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Benchmarking through an algorithm of repair methods of reinforcement corrosion: The repair index method

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Abstract

The aging of concrete structures and corrosion of reinforcing steel has resulted in an increasing need of repairs and strengthening. New repair materials and methods are developing which is not followed with enough experience on their performance. The selection of the best repair option should be based on technical and economical (apart from social) considerations and, therefore, its seems that a life cycle cost analysis, (LCCA) is the most suitable methodology for making an intercomparison between them. However, due to a lack of experience and of rigorous data, LCCA is very often not feasible. In this paper an alternative is presented: the repair index method, RIM. It is based on defining a set of requirements: safety, serviceability, environmental impact, durability and economy, that are quantified through repair performance indicators, RPI, ranked in four levels of importance (from 1 through 4). The RPI are averaged for each requirement, *R*, then, a repair index, RI, is calculated for comparative purposes through an algorithm for each repair option in each structure. The algorithm may suffer some objectivity, but when applied with some assumptions, can be an alternative to LCCA.

Keywords: Concrete repair; Indicators; Repair index; Life cycle cost analysis; Repair performance indicators; Durability; Economy

1. Introduction

Corrosion of reinforcement is the main reason for repairing reinforced concrete. The progressive aging of concrete structures, together with their exposure to very aggressive media, such as chloride-bearing environments, have led in some countries to investments in repair that are of the same economical magnitude as the building of new structures.

Parallel to the need for repair, several repair options are available in the market: patching, cathodic protection, realkalization or chloride extraction, application of corrosion inhibitors, concrete coatings and hydrophobic agents. The owner of the structure has to compare and benchmark the available options in order to optimise the new investment.

The selection of the best repair option for a particular structure should be based on technical and economical considerations. The technical issues are related to the suitability to reduce the rate of degradation and restore the aesthetic of the structure, and the economical factor is based on present and future costs. A rigorous life cycle cost analysis, LCCA, [1] is the appropriate methodology to evaluate and benchmark the duration of service life and the economical consequences of each of the alternative possibilities to reach the target. The LCCA tries to calculate the cost of all steps of a technical activity. In present case the repair of a concrete structure. The LCCA first identifies the individual components of such activity and then expresses through a mathematical

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formula the cost. The final step of the LCCA consists in the optimization of the calculated costs by comparing the available repair options.

However, at present, a rigorous LCCA is not always feasible particularly in many regions where the exact economical data are not available [2]. In addition, it has to be mentioned that many of the repair solutions available are relatively new and no knowledge exists on their expected performance and duration. The situation leads to a more or less subjective decision with regard to their selection and use.

With the aim of making, a more objective selection of the repair type selection, a methodology for the benchmarking of repair options is proposed in this paper. The methodology is similar to that adopted as "Simplified Method of Evaluation" in the Manual Contecvet [3,4] on assessment of corroding structures. It is based on: (a) the identification of the *requirements* to be fulfilled by the structure to be repaired, and (b) the application of an algorithm composed of the qualification of *repair performance indicators*, RPI, by means of ascribing weights from 1 to 4 and the calculation of a *repair index*, RI, for each repair option. The results of the algorithm allows the comparison and selection of the most suitable and economical method. It has been named RIM: repair index method.

2. Repair options considered

Either because it is the most economically detrimental mechanism or because it is the most frequent, corrosion of reinforcement will be taken up as an example.

The most common repair option of concrete structures deteriorated by corrosion is the so called "patching repair" in which deteriorated concrete is removed and the substrate and reinforcement are cleaned. Then, the geometry is restored by placing a primer on the reinforcement, applying a bonding agent between new and old concrete, placing a repair mortar and finishing the repair by applying with a coating. A patch can be simply a single repair material or a two or three component system. This repair method has been recently complemented with the embedment of zinc anodes in the repaired zones in order to avoid the progression of the corrosion in the zones adjacent to the repaired ones.

Cathodic protection is an old repair method that is gaining market in the case of concrete structures. Less applications are made however. Using realkalization or chloride extraction as these techniques are more modern, but few companies apply them.

Finally, another recent technique, that is still controversial in its efficiency, is the application of inhibitors from the concrete surface. However, the application of hydrophobic agents seems to be relatively efficient in keeping the concrete dry.

3. Algorithm for benchmarking

From these options the difficulty is the selection of the optimum for a particular application. In general, economy is the predominant criterion for the selection, together with the marketing efforts of the producers and the availability of the facilities for the application of a particular technique. In consequence, selection is made without studying in depth all the possibilities and without making a critical analysis at present and its projection towards the future.

As mentioned earlier, LCCA is the most advanced tool for making such a benchmark. However LCCA is complex and detailed knowledge is necessary on the different repair options, as well as data on uncertainties and probabilities of failure [1,5].

As an alternative, an algorithm is proposed. The analysis is based on the use of weights from 1 to 4 assigned to *repair performance indicators*, RPI, which are the manner of qualifying and quantifying the requirements, *R*, to be fulfilled by the structure. The RPIs are then averaged to obtain a *repair index*, RI, which is a final result allowing comparison.

3.1. Requirements, R, and repair performance indicators, RPI

Table 1 summarizes the methodology proposed. The requirements, *R*, identified for a structure to be repaired have been [5]: (1) safety, (2) serviceability, functionality and aesthetics, (3) environmental impact, (4) durability and (5) economy.

I. *Safety*—It is related to the structural safety during and after repair. Six RPIs identified are: (a) *structural consequences of the failure* and (b) *failure type*, (c) the *quality control of the repair execution* and (d) the feasibility *of post repair monitoring*. All indicators can be ranged in four categories as indicated in Table 1.
II. *Serviceability, functionality, aesthetics*—They are related to the limit state on serviceability during and after the repair. The two RPIs identified are: (a) *fitness for use* and (b) the *disturbance of the aesthetical appearance* of the structure due to the repair or to its dimensions or function. The four categories range from negligible to high.
III. *Environmental impact*—Two RPIs have been defined related to this requirement: (a) *Emission of pollutants* to the environment during and after application and (b) the *sustainability* of the materials and techniques used in the repair.
IV. *Durability*—The ranking of: (a) *the expected service life* of the repair itself has been identified as one of the RPI of this requirement. The four categories have been classified based on a repair dura-

Table 1
Requirements of the repaired structure and repair performance indicators classified by levels of importance (scoring)

Requirements *R*	Indicator RPI	Level of importance (weights)			
		1	2	3	4
Safety I	I.a. Structural consequences of failure	Very severe	Severe	Moderate	Slight
	I.b. Failure type	Very brittle	Brittle	Ductile	Very ductile
	I.e. Execution control	No guarantee (new method non-experienced applicator)	New method (experienced applicator)	High control (experienced applicator)	Guarantee or assurance is granted
	I.d. Method of post-repair monitoring	Any	Visual	Periodic with NDT	Sensors
	I.e. Safety of workers	Very low	Low	Moderate	High
	I.f. Safety of users	Very low	Low	Moderate	High
Serviceability functionality II	II.a. Disturbance	High	Moderate	Low	Negligible
	II.b. Fitness for use	Very low	Low	Moderate	High
Environmental impact III	III.a. Emission of pollutants to the environment	High	Moderate	Low	Negligible
	III.b. Sustainability	Very low	Low	Moderate	High
Durability IV	IV.a. Service life, year	<15	15–30	30–50	>50
	IV.b. Number of types of attack	>3	Three	2 types	Unique process
	IV.c. Exposure class (EN 206)	–		None defined	
Economy V	V.a. Direct cost, €/m^2	>200	100–200	50–100	<50
	V.b. Extension of damage, %	>80 of the structure	50–80	20–50	<20
	V.c. Period of disturbance, days	>15	7–15	1–7	0
	V.d. Maintenance cost, €/m^2	>50	30–50	20–30	<20
	V.e. Preparation of substrate	High	Moderate	Low	None

tion of 15, 30, 50 or more than 50 years. The other two RPI identified are: (b) *number of attack types*, and (c) the *aggressivity of exposure* classes which is categorized in the same manner as in the Manual Contecvet [3] as is depicted in Table 2, where the scores of each environmental class of EN-206 is shown.

V. *Economy*—This requirement has been defined through five RPIs: (a) *direct cost* by m^2 of structure, (b) *extension of the damage* (m^2), (c) *period* of disturbance or stopping of the functional use of the structure, (d) *maintenance cost* of the structure after being repaired and (e) *need of preparation of the substrate.*

In each requirement, weights or scores following the levels of importance of categories (in Arabic numbers) are assigned and average values calculated. Thus, the value of the RPI by requirement is calculated by averaging in the following form:

$$R_i = \frac{\sum \text{RPIs}}{\text{number of RPIs}} \qquad (1)$$

where R_i, is a particular requirement (safety, functionality, etc.).

3.2. Repair index, RI

The expression proposed for its calculation is:

$$\text{RI} = \sum_{0}^{n=5} (\text{Im})(R_i) \qquad (2)$$

where n = number of R and Im = percentage importance of each R in the work.

The calculation of the proposed RI, is the addition of all the values for each R multiplied by the percentages (referred to the unity) of importance for each one. The expression which results for the proportions of importance given in Table 3 is:

$$\text{RI} = (0.1 \times \text{I}) + (0.1 \times \text{II}) + (0.1 \times \text{III}) + (0.2 \times \text{IV}) + (0.5 \times \text{V}) \qquad (3)$$

That is, it has been given a high importance (50%) to the costs (economy) because it is thought that in many cases, the most cheap repair option is the selected one,

Table 2
Exposure scores for EN206 exposure classes

Class	X0	X1	XC3	XC3	XC4	XD1	XD2	XD3	XS1	XS2	XS3
Weight	0	1	1	2	3	2	3	4	2	3	4

Table 3
Proposed ranking of Importance, Im, in parts of unity of the weight, in the final decision of a repair work

Requirement *R*	Importance Im (in parts of unity)
R-I: Safety	0.10
R-II: Serviceability	0.10
R-III: Env. Impact	0.10
R-IV: Durability	0.20
R-V: Economy	0.50

together with that having the longer durability (20% of importance) without maintenance.

These percentages can be obviously varied at the convenience of the owner or the maintenance engineer and taking into account particular circumstances and management constrains. Thus, it may happen for instance that safety should be 20–30% of the total importance weight.

4. Application to reinforcement corrosion

The five methods of repair previously enumerated as the more commonly used to repair structures damaged by corrosion are:

1. patch repair,
2. cathodic protection,
3. realkalization/chloride extraction,
4. application of chemical inhibitors,
5. application of hydrophobic agents on the concrete surface.

The patching method is not a unique method, but a set of systems and materials, and in this paper, differentiation among the different market options and modes of operation will not be made.

Table 4 shows the exercise on the partial values of the RPI for each repair option, as well as their respective RI for the particular case of a corroding beam of a building. The partial values ascribed to the RPIs have been calculated by taking into account the availability of methods of repair in Spain and, therefore, can be different in other countries.

However, the calculation of the partial values of the RPI is not completely objective, because it is the result of the not quantified appreciation by the specialist. These partial values may vary, but should not vary for the same owner or maintenance engineer, who should establish their own set of values and

Table 4
Example of calculation of average weights given to the different RPI for the case of the repair of a beam in a building exhibiting corrosion

Requirement R	RPI	Cathodic protection	Electroch. Realkaliz.	Patching	Inhibitors	Hydrophobes
Safety I	I.a. Structural consequences of failure	1	1	1	1	1
	I.b. Failure type	3	3	3	3	3
	I.c. Execution control	4	2	4	1	2
	I.d. Feasibility of post-repair monitoring	4	3	2	2	2
	I.e. Safety of workers	3	2	3	4	4
	I.f. Safety of users	3	4	4	3	3
	Average R-I	3	2.5	2.66	2.16	2.83
Serviceability functionality II	II.a. Disturbance	1	2	3	4	4
	II.b. Fitness for use	1	1	4	2	2
	Average R-II	1	1.5	3.5	3	3
Environmental impact III	III.a. Emission pollutants	4	2	2	1	2
	III.b. Sustainability	2	1	2	3	3
	Average R-III	3	1.5	2	2	2.5
Durability IV	IV.a. Service life	4	2	4	1	1
	IV.b. Number of types of attack	4	4	4	4	4
	IV.c. Exposure class	4	4	4	4	4
	Average R-IV	4	3.33	4	3	3
Economy V	V.a. Direct cost/m^2	2	1	4	3	3
	V.b. Extension of damage	4	4	4	4	4
	V.c. Period of disturbance	2	1	3	2	2
	V.d. Maintenance cost	1	4	4	2	2
	V.e. Prep. of substance	1	1	2	1	1
	Average R-V	2	2.2	3.4	2.4	2.4

maintain them coherent until new information appears.

For the sake of illustration, the justifications of the partial values ascribed in Table 3 to the case of a cracked beams with corrosion are the following:

4.1. Safety

(a) *Consequences of failure*—the consequences of the structural failure are very important (level 1) as there is a risk of fatalities. All have the same weight as the consequences are the same.

(b) *Type of failure*—a ductile (level 3) type of failure has been assumed.

(c) *Execution control*
- Cathodic protection: (level 4)—due to the fact that usually the companies are very specialized and the quality control is high.
- Electrochemical treatments: (level 2)—because quality control is much more difficult in the sense that the end of the treatment is less defined and therefore the control is less clear.
- Patching: (level 4)—the quality control may be very efficient.
- Inhibitors: (level 1)—the quality control is not defined, the control of the critical amount in order to repassivate is not established.
- Hydrophobes: (level 2)—the quality control can be made through the change in colour and the number of applications although the real thickness of the product cannot be assessed.

(d) *Feasibility of post-repair monitoring*
- Cathodic protection: (level 4) due to the method enables the use of permanent sensors.
- Electrochemical treatments: (level 3) because periodical inspection of the efficiency of treatments is usually carried out.
- Patching: (level 2) because only visual observations are made in the post-repair period.
- Inhibitors: (level 2) as usually only visual observation is made although it is susceptible to be monitored by sensors (level 4) or by periodic measurements of the corrosion rate (level 3).
- Hydrophobes: (level 2) the explanation is very similar to that of inhibitors. Visual inspection seems to be the most common procedure of post-repair monitoring although sensors of periodic electrochemical techniques can be applied as well.

(e) *Safety of workers*: A level 4 was ascribed to inhibitors and hydrophobic agents as they are quick methods with no risk (except that of chemicals) towards the workers. A level 3 was given to patching due to the risk of accident when removing the concrete or cleaning the bars. The same weight level 3 was given to cathodic protection due to the patching repair and crack filling necessary prior to apply the current. In the case of Electrochemical, as high voltages are applied, a level 2 was given. Any level 1 was ascribed to any RPI as the repair is usually not large.

(f) *Safety of users*: Patching or electrochemical treatments are those that after being applied they are not disturbing at all the users (level 4). However, cathodic protection needs maintenance and therefore, the permanent current, although small, is always a certain risk in a house (a level 3 was given). Inhibitors and hydrophobic agents have to be periodically applied and therefore they are more disturbing (a level 3 was given as well).

4.2. Serviceability

(a) *Disturbance*
- Cathodic protection: (level 1)—due to the structure is modified by the permanent application of an anode, gunite and the rectifier to apply the current.
- Electrochemical treatments: (level 2)—being a non permanent system the disturbance is lower than cathodic protection.
- Patching: (level 2)—in the particular case considered, as the extension is not large, the disturbance of the removal of affected concrete is relatively small as well.
- Inhibitors: (level 4)—the treatment itself does not affect the structure.
- Hydrophobes: (level 4)—very similar to the case of inhibitors, the surface application does not affect the structure.

(b) *Fitness for use*: Patching is technically the most adequate repair method for the kind of problem studied and therefore a level 4 is given to it. Inhibitors and hydrophobic agents got a level 2 because they need the patching before their application and therefore each alone does not fulfill the fitness for use in present case. Cathodic protection or the Electrochemical treatments are technically not suitable for a small repair and level 1 was given to them.

4.3. Environmental impact

(a) *Emission of pollutants to the environment*: Cathodic protection has no chemicals able to release pollutants to the environment and therefore a level 4 is ascribed. However level 2 is given to realkalization as it needs the use of certain very alkaline solutions during the treatment. Patching gets a level 2 as well due these materials may be organic or polymeric-based. Inhibitors get 1 due to they are potential contaminants in the case of leaching, while hydrophobes get a level 2 due the shorter time they may release chemical contaminants.

(b) *Sustainability*: In terms of materials and energy consumed, the most demanding are the electrochemical treatments. As they apply high voltage and need materials that are removed at the end of treatment, a level 1 was ascribed. Cathodic protection and patching are also making use of a relatively higher amount of materials and energy and they got (level 2). The inhibitors need several applications at the beginning and (level 3) was given to hydrophobic agents as although they are the least demanding on materials, they need to be applied several times during the service life.

4.4. Durability

(1) *Service life*: Cathodic protection and patching will likely perform longer than 50 years without needing replacement as the repair extension is small (level 4). The length of duration of electrochemical treatment is not yet established and therefore level 2 was given to them. The inhibitors and hydrophobic agents need reapplications and level 1 was ascribed to them.

(2) *Number of attack types*—being only one (corrosion) the example considered all methods got level 4.

(3) *Exposure class*—is the same in all cases, XC2 or XC1 in the classification of EN206 [3] as was shown in Table 2.

4.5. Economy

(1) *Direct cost*—patching was considered the less expensive getting a level 4, while the other need a certain patching or filling of cracks prior to be applied. Thus, the hydrophobic agent and the inhibitors need to restore the initial geometry (they get level 3) plus their own cost, while the electrochemical treatments are more expensive (level 2) being the most the cathodic protection, because in addition, it needs maintenance (level 1).

(2) *Extension of damage*—is small in all cases (level 4).

(3) *Period of disturbance*—the longest would be the electrochemical treatments (level 1) while cathodic protection, inhibitors and hydrophobic agents need the restoring of the geometry plus their own application (level 2) and for patching a level 3 is ascribed.

(4) *Maintenance cost*—no maintenance is needed in the case of patching and the electrochemical treatments (level 4), while inhibitors and hydrophobic agents need periodical reapplication (level 2) and cathodic protection needs permanent monitoring (level 1).

(5) *Preparation of substrate*—all of them need the same preparation as patching plus the preparation for their own application. A level 2 is ascribed for patching and level 1 for the rest.

4.6. Calculation of repair index RI

From Table 2 and Eq. (2) the calculation of the RI results:

1.	Cathodic protection	RI = (0.30 + 0.1 + 0.30 + 0.8 + 1) = 2.50
2.	Electrochemical treatment	RI = (0.22 + 0.15 + 0.15 + 0.66 + 1.1) = 2.28
3.	Patching	RI = (0.25 + 0.35 + 0.20 + 0.8 + 1.70) = 3.30
4.	Inhibitors	RI = (0.17 + 0.3 + 0.20 + 0.6 + 1.2) = 2.47
5.	Hydrophobic agents	RI = (0.20 + 0.3 + 0.25 + 0.6 + 1.2) = 2.55

The above values that are plotted in Fig. 1 indicate that patching is the most feasible and economical repair method followed by the application of hydrophobic agents or cathodic protection.

5. Discussion

Till this time, the selection of a repair methodology depended very much on the local availability of repair methods and the judgements of specialists, usually based on technical merits. Owners are usually not specialists and they have their own economical or environmental requirements, in addition to the technical ones. The selection process results then to be a fragmented process neither comprehensive nor unified.

An algorithm to avoid the fragmented decision process is proposed. It is based on defining requirements, through RPI, and ascribing to them relative levels of importance (weights from 1 to 4) and the calculation of a repair index, RI, in which several RPI are summed up in different proportions.

The algorithm proposed implies a certain self-judgement not fully quantified when ascribing levels of importance or weights to each of the repair performance indicators, RPI. This lack of complete objectivity may seem a lack of rigour, however, life cycle cost

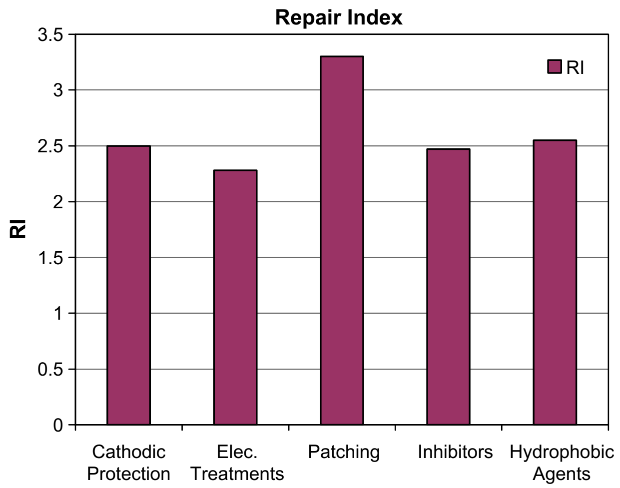

Fig. 1. Repair index obtained for the case of the repair of the beam of the figure.

analysis, LCCA, which may appear to be more rigorous, still lacks of enough data to be reliable. Both methods, (the RIM proposed here and the LCCA) are at present partially subjective, although it is expected that LCCA will be fully quantified and then, the RIM would be calibrated remaining as a more direct alternative.

One remark to be made is that the example presented shows that the RPI: Ib, IVb, IVc and Vb (see Table 4) do not help to distinguish differences among the several repair methods and, therefore, it might be better not to consider them.

It has to be stressed as well that the RI Method proposed obviously has to be adapted to the owners needs and to the local availability, workers and economy of each of the repair methods to be used.

Finally, the RIM enables the possibility to include other non-technical requirements that would be difficult to quantify in a LCCA. Thus, aspects like ecology, legal or social aspects, can be scored from 1 to 4 more easily and incorporated into the algorithm of RIM for the particular repair work. Their quantification through a LCCA seems more difficult.

6. Conclusions

The present decision process to select a repair option lacks of quantification unless a life cycle cost analysis, LCCA, is undertaken. However, it is difficult to rigorously perform a LCCA as several of its steps lack accurate information. In this paper an alternative to a LCCA named the repair index method, RIM is presented based on an algorithm which contains the following steps:

(1) The definition of requirements, R, through repair performance indicators, RPI. Five R have been selected: (1) Safety, (2) serviceability, (3) environmental impact, (4) durability and (5) economy, each with several RPI.
(2) The RPI are quantified by means of ranking them from 1 to 4 and an average value or score for each R_i is obtained through:

$$R_i = \frac{\sum \text{RPI}_i}{\text{number of RPI}_i}$$

(3) A repair index, RI, is then calculated through an expression which multiplies the value of each R_i by its proportional importance, Im, in the total value of the repair work:

$$\text{RI} = \sum_{0}^{n=5} (\text{Im})(R_i)$$

(4) The benchmarking is made through the comparison of the RI obtained for each repair option.

Finally, it has to be stressed that this algorithm enables the incorporation of non-technical requirements, as of social and legal type, in the decision process of repair method selection by defining indicators and scoring them from 1 to 4.

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