the considered lifespans are below 200 years the value of the indicator is sensitive to time. A nearly constant tendency is only reached after long periods of time that do not correspond to the commonly used lifespans in the LCA of buildings.

In addition, when comparing R and D&N, the lifespan of the refurbished and the new building will not probably be the same. It is reasonable to think that a new building will have a longer lifespan than a similar one built 60 years ago. This is because the new building will comply with current regulation, and therefore will consider phenomena that were not even known before (as AAR) and will include strong control procedures. Additionally, if the same lifespan is considered for both R and D&N, it is as if the opposite assumption was done (the existing buildings lasts longer), because in R 50 years have already elapsed.

For this reason, we consider that estimating lifespans is necessary to obtain more robust results in LCAs of buildings.

3.2. Lifespan results

According to the methodology exposed in 2.2, the structural capacity decreases with time. In Fig. 3, the case of the existing building is

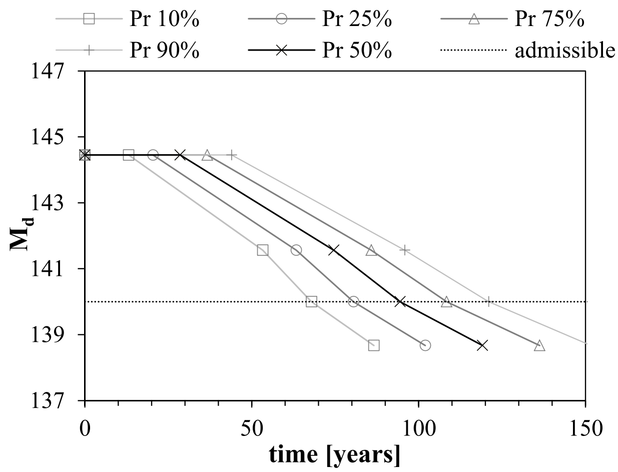


Fig. 3. Decrease of the bending resistance of the original building beam with time.

presented. The structural element, in this case, a beam of the original building, has an initial bending resistance of 144.45 kN m, in design value. A final resistance of 140 kN m is considered to be the admissible limit in this case study. The admissible limit is reached before 80 years with 25% probability, before 95 years with 50% probability (mean value) or before 110 with 75% probability.

In Table 4 the values of lifespan for the different structural elements of both the original and the new building are shown.

As exposed in 2.2, the smaller value (the most adverse) is chosen as the structure lifespan. In Table 5 the values actually used for the lifespan of the whole building for the different alternatives are presented. As previously mentioned, in real practice, physical degradation is not the only cause of building demolition. Deterioration was the cause of only 17% of the projects [28] > .

In the case of Spain, statistical lifespan data, depending on their construction period, can be found in Rincón et al. [51]. This value is also included in Table 5.

As can be seen in Table 5, the new building has a lifespan 2.2 times greater than the original one, for the same structural reliability level. If we also take into account that a part of the lifespan of the existing building has already elapsed at the time of refurbishment, the lifespan of the new building is about 6 times longer than the refurbished, in this case study.

3.3. Results obtained taking into account the calculated value of lifespan

In Fig. 4 the value of kg CO_2/m^2.year is shown taking into account a lifespan of: (a) 100 years for all the solutions (as default value, similar to usual practice), (b) the durability-based estimation of lifespan for each of the solutions, and (c) the statistical data of lifespan according to

Table 5
Lifespan results.

	Estimated lifespan		Average lifespan of buildings considering also other factors than degradation [51]
	mean	deviation	
Original building	94.45	20.77	90
SR at t = 60	34.45	20.77	30
PR at t = 60	34.45	20.77	30
SD&N	210.03	47.93	80
PD&N	210.03	47.93	80

Ref. [51], which is also different for each solution. In Fig. 4 b), the results obtained considering the mean value of the lifespan, the mean plus its standard deviation and the mean minus its standard deviation are displayed.

According to these results, when the same lifespan is considered (Fig. 4a), PR is, by large, the best alternative, but this is not a reliable result as discussed before. PR also results to be the best option when the statistical values of lifespan are considered (Fig. 4c), although the difference with the other alternatives is significantly reduced. According to Fig. 4b PR is the second best option. Therefore, we can conclude that PR is one of the best alternatives from the point of view of CO_2 emissions.

PD&N obtains the best results when the estimated lifespans are considered (Fig. 4b). However, it requires to ensure a very long lifespan (around 210 years) which is very difficult to guarantee in practice.

SR is the worst solution when lifespans are estimated using degradation models (Fig. 4b). This reveals that SR requires a CO_2-eq. investment which does not provide an optimal performance of the building and its useful life is short. Refurbishment should therefore aim to reach passive standards to optimise the CO_2-eq. investments.

The estimated value of lifespan has an uncertainty that derives from the degradation model. This uncertainty has different effects in the results of the kg CO_2-eq./m^2·year indicator. In the case R solutions, the influence of this uncertainty in the results is higher because the lifespan is shorter. This is aligned with the findings in Fig. 2. For short lifespans, the value of the indicator significantly varies with little time increments. This is because the contribution of the construction and demolition stages to the global impact is high. On the contrary, in the case of new buildings, as their lifespan is long, the value of the indicator is almost established, and it is not so sensitive to changes. In the case of the new buildings, the uncertainty is produced mostly because of the huge difference between the estimated physical lifespan and the statistical data rather than because of the durability model. This statistical data takes into account that buildings are often demolished for reasons other than degradation.

Comparing Fig. 4b and b, the reductions in CO2-eq. annual emissions using durability-based lifespans instead of statistical lifespans are up to 1,36% for SR, 1.52% for PR, 10.66% for SD&N and 11.40% for PD

Table 4
Calculated lifespan data depending on the element.

	t_i [years]			v_{corr} [mm/año]			Serivce life [years]	
	mean	σ	Dist.	mean	σ	Dist.	mean	σ
Original building 1956								
Exterior beam	28.54	12.09	Normal	0.005	0.00125	Normal	94.45	20.77
Sanitary slab beam	33.32	13.65	Normal	0.004	0.00100	Normal	125.60	28.76
Interior beam	22.04	9.03	Normal	0	0	Normal	–	–
Roof beam	33.32	13.65	Normal	0.002	0.00050	Normal	204.25	44.34
New building 2018								
Exterior beam	40.80	17.54	Normal	0.005	0.00125	Normal	210.03	47.93
Sanitary slab beam	47.48	19.70	Normal	0.004	0.00100	Normal	249.5	53.78
Interior beam	31.40	13.03	Normal	0	0	Normal	–	–
Roof beam	47.48	19.70	Normal	0.002	0.00050	Normal	456.5	104.18

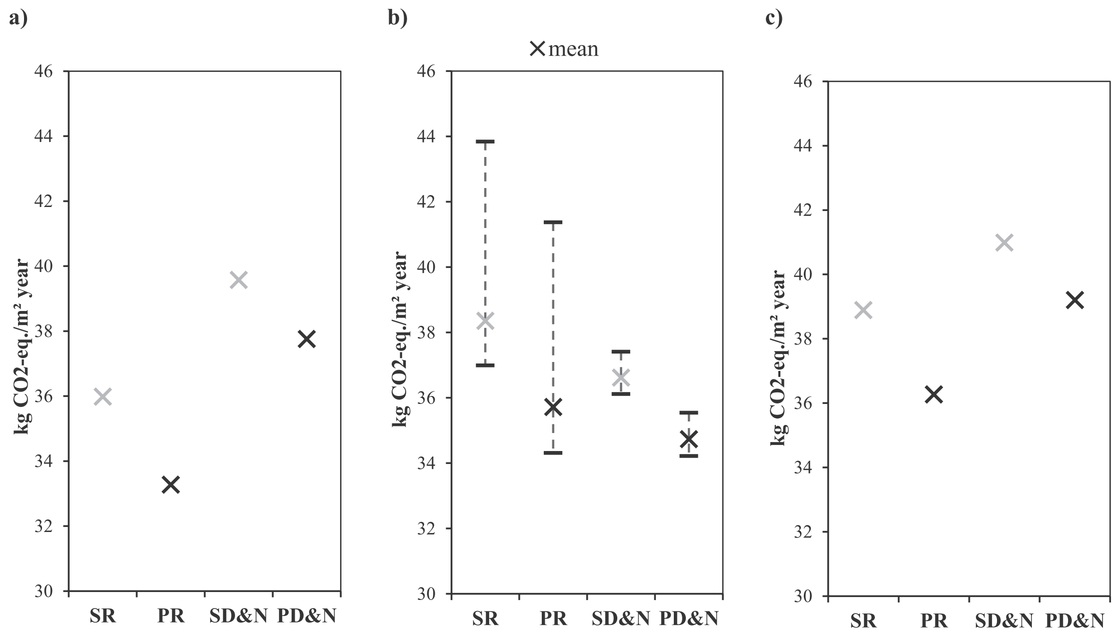


Fig. 4. kg CO2-eq./m^2 year taking into account: (a) 100 years for all the alternatives; (b) their specific durability-based estimation for lifespan according to Table 5; and (c) their statistical lifespan according to Ref. [51].

&N. These percentages represent the improvement margin in sustainability if we extend the service life of buildings up to the physical limit of its original structures. The low reductions in the case of R are due to the fact that the difference between the statistical and the durability-based estimation of the buildings lifespan is small, just of 4.45 years (Table 5). The reduction in D&N is more significant because so is the difference between the two estimations of lifespans, of 130.03 years (Table 5).

3.4. Limits of the study

The estimated lifespans can be considered optimistic, since degradation is not the main cause of building demolition, as already mentioned. In addition, not all the degradation models have been included but just corrosion, which is the most common one. However, the results illustrate the durability of reinforced concrete structures considering its physical potential. This gives us an idea of the environmental benefit margin compared to usual demolition trends.

It must also be noted that results are case dependent as each building has its own durability depending on the concrete, the exposure conditions, etc. The available options both for refurbishment and new building are multiple. Anyhow, the methodology proposed can be extended to other cases.

Static life cycle inventory data were used, but there is uncertainty regarding their long-term values (e.g. electricity mix, production processes, etc.). This long-term uncertainty does exit also regarding energy demand, as climate change can lower the heating loads and increase the cooling ones. In addition, the cooling needs could be lower by incorporating solar blinds or increasing night ventilation. In this study we considered the operational conditions of current regulations in Spain.

4. Conclusions

In this paper refurbishment (R) versus demolition and new building (D&N) have been evaluated from an environmental point of view, using three different approaches to determine lifespans: a) the broadly used method of taking a default value for all the buildings compared, b) a new approach proposed here that allows to make a durability-based estimation of the different lifespans of the buildings in a comparative LCA, and c) an estimation based on lifespans statistical data for each building compared. Two energy performance levels have been analysed, standard (S) and passive (P), resulting in four alternatives: SR, PR, SD&N, PD&N.

The main conclusions can be summarised as follows:

- Estimating the different lifespans of each specific building compared is fundamental in buildings LCA, especially when comparing R with D&N, where the differences can be significant. In this case study the difference in the lifespan of the refurbished and the new building is up to 176 years.
- Considering the same lifespan for both the refurbished and the new building, as it is done in common practice, can lead to important errors in the results. In this case study, the difference in the results obtained when a fixed 100 years value for both the refurbished and the new building is assumed, and results obtained when the lifespan is estimated using a durability-based approach is of 6.50%, 7.36%, −7.53% and −8.02% for the SR, PR, SD&N and PD&N alternatives. This implies that in the comparison of SR and SD&N alternatives a cumulative difference of 14.03% is obtained. In the comparison of PR and PD&N the difference is of 15.38%. It must be noted, that in this study a 100 years lifespan is considered as the "default value" alternative. If a 50 years lifespan for both the refurbished and the new building had been considered in the analysis, as it is often done in LCA, the difference in the results would be even greater.
- Statistical studies of buildings lifespan provide more realistic results. In this case, 30 and 80 years for the refurbished and the new building compared to the estimated lifespan value of 34 and 210 years, for the refurbished and the new building. However, they reflect human behaviour regarding buildings lifespan, this is, that buildings tend to be demolished before they reach their physical end of life, but not their potential physical durability. In addition, although they can be accurate in general terms, they might not be accurate for the particular building that is being analysed.
- Extending the service life of buildings is a good strategy towards sustainability. Lifespans of 210 years should be promoted in new buildings, particularly using LCA thinking in their design, by defining adaptable building structures allowing changing the use of buildings (flexibility between housing and tertiary uses, adaptability

according to the changing need of spaces). This paper shows that reductions around 11% in CO2-eq. annual emissions can be achieved with such a lifespan compared to a statistical value of 80 years. Therefore, increasing buildings lifespan is one of the important ways to progress towards sustainability.

Acknowledgements

This work was funded by the Spanish Ministry of Education, Culture and Sports, through a FPU research grant [grant FPU15/01069], by Gobierno de Aragón (Research Group GIA T37_17R) and by FEDER 2014–2020 "Construyendo Europa desde Aragón".

Appendix A

In this appendix, materials that have been taken into account in the different LCAs are displayed.

Materials considered for the equipment are similar for all the standard refurbishment (SR), passive refurbishment (PR), standard demolition and new building (SD&N) and passive demolition and new building (PD&N) options. They are presented in Table A1.

Table A1
Materials considered as equipment in SR, PR, SD&N and PD&N alternatives

Name	Weight [Kg]	Volume [l]	Length [m]	Unit [−]	Surface [m^2]
Galvanised steel	1320.310				
Aluminium (50% recycled)	400.57				
Clay	2514.938				
Tank for DHW	375	375			
Electric cable	6287.20		6287.20		
Gas boiler				1	
Cobre	438.143				
PVC	273.938				
Ventilation system 720 m^3/h				1	
Solar thermal system					40
Polyethylene	653.869				

The constructive materials that have been considered in the LCA of the SR, PR, SD&N and PD&N alternatives are presented in Table A2, Table A3, Table A4 and Table A5, respectively. In SD&N and PD&N alternatives the environmental impacts associated to the existing building demolition are added to the final result. That is why no demolished materials weight are included in Table A4 and Table A5.

Table A2
Constructive materials considered in SR alternative

Name	Weight [Kg]	Surface [m^2]
Alloyed Steel	220.00	
Glass wool	2017.54	
Cement mortar	67,465.60	
Double glazing wood window		221.44
Inert waste from demolished materials	2,056,197.16	

Table A3
Constructive materials considered in PR alternative

Name	Weight [Kg]	Surface [m^2]
Alloyed Steel	220.00	
Glass wool	3037.16	
Cement mortar	67,465.60	
Triple glazing wood window		221.44
Inert waste from demolished materials	2,056,197.16	

Table A4
Constructive materials considered in SD&N alternative

Name	Weight Kg	Surface [m^2]
Gypsum	101,395.47	
Glass wool	2828.90	
Wood interior door		27.09
Cement mortar	195,909.28	
Ceramic tiles	9679.54	
Brick	74,073.38	
Ceramic lighten pieces in slabs	90,342.42	

(*continued on next page*)

Table A4 (*continued*)

Name	Weight Kg	Surface [m^2]
Double glazing wood window		221.44
Reinforcing steel for concrete	3435.77	
Concrete	1,412,996.23	

Table A5
Constructive materials considered in PD&N alternative

Name	Weight Kg	Surface [m^2]
Gypsum	101,395.47	
Glass wool	3098.97	
Wood interior door		27.09
Cement mortar	195,909.28	
Ceramic tiles	9679.54	
Brick	74,073.38	
Ceramic lighten pieces in slabs	90,342.42	
Triple glazing wood window		221.44
Reinforcing steel for concrete	3435.77	
Concrete	1,412,996.23	

References

[1] COM, Communication from the Commission to the Council and the European Parliament Integrated Product Policy Building on Environmental Life-Cycle Thinking, vol. 302, (2003), https://doi.org/10.1117/1.NPh.2.2.025001.
[2] European Commission, Commission Recommendation (EU) 2016/1318, (2016).
[3] B. Palacios-Munoz, L. Gracia-Villa, I. Zabalza-Bribián, B. López-Mesa, Simplified structural design and LCA of reinforced concrete beams strengthening techniques, Eng. Struct. 174 (2018) 418–432, https://doi.org/10.1016/j.engstruct.2018.07.070.
[4] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (2009) 2510–2520, https://doi.org/10.1016/j.buildenv.2009.05.001.
[5] I. Zabalza Bribián, A. Valero, A. Aranda Usón, E. Llera, Methodological Aspects and Design Implications to Achieve Life Cycle Low Emission Buildings. A Case Study: LCA of a New University Building, (2013) Strojarstvo.
[6] O. Ortiz-Rodríguez, F. Castells, G. Sonnemann, Life cycle assessment of two dwellings: one in Spain, a developed country, and one in Colombia, a country under development, Sci. Total Environ. 408 (2010) 2435–2443, https://doi.org/10.1016/j.scitotenv.2010.02.021.
[7] R.M. Cuéllar-Franca, A. Azapagic, Environmental impacts of the UK residential sector: life cycle assessment of houses, Build. Environ. 54 (2012) 86–99, https://doi.org/10.1016/j.buildenv.2012.02.005.
[8] F. Nemry, A. Uihlein, C.M. Colodel, C. Wetzel, A. Braune, B. Wittstock, I. Hasan, J. Kreißig, N. Gallon, S. Niemeier, Y. Frech, Options to reduce the environmental impacts of residential buildings in the European Union-Potential and costs, Energy Build. 42 (2010) 976–984, https://doi.org/10.1016/j.enbuild.2010.01.009.
[9] A. Vilches, A. Garcia-Martinez, B. Sanchez-Montañes, Life Cycle Assessment (LCA) of Building Refurbishment: A Literature Review, Energy Build, 2017, https://doi.org/10.1016/j.enbuild.2016.11.042.
[10] A.A. Famuyibo, A. Duffy, P. Strachan, Achieving a holistic view of the life cycle performance of existing dwellings, Build. Environ. 70 (2013) 90–101, https://doi.org/10.1016/j.buildenv.2013.08.016.
[11] H. Mohammadpourkarbasi, S. Sharples, Eco-retrofitting very old Dwellings : current and future energy and carbon performance for two UK cities, PLEA 2013 Sustain. Archit. A Renew, Futur, Munich (Germany), 2013.
[12] B. Peuportier, Assessment and design of a renovation project using life cycle analysis and Green Building Tool, in: T.D. Pettersen (Ed.), Proc. Int. Conf. - Challenge, Knowledge, Solut. house publishing, Orlo, 2002, pp. 352–357.
[13] G. Assefa, C. Ambler, To demolish or not to demolish: life cycle consideration of repurposing buildings, Sustain. Cities Soc. 28 (2017) 146–153, https://doi.org/10.1016/j.scs.2016.09.011.
[14] G. Ding, Demolish or refurbish–Environmental benefits of housing conservation, Australas. J. Constr. Econ. Build. 13 (2013) 18–34, https://doi.org/10.5130/ajceb.v13i2.3322.
[15] M.D. Alba-Rodríguez, A. Martínez-Rocamora, P. González-Vallejo, A. Ferreira-Sánchez, M. Marrero, Building rehabilitation versus demolition and new construction: economic and environmental assessment, Environ. Impact Assess. Rev. 66 (2017) 115–126, https://doi.org/10.1016/j.eiar.2017.06.002.
[16] Y. Schwartz, R. Raslan, D. Mumovic, The life cycle carbon footprint of refurbished and new buildings – a systematic review of case studies, Renew. Sustain. Energy Rev. 81 (2018) 231–241, https://doi.org/10.1016/j.rser.2017.07.061.
[17] W. Pan, K. Li, Y. Teng, Rethinking system boundaries of the life cycle carbon emissions of buildings, Renew. Sustain. Energy Rev. 90 (2018) 379–390, https://doi.org/10.1016/j.rser.2018.03.057.
[18] H. Islam, M. Jollands, S. Setunge, Life cycle assessment and life cycle cost implication of residential buildings - a review, Renew. Sustain. Energy Rev. 42 (2015) 129–140, https://doi.org/10.1016/j.rser.2014.10.006.
[19] R. Marsh, Building lifespan : effect on the environmental impact of building components in a Danish perspective, Architect. Eng. Des. Manag. 13 (2017) 80–100 https://doi.org/10.1080/17452007.2016.1205471Check.
[20] K. Adalberth, A. Almgren, E.H. Petersen, Life-cycle assessment of four multi-family buildings, Int. J. Low Energy Sustain. Build. 2 (2001) 1–21.
[21] C.D. Frenette, C. Bulle, R. Beauregard, A. Salenikovich, D. Derome, Using life cycle assessment to derive an environmental index for light-frame wood wall assemblies, Build, Environ. Times 45 (2010) 2111–2122, https://doi.org/10.1016/j.buildenv.2010.03.009.
[22] U. Iyer-Raniga, J.P.C. Wong, Evaluation of whole life cycle assessment for heritage buildings in Australia, Build. Environ. 47 (2012) 138–149, https://doi.org/10.1016/j.buildenv.2011.08.001.
[23] O. Ortiz, C. Bonnet, J.C. Bruno, F. Castells, Sustainability based on LCM of residential dwellings: a case study in Catalonia, Spain, Build. Environ. (2009), https://doi.org/10.1016/j.buildenv.2008.05.004.
[24] K. Adalberth, Energy use during the life cycle of single-unit dwellings: examples, Build, Environ. Times 32 (1997) 321–329, https://doi.org/10.1016/S0360-1323(96)00069-8.
[25] I.M. Johnstone, Energy and mass flows of housing: a model and example, Build. Environ. 36 (2001) 27–41, https://doi.org/10.1016/S0360-1323(99)00065-7.
[26] H. Bergsdal, H. Brattebø, R.A. Bohne, D.B. Müller, Dynamic material flow analysis for Norway's dwelling stock, Build. Res. Inf. 35 (2007) 557–570, https://doi.org/10.1080/09613210701287588.
[27] M. Aksözen, U. Hassler, N. Kohler, Reconstitution of the dynamics of an urban building stock, Build. Res. Inf. (2017), https://doi.org/10.1080/09613218.2016.1152040.
[28] B. Marteinsson, Service Life Estimation in the Design of Buildings, University of Gävle, 2005.
[29] A. Haapio, Service Life of a Building in Environmental Assessment of Buildings, (2008).
[30] B. Palacios-Munoz, B. López-Mesa, L. Gracia-Villa, Influence of refurbishment and service life of reinforced concrete buildings structures on the estimation of environmental impact, In press, Int. J. Life Cycle Assess. 18 (2019), https://doi.org/10.1007/s11367-019-01622-w.
[31] J. Monjo Carrió, Durability vs vulnerability, Inf. La Construcción. 59 (2007) 43–58, https://doi.org/10.3989/ic.2007.v59.i507.531.
[32] H. Budelmann, A. Holst, A. Wachsmann, Durability related life-cycle assessment of concrete structures : mechanisms , models , implementation, in: F.B. Strauss (Ed.), Life-Cycle Sustain. Civ. Infrastruct. Syst. Taylor and Francis Group, 2013, pp. 75–86.
[33] V.L. Ta, S. Bonnet, T. Senga Kiesse, A. Ventura, A new meta-model to calculate carbonation front depth within concrete structures, Constr. Build. Mater. 129 (2016) 172–181, https://doi.org/10.1016/j.conbuildmat.2016.10.103.
[34] F. Pedrosa, C. Andrade, Corrosion induced cracking: effect of different corrosion rates on crack width evolution, Constr. Build. Mater. 133 (2017) 525–533, https://doi.org/10.1016/j.conbuildmat.2016.12.030.

[35] K. Tuutti, Corrosion of steel in concrete, Swedish Cem, Concr. Res. Inst. (1982) 469, https://doi.org/10.4324/9780203414606_chapter_2.
[36] S.W. Tang, Y. Yao, C. Andrade, Z.J. Li, Recent durability studies on concrete structure, Cement Concr. Res. 78 (2015) 143–154, https://doi.org/10.1016/j.cemconres.2015.05.021.
[37] Ministry of Development (Spain), Proyecto de Real Decreto por el que se modifica el Real Decreto 314/2006, de 17 de marzo, por el que se aprueba el Código Técnico de la Edificación_Anejo I DB HE Ahorro de Energía, (2018), pp. 1–51.
[38] Passive House Institute, Criteria for the Passive House, EnerPHit and PHI Low Energy Building Standard, 2016.
[39] B. Peuportier, I. Blanc Sommereux, Simulation tool with its expert interface for the thermal design of multizone buildings, Int. J. Sol. Energy 8 (1990) 109–120.
[40] European Union, EN-1992-1-1: Eurocode 2: Design of Concrete Structures - Part 1-1 : General Rules and Rules for Buildings, The European Union Per Regulation 305/2011, Directive 98/34/EC, Directive 2004/18/EC, 2004. papers2.
[41] I.E. Torroja, H.A. Instrucción, 61 Especial para estructuras de hormigón armado, (1961).
[42] Ministry of Development (Spain), Instrucción de Hormigón Estructural (EHE-08), (2008), https://doi.org/10.1017/CBO9781107415324.004.
[43] The international federation for structural concrete (fib), model code 2010, Fib Model Code Concr. Struct 2011 (2010) 114–148, https://doi.org/10.1002/9783433604090.ch6.
[44] C. Andrade, Modelos de propagación del deterioro del hormigón, REHABEND 2018, Constr. Pathol. Rehabil. Technol. Herit. Manag. University of Cantabria, Cáceres (Spain), 2018, pp. 835–842.
[45] M. Šomodíková, D. Lehký, J. Doležel, D. Novák, Modeling of degradation processes in concrete: probabilistic lifetime and load-bearing capacity assessment of existing reinforced concrete bridges, Eng. Struct. 119 (2016) 49–60, https://doi.org/10.1016/j.engstruct.2016.03.065.
[46] International Federation for Structural Concrete (fib), Bulletin No 80, Partial Factor Methods for Existing Concrete Structures. Recommendation, (2016).
[47] R. Frischknecht, N. Jungbluth, H.-J. Althaus, G. Doka, T. Heck, S. Hellweg, R. Hischier, T. Nemecek, G. Rebitzer, M. Spielmann, Overview and Methodology, Ecoinvent Report No. 1, Dübendorf, Switzerland, (2004).
[48] B. Polster, B. Peuportier, I. Blanc Sommereux, P. Diaz Pedregal, C. Gobin, E. Durand, Evaluation of the environmental quality of buildings - a step towards a more environmentally conscious design, Sol. Energy 57 (1996) 219–230.
[49] European Parliament and the Council of the European Union, Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on Waste and Repealing Certain Directives, (2008).
[50] N. Bizcocho Tocón, Aplicación del análisis de ciclo de vida a la gestión de los residuos de construcción, University of Sevilla, 2014, https://idus.us.es/xmlui/handle/11441/56324.
[51] L. Rincón, G. Pérez, L.F. Cabeza, Service life of the dwelling stock in Spain, Int. J. Life Cycle Assess. 18 (2013) 919–925, https://doi.org/10.1007/s11367-013-0552-x.

PAPER 3

Palacios-Munoz, B., López-Mesa, B., & Gracia-Villa, L. (2018). "Structural design and comparative LCA of two strengthening techniques: Concrete beams under flexural loads". In L. Villegas, I. Lombillo, H. Blanco, & Y. Boffil (Eds.), Construction pathology, Rehabilitation technology and heritage management (Digital Book of Articles- REHABEND 2018, Euro-American Congress) (pp. 1609–1617). https://doi.org/2386-8198

CODE 105

STRUCTURAL DESIGN AND COMPARATIVE LCA OF TWO STRENGTHENING TECHNIQUES: CONCRETE BEAMS UNDER FLEXURAL LOADS

Palacios-Munoz, Beatriz[1]*; López-Mesa, Belinda[2]; Gracia Villa, Luis[3]

1: School or Engineering and Architecture, Department of Mechanical Engineering
University of Zaragoza
e-mail: bpalacios@unizar.es

2: School or Engineering and Architecture, Department of Architecture
University of Zaragoza
e-mail: belinda@unizar.es

3: School or Engineering and Architecture, Department of Mechanical Engineering
University of Zaragoza
e-mail: lugravi@unizar.es

KEYWORDS: Environmental impact; Life Cycle Assessment; reinforced concrete strengthening.

ABSTRACT

The recognized environmental benefits of upgrading existing reinforced concrete structures or extending their service life have led to the need of including environmental criteria when a structural intervention is designed. Life Cycle Assessment (LCA) is a methodology to assess environmental impacts associated to a product or a process which considers energy, materials, and emissions over its whole life.

This study presents a LCA comparison between two techniques used when reinforcing concrete beams: steel sheets, placed with metallic anchors and epoxy resin, and carbon fibre reinforced plastic laminates (CFRP laminates) attached with epoxy resin. The objective is to provide environmental decision criteria as well as scientific data able to be incorporated in a whole building LCA.

Results reveal that the environmental impact of carbon-fibre production is greater than that of steel. Nevertheless, the whole CFRP reinforcement has a better environmental behaviour compared to steel/epoxy due to the mechanical properties of CFRP that leads to a reduction of the required material. Using metallic anchors results in a significant reduction of environmental impact revealing the responsibility of epoxy resin and the importance of considering the constructive process.

1. INTRODUCTION

Energy saving is a major concern in Europe and existing building stock is one of the biggest challenges, as they account for nearly 40% of final energy consumption and about 35-50% of CO2 emissions of EU in 2011 [1]. Buildings demand energy in their life cycle both directly (construction, operation, refurbishment and demolition) and indirectly (production of the materials and technical systems involved) [2]. To rigorously analyse the potential environmental impact of a building we must consider all these stages, which means that a life cycle approach is required. Life Cycle Assessment (LCA) is a methodology to assess environmental impacts associated to a product or process which considers energy, materials, and emissions over its whole lifespan [1]. This methodology is defined in the ISO 14040:2006 [3] and ISO 14044:2006 standards. Due to the convenience of applying this methodology to buildings, extended research has been produced in recent years (among others [1,4]). According to

Vilches et al. [1], most of studies regarding LCA of buildings are focused on energy refurbishment but almost none of them study the environmental impact of building system reparations, such as that of structure or finishing.

Building structure, due to the materials and processes involved, represents an important percentage of the total environmental impact of the construction phase (around 11.7 %, according to [5]). Besides, buildings have a considerably long life and throughout their service life, structural interventions might be needed if the building must be restructured to new functional goals and new loading requirements or due to technical wear. According to different authors and statistical data in Spain [6–9] most problems are shown in elements under bending forces (slabs plus beams). Depending on the magnitude, structure interventions can account for nearly 50% of original construction costs. Despite the lack of data regarding environmental impact of structural interventions, the stated data can be shown as an indicator that their impact might not be negligible.

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. Available strengthening techniques are abundant and decision criteria are needed regarding different parameters such as economy, functionality or environment.

Traditionally, the most popular way of strengthening reinforced concrete (RC) beams has been to stick or anchorage flat bars or steel plates on them [10]. Despite this method is highly effective, some associated drawbacks have facilitated the extended use of composite materials such as carbon fibre reinforced polymer (CFRP). As opposed to steel, CFRP materials do not corrode and are lighter and easier to apply and transport [10]. In addition, CFRP materials have superior mechanical properties such as a high strength to weight ratios. On the other hand, CFRP are stacked with epoxy resin which has a very low resistance to fire, while steel is usually placed both with epoxy resin and mechanical anchors. Together with technical considerations and aligned with EU interests, environmental impact must be analysed. Comparative LCA of those materials have been found in the automotive industry [11,12]. These studies constitute a valuable departure point, but cannot be directly extrapolated to buildings, as the construction process has its own particularities.

This study develops an environmental LCA comparison between these two materials and techniques: steel sheets and CFRP laminates. To be able to compare techniques, an equivalent behaviour must be ensured. In this study, firstly, structural assessment to obtain equivalent mechanical behaviour is made. Secondly, two comparative LCA are performed. The first one compares steel sheet and CFRP reinforcements, both attached with epoxy resin. Steel is also usually placed with metallic anchors, therefore, the second comparative LCA is between CFRP attached with epoxy and steel sheet placed with mechanical anchorages. Direct comparison between them is not possible as due to the limited resistance to fire of the epoxy resin, additional treatment must be added to the composite material to ensure equivalent behaviour to fire.

2. MATERIAL AND METHODS

This study is performed taking as a case study a RC beam of 6.00 m of span and cross section of 25 cm x 40 cm (b x h), with a concrete cover (c) of 2 cm. Mechanical properties of reinforcement and concrete are shown in Table 1. The analysis comprises two different parts: a structural assessment (section 2.1) and the comparative LCA of strengthening techniques (section 2.2).

Table 1. Properties of beam materials

Concrete		Inner rebar		New steel sheet		New CFRP	
Property	Value	Property	Value	Property	Value	Property	Value
f_{ck} [MPa]	16.00	f_{yk} [MPa]	400.00	f_{yk} [MPa]	400.00	f_{yk} [MPa]	3000.00
γ_c	1.50	γ_s	1.15	E_s [MPa]	200000	E_s [MPa]	165000
f_{cd}[MPa]	10.67	f_{yd}[MPa]	347.83				
E_c [MPa]	24260.00	E_s [MPa]	200000.00				
		A_{upper} [mm²]	157.08				
		A_{lower} [mm²]	314.16				

2.1. Structural assessment

The structural assessment comprises three different steps: (i) Determining the section of the strengthening material; (ii) Obtaining the length and anchorage length of the reinforcement; (iii) Verifying bonding stress and anchorage calculation.

(i) Determining the real range of required strengthening and the reinforcement element section.
To appropriately determine the section required for each material it is necessary to take into account the existing deformation of the fibre where the reinforcement is placed. This is because the beam is not considered to be completely discharged before the operation due to practical reasons. Because of that, a two-stage analysis is needed.

The first stage consists of a calculation only under permanent load and without security factors. In this study, internal forces due to permanent load are M^S_{perm} = 20,25 m.kN; N^S_{perm} = 0 kN with γ= 0. RC beam is not at the limit of its bearing capacity, so results are obtained by successively applying the following set of equations:

- Strain compatibility

$$\frac{\varepsilon_c^{0max}}{x^0} = \frac{\varepsilon_{s1}^0}{d \quad - x^0} = \frac{\varepsilon_{s2}^0}{x^0 \; - d'} \tag{1}$$

where $\varepsilon_c^{0máx}$ is the maximum strain in the concrete compressed zone; ε_{s1}^0, ε_{s2}^0 are the strains in the steel rebar; x^0 is the neutral axis depth; d is the distance between the most compressed concrete fibre and the most tensioned rebar; d' is the rebar cover. A linear strain distribution according to Navier-Euler-Bernouilli beam model was assumed (Figure 1).

- Materials behaviour

$$N_c = f(\varepsilon_c^{0max}, x) \tag{2a}$$

$$M_c = f(\varepsilon_c^{0max}, x) \tag{2b}$$

$$\sigma^0{}_{s1} = \begin{cases} E_s\varepsilon_{s1}^0\,, & \varepsilon_{s1}^0 \le \varepsilon_{lim} \\ f_y\,, & \varepsilon_{s1}^0 > \varepsilon_{lim} \end{cases} \tag{2c}$$

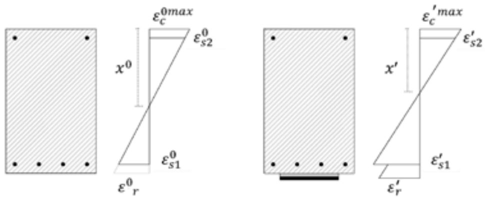
$$\sigma^0{}_{s2} = \begin{cases} E_s\varepsilon_{s2}^0\,, & |\varepsilon_{s2}^0| \le \varepsilon_{lim} \\ f_y\,, & |\,\varepsilon_{s2}^0| > \varepsilon_{lim} \end{cases} \tag{2d}$$

where N_c, M_c are the stress resultants in concrete (force and moment, respectively); E_s is the Young modulus of rebar steel; f_y is the yielding stress of rebar steel; ε_{lim} is the strain corresponding to the yielding stress ($\varepsilon_{lim}=f_y/E_s$). Ideal elasto-plastic behaviour was considered for rebar steel.

- Equilibrium

$$N_s = -N_c + A_{s1}\sigma^0{}_{s1} + A_{s2}\sigma^0{}_{s2} \tag{3a}$$
$$M_s = M_c - A_{s2}\sigma^0{}_{s2}(d - d') \tag{3b}$$

where N_s, M_s are the external forces acting on the section; A_{s1}, A_{s2} are the areas of rebar. The corresponding non-linear system was solved by means of a Newton-Raphson algorithm.



a) State without strengthening b) Strengthened state

Figure 1. Strain distribution according to Navier-Euler-Bernouilli beam model

The initial deformation at the fiber where reinforcement is placed ($\varepsilon^o{}_{fr}$) was obtained from an additional compatibility equation:

$$\varepsilon^0{}_{fr} = \frac{\varepsilon_c^{0max}(d + d' - x^0)}{x^0} \tag{4}$$

Dimensioning of strengthening is done on a second stage. Results are obtained with an interaction diagram where $\varepsilon^0{}_{fr}$ must be subtracted to the strain of the added reinforcement, ε'_r (ec. 6), as the beam is already deformed when new reinforcement is placed; so, this strain is not transmitted to the new reinforcement:

$$\varepsilon'_r = \frac{\varepsilon_c^{\prime max}(d + d' - x')}{x'} - \varepsilon^0{}_r \tag{2}$$

In this case, all loads are considered ($N^k{}_{total}$ = 1 kN; $M^k{}_{total}$= 49,05 m.kN) and also a safety factor is applied to material properties.

(ii) Obtaining length and anchorage length

The length of reinforcement needed is obtained through the bending moment diagram (Figure 2). To calculate anchorage length which must be added in each edge, model A from the FIB Model Code 2010 is applied.

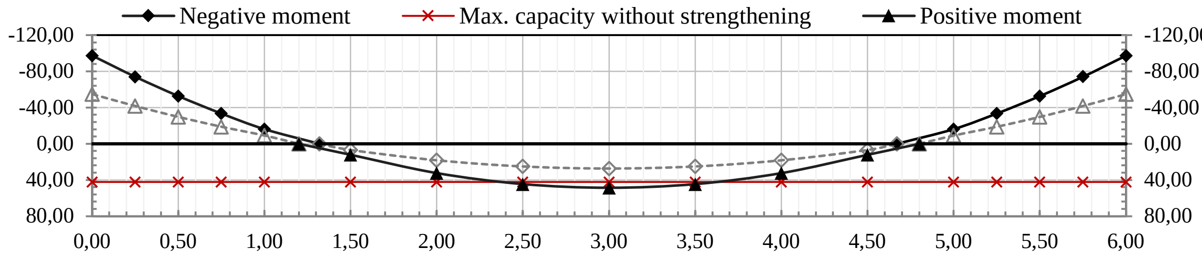


Figure 2 Bending moment diagram and length calculation

(iii) Verifying bonding stress and anchorage calculation

Bonding stress verification consists of ensuring that existing stress in the homogenized section (concrete + existing inner rebar + new reinforcement at the underside), at the point where strengthening is placed, is less than concrete and epoxy resin strength. Anchorage calculation has been made applying a simplification of method A proposed in ETAG 001 - Annex C: Design methods for anchorages.

2.2. Environmental comparative LCA

The general methodological approach regarding LCA is described in the ISO 14040:2006 standard [3]. Particularly when applied to buildings, methodological approach can be found on the CEN/TC 350 standard, EN 15643-2. This study is based on it.

This study comprises two comparative LCAs. The first one (case A) is made between steel sheet and CFRP, both stacked with epoxy resin. Both techniques are broadly applied and are suitable in situations with similar needs: they hardly modify beam size and are used when flexural strengthening is needed. Epoxy resin is considered to fail in case of fire due to its little resistance to high temperature. Because of that, it is recommended to use both techniques in elements able to resist loads with a security factor before reinforcing of at least 1 (see M^{S}_{total} in Figure 3), or to protect the reinforced element with additional treatments. The second one (case B) is made between steel sheet placed with mechanical anchorages and CFRP stuck with epoxy with an additional insulating layer to protect it against fire.

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 considered in a LCA, although in this case, as being a comparative study, impacts included in both techniques can be neglected. In this paper, use stage is assumed to be zero and end of life stage has been considered on a simplified way (landfill with no recycling). As an example, processes and materials that have been taken into account in case A are displayed in Table 2 and Table 3 respectively.

Table 2. Impacts assigned to steel sheet. Case A

Stage/process	Description	Value
(i) product stage		
Material of reinforcement "cradle to door"	Hot-laminated steel sheet S235JR	1,07 kg
	Epoxy resin	1,09 kg
	Steel transportation to working site	9.70 km
	Epoxy resin transportation to working site	311 km
(ii) construction process stage		
Steel sheet treatment	Sandblasting (sand: 0.0352 t/m² and equipment: 0.25 hours/m²)	0.0908 m² surface
	Anti-corrosion treatment of steel and base needed to apply epoxy resin	0.0908 m²
	Detergent with acid ph. (hydrochloric acid)	0.0908 m²
	Degreasing solvent (trichlorethylene)	0.0908 m²
Building execution	Bracing for uniform pressure application. Props transportation and use	10 units 4 kg.km
Protection	Anti-humidity mortar covering in the edges and mortar transportation to working site	3.73 m
(iv) end of life stage		
Scenario	Disposal: landfill	All
	Transportation to landfill	Total mass

Table 3. Impacts assigned to CFRP reinforcement. Case A

Stage/process	Description	Value
(i) product stage		
Material of reinforcement "cradle to door"	CFRP laminate (70% carbon fibber + 30% epoxy resin, modelled from PAN)*	0.0427 kg
	Epoxy resin applied to CFRP and concrete surface	0.875 kg
	Transportation of CFRP laminate to working site	1755 km
	Transportation of epoxy resin to working site	311 km
(ii) construction process stage		
Concrete surface treatment	Transparent and viscous epoxy resin Density 1050 kg/m³, quantity 300g/m²	0.6 kg
CFRP laminate treatment	Cutting of laminates on site	0.171 kWh
(iv) end of life stage		
Scenario	Disposal: landfill	All
	Transportation to landfill	Total mass

* A commercial product is taken as a reference. It is produced in Germany (Trostberg)

The software tool used is SimaPro v7.3. Solutions are evaluated according to Cumulative Energy Demand (CED) v.1.08 indicator (in MJEq or kWh-Eq) and the Global-Warming Potential (GWP) indicator, based on 2007 IPCC v1.02 methodology, considering a time horizon of 100 years. Inventory is created using Ecoinvent 2.2, ELCD and Bedec databases and [13] is used as a reference to model the CFRP production.

3. RESULTS

Results obtained from the structural assessment are described in Figure 3 and summarized in Table 4. In the case of mechanical anchorage, four steel anchorages, ϕ 10 mm, are needed.

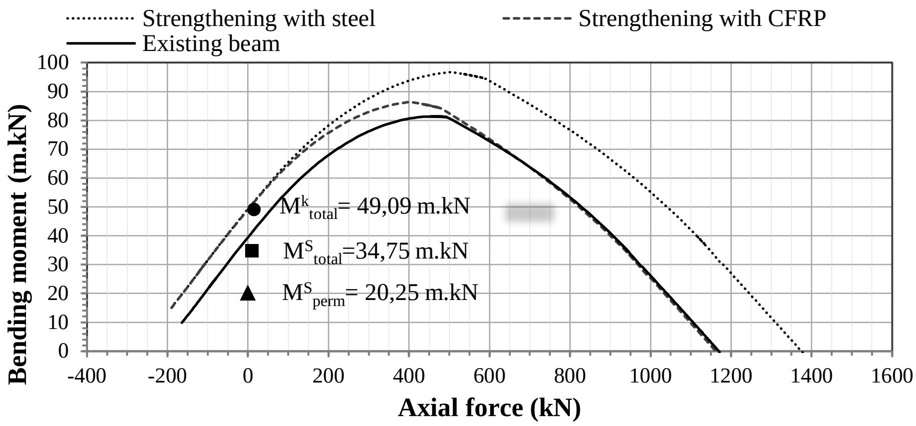


Figure 3 Diagram M – N

Table 4 Reinforcement sizing

Parameter	Steel reinf.	CFRP reinf.
width	50 mm	13 mm
thickness	1.5 mm	1.2 mm
length	1816 mm	1711 mm

Regarding LCA, firstly, a comparison between environmental impact of producing 1 kg of steel (S), 1 kg of carbon fiber (CF) and 1 kg of CFRP is done. Results are shown in Figure 4 and Figure 5.

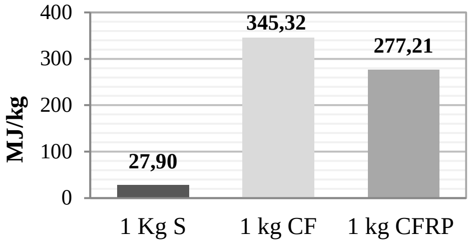


Figure 4 CED of producing 1kg of steel, CF and CFRP

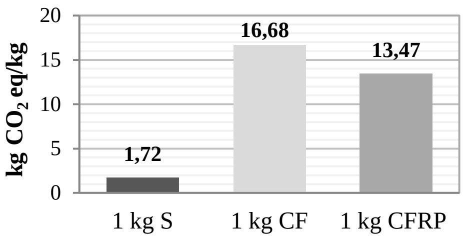


Figure 5 GWP of producing 1kg of steel, CF and CFRP

Results of comparative LCA between steel sheet reinforcement and CFRP, both stuck with epoxy resin (Case A) are shown in Figure 6 and Figure 7.

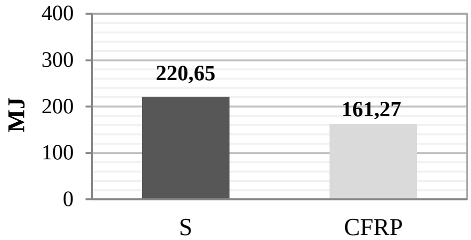


Figure 6 Comparison according CED of steel/epoxy reinf. and CFRP/epoxy reinf.

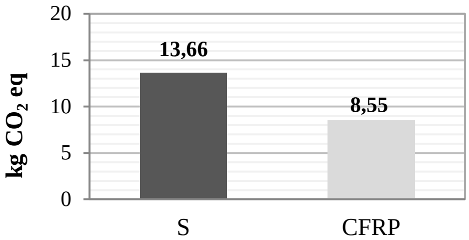


Figure 7 Comparison according GWP of steel/epoxy reinf. and CFRP/epoxy reinf.

Finally, analysis of steel sheet placed with mechanical anchorage and 24 mm of light mortar to protect from fire and CFRP stuck with epoxy and 50 mm of light mortar (Case B), is presented in Figure 8 and Figure 9.

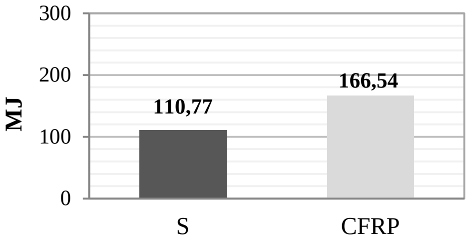


Figure 8 Comparison according CED of steel/anchorage reinf. and CFRP/epoxy reinf.

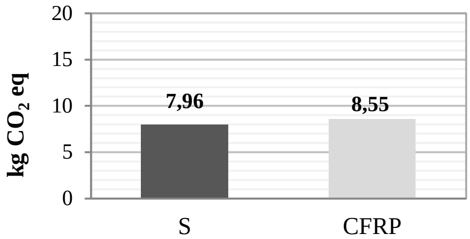


Figure 9 Comparison according GWP of steel/epoxy reinf. and CFRP/epoxy reinf.

4. DISCUSSION AND CONCLUSION

Results show that producing 1 kg of steel is considerably less harmful than producing 1 kg of carbon fibre (90% less) both in terms of final energy consumption and GWP. Producing 1 kg of steel also implies more energy consumption and CO_2 equivalent than producing 1 kg of the final CFRP matrix (which is made of carbon fibre and epoxy resin).

Nevertheless, when comparing globally both techniques stuck with epoxy resin (Case A), CFRP results in a better environmental behaviour which is mainly explained because of the reduction on the material needed due to the higher mechanical properties of CFRP, compared to steel. Construction processes are quite similar in both reinforcement techniques stuck with epoxy resin. Most apparent differences arise from the need of treatment of the steel sheet, as it should be cleaned and protected against corrosion.

On a second phase (Case B), results differ from previous one and steel results in a better behaviour. This is because epoxy resin (a highly harmful material) is no longer needed to attach the sheet. In this case, construction phase contribution is greater because drilling is needed but, on the other hand, product production phase is considerably lower.

It must be noted that to rigorously compare both techniques, end of life stage must be analysed in a deeper way. Apparently, steel is easier to reuse or recycle than CFRP, although improvements are being made in that direction. In this study, a simplified scenario with no recycling and disposal to a landfill is used, which is often the real case in practice.

The importance of considering environmental criteria in building interventions is crucial, especially considering the aged building stock of most European cities and the nowadays trend towards refurbishment instead of demolition and new construction. This study contributes to this field with the objective of developing environmental decision criteria as well as scientific data regarding structural strengthening, able to be incorporated in a whole building LCA.

Regarding environmental criteria some key findings are derived from this study. Not only the material or technique but also the construction process, which includes the way of fixing the material, have a great influence in results. Differences between techniques can account for a 25% of energy consumption and 37% of CO_2-eq emissions. When strengthening a complete building structure, this percentage can lead to a significant difference on total energy consumption and CO_2 emitted.

Upgrading building structures can extend their service life which results in many environmental benefits but also in some burdens. In this paper, the environmental impact differences between the different techniques have been found to be significant. Therefore, environmental criteria must be considered when intervening in existing structures, especially when the whole building retrofit is justified according to energy and environmental purposes.

5. ACKNOWLEDGMENTS

This research was supported by the Spanish Ministry of Education, Culture and Sports through FPU15/01069 grant.

6. BIBLIOGRAPHY

[1] A. Vilches, A. Garcia-martinez, B. Sanchez-monta, Life cycle assessment (LCA) of building refurbishment : A literature review, 135 (2017) 286–301. doi:10.1016/j.enbuild.2016.11.042.

[2] I. Sartori, A.G. Hestnes, Energy use in the life cycle of conventional and low-energy buildings: A review article, Energy Build. 39 (2007) 249–257. doi:10.1016/j.enbuild.2006.07.001.

[3] ISO, ISO 14040:2006 Environmental management - Life cycle assessment principles and framework, 2006.

[4] I. Zabalza Bribián, A. Aranda Usón, S. Scarpellini, Life cycle assessment in buildings: State-of-the-art and simplified LCA methodology as a complement for building certification, Build. Environ. 44 (2009) 2510–2520. doi:10.1016/j.buildenv.2009.05.001.

[5] A. Dobbelsteen, A. van den Linden, C. van der Ravesloot, Defining the reference for environmental performance, in: Proc. Int. Conf. Adv. Build. Technol., Hong-Kong, 2002: p. Vol II, 1509-1516.

[6] J. Escribano, Siniestralidad Arquitectónica en el Estado Español desde 1984 a 1987, University of the Basque Country, Bilbao, Spain. (in Spanish), 1992.

[7] I. Marcos, J.-T. San-José, L. Garmendia, A. Santamaría, J.M. Manso, Central lessons from the historical analysis of 24 reinforced-concrete structures in northern Spain, J. Cult. Herit. 20 (2016) 649–659. doi:10.1016/j.culher.2016.03.003.

[8] J.A. Vieitez Chamosa, Patología estructural. Aspectos Químicos, Normativa y Estadística, University of the Basque Country, Bilbao, Spain. (in Spanish), 1984.

[9] A. Cansado Carretero, Manuel Jesús; Moreno Cansado, Análisis estadístico nacional sobre patologías en la edificación (II) - Resumen, n.d.

[10] M. Kaminski, E. Kusa, Strains in CFRP - strengthened reinforced concrete beams, in: M. Grantham, P.A. Muhammed Basheer, B. Magee, M. Soutsos (Eds.), Concr. Solut. 5th Int. Conf. Concr. Repair, CRC Press, Belfast, 2014: pp. 297–304.

[11] T. Suzuki, T. Odai, R. Hukui, J. Takahashi, LCA of Passenger Vehicles Lightened by Recyclable Carbon Fiber Reinforced Plastics, Energy. (2000) 3–5.

[12] Y.S. Song, J.R. Youn, T.G. Gutowski, Life cycle energy analysis of fiber-reinforced composites, Compos. Part A Appl. Sci. Manuf. 40 (2009) 1257–1265. doi:10.1016/j.compositesa.2009.05.020.

[13] S. Das, Life cycle assessment of carbon fiber-reinforced polymer composites, Int. J. Life Cycle Assess. 16 (2011) 268–282. doi:10.1007/s11367-011-0264-z.

PAPER 4

B. Palacios-Munoz, L. Gracia-Villa, I. Zabalza-Bribián, and B. López-Mesa, "Simplified structural design and LCA of reinforced concrete beams strengthening techniques," *Eng. Struct.*, vol. 174, no. July, pp. 418–432, Nov. 2018, https://doi.org/10.1016/j.engstruct.2018.07

Engineering Structures 174 (2018) 418–432

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

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

ARTICLE INFO

Keywords:
Life cycle assessment
Building structures
Concrete strengthening
Sustainable construction
Construction and demolition waste
Building refurbishment

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).

https://doi.org/10.1016/j.engstruct.2018.07.070
Received 21 March 2018; Received in revised form 2 July 2018; Accepted 23 July 2018
Available online 31 July 2018
0141-0296/© 2018 Elsevier Ltd. All rights reserved.

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.

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.

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 (h × b:150 × 300, 200 × 400, 250 × 500), three square beams (h × b: 250 × 250, 300 × 300, 500 × 500) and three suspended beams (h × b: 400 × 200, 500 × 250, 600 × 300). All the beams have a length of 6 m.

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 Fig. 1:

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

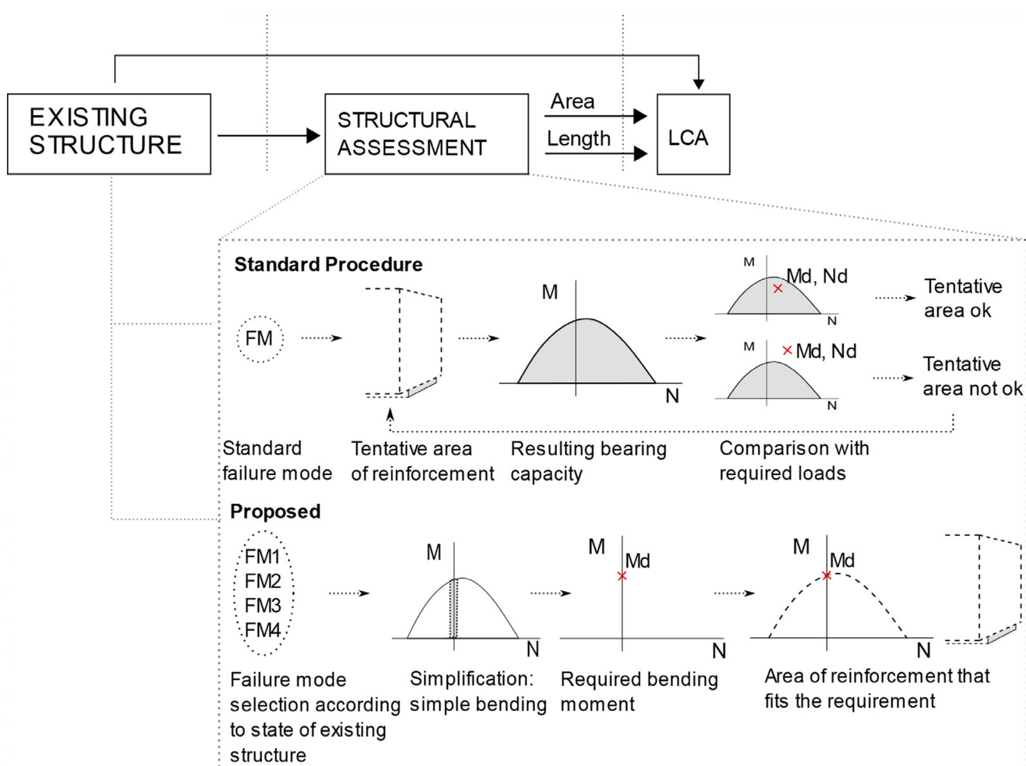


Fig. 1. Summary of the proposed methodology.

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 $\alpha(x, t)$ and $\beta(x, t)$, Eqs. (1) and (2), respectively, are obtained by doing $N_c^p = N_c^r$ and $M_c^p = M_c^r$.

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

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

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.

A linear strain distribution according to Navier-Euler-Bernoulli 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 (Fig. 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.

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 Eq. (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 $\tau_{ad,max} = 2\frac{f_{ctm}}{\gamma}$ 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

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

f_{cd} [MPa]/E_c [MPa]	α [–]		β [–]	
	Mean	Deviation	Mean	Deviation
16/29,000	0.18	0.008	0.73	0.007
20/30,000	0.25	0.008	0.70	0.005
25/31,000	0.30	0.008	0.70	0.004
30/33,000	0.37	0.008	0.70	0.003
35/34,000	0.42	0.008	0.69	0.003
40/35,000	0.47	0.007	0.69	0.002

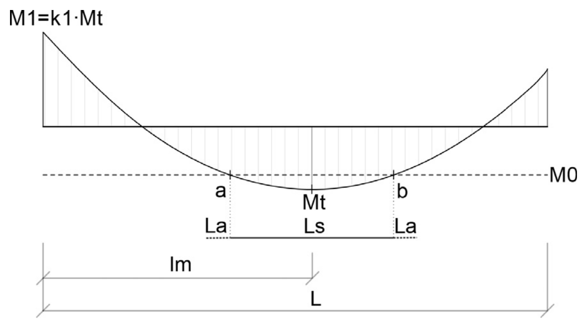


Fig. 2. Relation between the length of the strengthening and the maximum positive moment line.

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.

(iii) *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 [34,38], 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 Tables 3–5, respectively. In the no-recycling scenario, 100% of the materials are obtained from raw materials. Data relate to plants in the EU.

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 Eq. (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.

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

Coefficients obtained in the case of FM 1 are obtained from Eqs. (6)–(9), respectively.

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

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

$$a_3^{FM1} = M_T \quad (8)$$

$$a_4^{FM1} = -M_T z \quad (9)$$

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

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 min with light mortar (60 mm thickness), density = 500 kg/m^3)
	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[a]
	Inner rebar cleaning, passivation and treatment against corrosion[a]
	Original concrete section restitution[a]
	Epoxy resin junction between new and existing concretea
	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

[a] 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 min with light mortar (24 mm thickness), density = 500 kg/m^3)
	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[a]
	Inner rebar cleaning, passivation and treatment against corrosion[a]
	Original concrete section restitution[a]
	Epoxy resin junction between new and existing concrete[a]
	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

[a] 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

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

3.1.1.2. CFRP laminates strengthening technique. Firstly, x is obtained from Eq. (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 Eqs. (12)–(14), respectively.

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

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

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

By applying Eq. (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 Eq. (16).

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

In the case of the RC technique, composed of new concrete and rebars, Eq. (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 Eq. (17), where x_1 and x_2 are the solutions of Eq. (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 (Fig. 2).

For a single beam with constraints in both edges, $k_1 = 2$ and $l_m = L/2$, and Eq. (18) can be simplified as Eq. (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 Eq. (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 Eq. (21). In FM4, Eq. (22) is obtained.

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

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

(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 Eq. (23).

$$L_a = \max\begin{Bmatrix} m\varnothing^2 \geqslant \frac{f_{yk}}{14}\varnothing \\ 10\varnothing \\ 200 \end{Bmatrix} \quad (23)$$

3.1.3. Mechanical anchorage calculation

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

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

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 × 300 mm (b × 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 mm^2 and A_{s2} is 100.53 mm^2. A RC of $f_{ck} = 20$ 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.

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

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, $\alpha = 0.25$ and $\beta = 0.70$. 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).

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, Eq. (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 Eqs. (20)–(23). As an example, in the FM1, with $\gamma = 1.5$, in the case of steel sheet technique, $L_a^s = 0.33$ m. Applying Eq. (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 Tables 8–10, for beams with a h/b relation of 0.5, 1 and 2, respectively.

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 30 × 30 (b × h) when its bending capacity is increased a 10%, 30% and 50%, are presented in Fig. 3.

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

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 300 × 300 mm cross section beam, with a 50% increase on its bending capacity has been taken as a case study. In Fig. 6, the decreasing in the non-renewable energy consumption as the percentage of recycled material increases, in different technologies, is presented. In Fig. 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.

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 7273.64 MJ-Eq/m^3 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 150 × 300 cross section beams. This scenario is summarized in Fig. 8.

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

Table 6
Materials mechanical properties.

Material	f_k [MPa]	γ	E_c [MPa]	f_{ctm} [MPa]
Existing materials				
Concrete	20	1.5	30,000[a]	2.20[a]
Inner rebar (ϕ20)[b]	400	1.15	200,000	
Strengthening materials				
Steel sheet (S 355 N/NL)	355	1.10	200,000	
CFRP laminate	3000[c]	1.15	165,000[c]	

[a] Table 3.1 Eurocode 2 [42].
[b] Supposed similar to B 400 S [44].
[c] Product MasterBrace LAM 165/3000, company BASF, Construction Chemicals Spain.

Table 7
Results for steel-sheets strengthening technique.

	Simplified method						General method
	a_1	a_2	a_3	a_4	x [mm]	A_r^s [mm^2]	A_r^g [mm^2]
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

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.

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 Fig. 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.

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 Fig. 3 for the case of a RC beam of 6.00 m of span and cross section of 30 cm × 30 cm (b × 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

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 × 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
150 × 300								
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
200 × 400								
10%	238.18	21.43	178.26	14.58	198.83	42.89	1334.36	109.82
30%	419.00	31.38	264.83	21.43	238.59	44.99	1359.99	111.46
50%	657.09	44.67	380.46	30.57	286.51	47.52	1393.03	113.58
250 × 500								
10%	302.85	26.97	214.38	17.51	254.03	53.91	1745.76	141.58
30%	578.48	42.23	347.17	28.01	311.53	56.95	1787.48	144.25
50%	960.22	63.58	532.99	42.70	384.16	60.78	1843.68	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 × *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
250 × 250								
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
300 × 300								
10%	193.61	16.92	159.10	12.63	162.94	32.93	1175.41	89.83
30%	399.96	28.37	258.76	20.51	211.46	35.49	1208.42	91.94
50%	689.74	44.61	400.11	31.68	275.93	38.89	1253.75	94.84
500 × 500								
10%	398.39	32.41	275.34	21.71	294.54	56.12	2329.71	168.96
30%	1068.99	69.85	601.16	47.46	431.88	63.36	2446.80	176.45
50%	2093.14	127.38	1101.88	87.03	622.85	73.43	2621.02	187.60

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 Figs. 5–7 for beams with different h/b relation. In the 300 × 300 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 Fig. 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

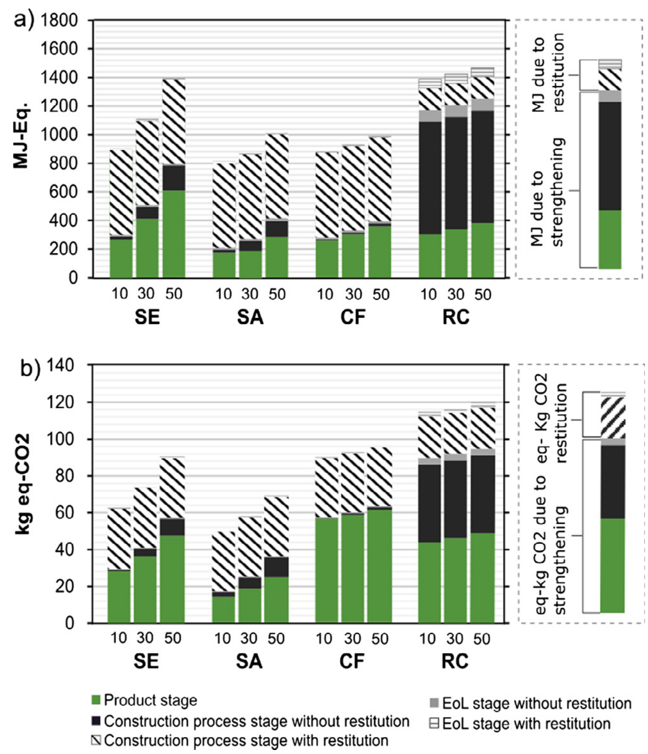


Fig. 3. Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent (b) when strengthening a 300 × 300 mm (h × b) beam.

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 × *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
400 × 200								
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
500 × 250								
10%	215.08	17.11	178.98	13.61	167.53	29.18	1237.90	86.52
30%	518.89	34.09	326.77	25.29	241.85	33.10	1291.94	89.98
50%	957.09	58.73	541.17	42.23	346.21	38.60	1368.34	94.87
600 × 300								
10%	280.88	21.80	217.90	16.53	208.36	35.41	1596.83	109.60
30%	744.09	47.73	443.55	34.37	317.42	41.16	1681.18	115.01
50%	1432.85	86.48	780.73	61.02	473.33	49.38	1804.03	122.87

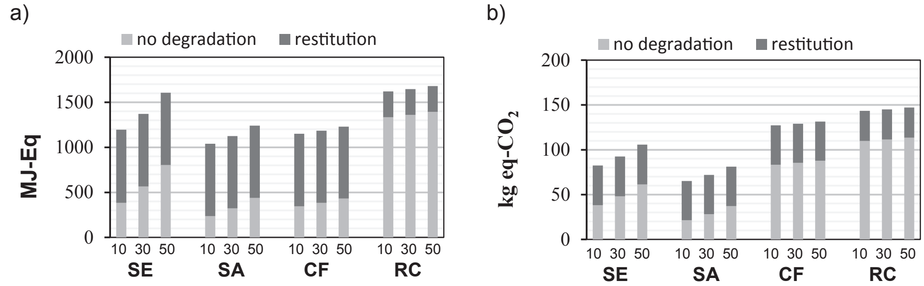


Fig. 4. Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent emitted (b) when strengthening a 200 × 400 mm (h × b) beam.

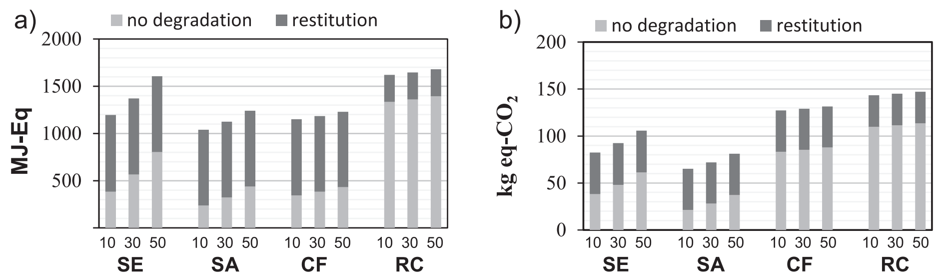


Fig. 5. Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent emitted (b) when strengthening a 400 × 200 mm (h × b) beam.

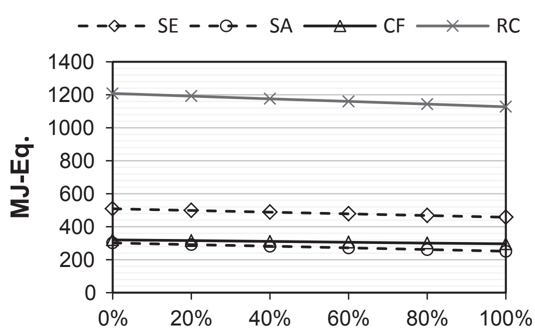


Fig. 6. Non-renewable primary energy consumption of the study case beam (300 × 300) according to different % of recycled material.

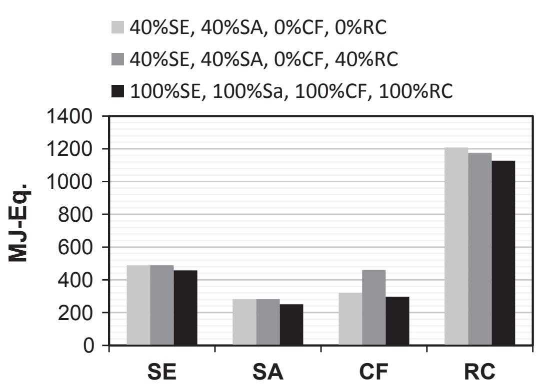


Fig. 7. Non-renewable primary energy consumption comparison between three different recycling scenarios.

of a 30 × 30 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 200 × 400 mm cross section beam (h × b), flat beam, as can be shown in Fig. 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.

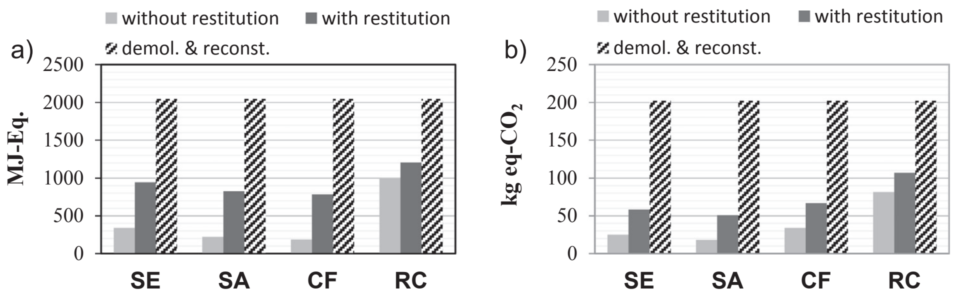


Fig. 8. Non-renewable primary energy consumption (a) and kilograms of CO_2 equivalent (b) when increasing a 50% the bending capacity of a 150 × 300 mm cross section beam, with and without repairing process, compared to demolition and reconstruction.

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 complete and materials and execution were controlled when built. Structure is, apparently, in good state of conservation	Applicable in steel, RC section 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

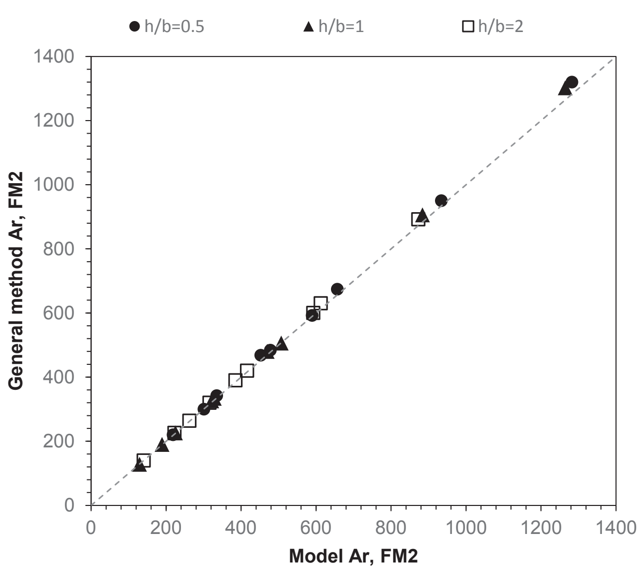


Fig. 9. Relation between results of simplified and general method.

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 15 × 30 (h × b) 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 A

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 Eq. (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 Eq. (5) can be obtained from Eqs. (25)–(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 Eq. (29).

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

– **FM3:**

In FM3, the coefficients of Eq. (5) are obtained from Eqs. (30)–(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 Eq. (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 Eq. (5) are obtained from Eqs. (35)–(38), respectively.

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

$$a_2^{FM4} = -0.5693\frac{f_{yr}}{d} \quad (36)$$

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

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

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

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

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 Eq. (11). The coefficients b_1, b_2 and b_3 in FM4 are obtained from Eqs. (40)–(42), respectively.

$$b_1^{LS4} = -0.5693f_{yr}b \quad (40)$$

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

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

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

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

References

[1] Vilches A, Garcia-martinez A, Sanchez-monta B. Life cycle assessment (LCA) of building refurbishment: a literature review 2017;135:286–301. http://doi.org/10.1016/j.enbuild.2016.11.042.
[2] ISO. ISO 14040:2006 Environmental management - life cycle assessment principles and framework; 2006.
[3] ISO 14044:2006. ISO 14044:2006 Life cycle assessment—requirements and guidelines. Int Organ Stand 2006;14044:46. https://doi.org/10.1136/bmj.332.7550.1107.
[4] Zabalza Bribián I, Aranda Usón A, Scarpellini S. Life cycle assessment in buildings: state-of-the-art and simplified LCA methodology as a complement for building certification. Build Environ 2009;44:2510–20. https://doi.org/10.1016/j.buildenv.2009.05.001.
[5] Russell-Smith SV, Lepech MD. Cradle-to-gate sustainable target value design: integrating life cycle assessment and construction management for buildings. J Clean Prod 2015;100:107–15. https://doi.org/10.1016/j.jclepro.2015.03.044.
[6] Hájek P, Fiala C, Kynčlová M. Life cycle assessments of concrete structures - a step towards environmental savings. Struct Concr 2011;12:13–22. https://doi.org/10.1002/suco.201000026.
[7] Vieira DR, Calmon JL, Coelho FZ. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: a review. Constr Build Mater 2016;124:656–66. https://doi.org/10.1016/j.conbuildmat.2016.07.125.
[8] Rehm M, Ade R. Construction costs comparison between “green” and conventional office buildings. Build Res Inf 2013;41:198–208. https://doi.org/10.1080/09613218.2013.769145.
[9] López-Mesa B, Pitarch Á, Tomás A, Gallego T. Comparison of environmental impacts of building structures with in situ cast floors and with precast concrete floors. Build Environ 2009;44:699–712. https://doi.org/10.1016/j.buildenv.2008.05.017.
[10] Caruso MC, Menna C, Asprone D, Prota A, Manfredi G. Methodology for life-cycle sustainability assessment of building structures. ACI Struct J 2017;114:323–36. https://doi.org/10.14359/51689426.
[11] Guggemos Acree A, Horvath A. Comparison of environmental effects of steel- and concrete-framed buildings. J Infrastruct Syst 2005;11:93–101. https://doi.org/10.1061/(ASCE)1076-0342(2005) 11:2(93).
[12] Maxineasa SG, Taranu N, Bejan L, Isopescu D, Banu OM. Environmental impact of carbon fibre-reinforced polymer flexural strengthening solutions of reinforced concrete beams. Int J Life Cycle Assess 2015;20:1343–58. https://doi.org/10.1007/s11367-015-0940-5.
[13] Napolano L, Menna C, Asprone D, Prota A, Manfredi G. LCA-based study on structural retrofit options for masonry buildings. Int J Life Cycle Assess 2015;20:23–35. https://doi.org/10.1007/s11367-014-0807-1.
[14] ACI Committee 440. ACI 440.2R-08 guide for the design and construction of externally bonded FRP systems; 2008.
[15] FIB. Externally bonded FRP reinforcement for RC structures, vol. 14; 2001. http://doi.org/10.1016/0262-5075(85)90032-6.
[16] Oehlers DJ. Development of design rules for retrofitting by adhesive bonding or bolting either FRP or steel plates to RC beams or slabs in bridges and buildings. Compos Part A Appl Sci Manuf 2001;32:1345–55. https://doi.org/10.1016/S1359-835X(01)00089-6.
[17] Solis-Guzman J, Marrero M. Ecol footpr assess build constr. Sharjah (UAE): Bentham Science Publishers; 2015. p. 111–44 [Chapter 6 Case Study].
[18] Zabalza Bribián I, Valero Capilla A, Aranda Usón A. Life cycle assessment of building materials: comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency improvement potential. Build Environ 2011;46:1133–40. https://doi.org/10.1016/j.buildenv.2010.12.002.
[19] CEB Comite euro-international du beton. No. 162. Assessment of concrete structures and design procedures for upgrading (redesign); 1983.
[20] Fomento M. Instrucción de Hormigón Estructural (EHE-08); 2008. http://doi.org/10.1017/CBO9781107415324.004.
[21] EN. EN 15643-2:2011 - sustainability of construction works - assessment of buildings - Part 2: framework for the assessment of environmental performance. Int Stand 2012:1–36.
[22] Lasvaux S, Achim F, Garat P, Peuportier B, Chevalier J, Habert G. Correlations in Life Cycle Impact Assessment methods (LCIA) and indicators for construction materials: What matters? Ecol Indic 2016;67:174–82. https://doi.org/10.1016/j.ecolind.2016.01.056.
[23] Vilches A, Garcia-Martinez A, Sanchez-Montañes B. Life cycle assessment (LCA) of building refurbishment: a literature review. Energy Build 2017. https://doi.org/10.1016/j.enbuild.2016.11.042.
[24] Mohammadpourkarbasi H, Sharples S. Eco-retrofitting very old dwellings: current and future energy and carbon performance for two UK cities. PLEA 2013 Sustain. Archit. a Renew. Futur., Munich (Germany) 2013.
[25] Famuyibo AA, Duffy A, Strachan P. Achieving a holistic view of the life cycle performance of existing dwellings. Build Environ 2013;70:90–101. https://doi.org/10.1016/j.buildenv.2013.08.016.
[26] Institution BS. Eurocode 0 - basis of structural design. En 2002;3:89. https://doi.org/10.1680/cien.144.6.8.40609.
[27] Tang SW, Yao Y, Andrade C, Li ZJ. Recent durability studies on concrete structure. Cem Concr Res 2015;78:143–54. https://doi.org/10.1016/j.cemconres.2015.05.021.
[28] Budelmann H, Holst A, Wachsmann A. Durability related life-cycle assessment of concrete structures: mechanisms, models, implementation. In: Strauss F, editor. Life-cycle sustain civ infrastruct syst. Taylor and Francis Group; 2013. p. 75–86.
[29] Bovea MD, Powell JC. Developments in life cycle assessment applied to evaluate the environmental performance of construction and demolition wastes. Waste Manage 2016;50:151–72. https://doi.org/10.1016/j.wasman.2016.01.036.
[30] Blengini GA. Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 2009;44:319–30. https://doi.org/10.1016/j.buildenv.2008.03.007.
[31] Dahlbo H, Bachér J, Lähtinen K, Jouttijärvi T, Suoheimo P, Mattila T, et al. Construction and demolition waste management - a holistic evaluation of

environmental performance. J Clean Prod 2015;107:333–41. https://doi.org/10.1016/j.jclepro.2015.02.073.
[32] Mercante IT, Bovea MD, Ibáñez-Forés V, Arena AP. Life cycle assessment of construction and demolition waste management systems: a Spanish case study. Int J Life Cycle Assess 2012;17:232–41. https://doi.org/10.1007/s11367-011-0350-2.
[33] European Commission (DG ENV). Service contract on management of construction and demolition waste - SR1. Final report task 2. A project under the Framework contract ENV.G.4/FRA/2008/0112, vol. 33; 2011.
[34] Gao W, Ariyama T, Ojima T, Meier A. Energy impacts of recycling disassembly material in residential buildings. Energy Build 2001;33:553–62. https://doi.org/10.1016/S0378-7788(00)00096-7.
[35] Pimenta S, Pinho ST. Recycling carbon fibre reinforced polymers for structural applications: technology review and market outlook. Waste Manage 2011;31:378–92. https://doi.org/10.1016/j.wasman.2010.09.019.
[36] Suzuki T, Odai T, Hukui R, Takahashi J. LCA of passenger vehicles lightened by recyclable carbon fiber reinforced plastics. Energy 2000:3–5.
[37] Howarth J, Mareddy SSR, Mativenga PT. Energy intensity and environmental analysis of mechanical recycling of carbon fibre composite. J Clean Prod 2014;81:46–50. https://doi.org/10.1016/j.jclepro.2014.06.023.
[38] Witik RA, Teuscher R, Michaud V, Ludwig C, Månson J-AE. Carbon fibre reinforced composite waste: an environmental assessment of recycling, energy recovery and landfilling. Compos Part A Appl Sci Manuf 2013;49:89–99. https://doi.org/10.1016/j.compositesa.2013.02.009.
[39] Pacheco-Torgal F, Tam VWY, Labrincha JA, Ding Y, De brito J. Handbook of recycled concrete and demolition waste; 2013. http://doi.org/10.1533/9780857096906.
[40] Das S. Life cycle assessment of carbon fiber-reinforced polymer composites. Int J Life Cycle Assess 2011;16:268–82. https://doi.org/10.1007/s11367-011-0264-z.
[41] Institut de Tecnología de la Construcció de Catalunya. BEDEC - Banco de datos de elementos constructivos; 2017.
[42] European Union T. Eurocode 2, vol. 2; 2004.
[43] Torroja IE. Instrucción H.A. 61 Especial para estructuras de hormigón armado; 1961.
[44] ISO (the International Organization for Standardization). ISO 6935-1:2015 Steel for the reinforcement of concrete – Part 2: ribbed bars; 2015.