Elements with shorter lifespan and their maintenance, the impact of a poor design on cost and carbon foot-print

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Summary

The lifespan of a structure is established in the national code and the project; however, all structures contain elements with a shorter lifespan that require repair or replacement. Supports, parapets, drainage, joints, waterproofing, cables, tendons, and seismic devices are included in this group. When accounting for carbon emissions and their costs at the design stage, replacement and maintenance are considered but are sometimes underestimated and overlooked. Frequently, designers even disengage themselves from this part of the design and these types of devices are made by a different and independent team. This paper showcases four examples of how neglecting these shorter lifespan elements and their maintenance significantly impacts the whole-life cycle carbon footprint and cost.

1 INTRODUCTION

How a structure balances the cost, the environmental impact and the social outcomes during the whole-life cycle will define it as more or less sustainable. Studies on life cycle assessments already state that « ...the maintenance stage has been identified as the longest and most influential through the life cycle. Individual design which reduced maintenance activities and therefore material consumption, and waste is highly recommended. It is thus proposed for the designer to utilise structural components with suitable maintenance solutions, such as fewer small components » [1]. However, besides components themselves, other factors influence the reduction of maintenance activities, materials, and waste. Poor detailing is a key factor, especially where it allows water ingress into the structure.

2 MAINTENANCE AT DESIGN STAGE

A maintenance plan should be an integral part of the design [2] and its aspects should be considered from the conceptual design stage. We propose two steps of thinking at this stage.

2.1 Causes

An exercise to envisage future problems is required at the conceptual and detailed design stage with the aim to foresee as much as possible unexpected accidents, deterioration agents and changes.

Certainly, accidents are a reason for replacements and repairs before the lifespan, from bridge strikes to fires, yet premature deterioration due to poor design of the expansion joints and failures of waterproofing leading to corrosion might be more common (Fig. 1).

Fig. 1 (Left) Beams and bearings affected by a fire beneath the deck of a bridge. (Right) Premature deterioration due to a design of the expansion joint in zig-zag with the beams instead of skewed.

Similarly, a bad enlargement design could significantly affect the condition of the bridge. Fig. 2 shows the deterioration after a defective modification of the drainage during an enlargement.

Fig. 2 Concrete spalling as a consequence of an inadequately modified drainage system.

There are also other reasons behind the need to change components before the expected. During the twentieth century, for example, prestressed tendons were an innovation and at that time their maintenance and durability in the long term were not known as well as nowadays. This led to protection failures in some designs of the time. Innovative products and materials should be included in the design with the caveat of unforeseen maintenance actions.

2.2 Reviewing the design

After the exercise of visualising potential problems in the future, it is required to evaluate the design concerning the maintenance and repair situation. Some basic aspects that must be covered are:

- Temporary works required and how they will be secured.
- The magnitude of the temporary reactions and where they will be applied.
- Changes of loads during maintenance and repair situations and auxiliary means required.
- The access to the works and its room for materials and tools.

This task requires knowledge, experience and creativity to be able to anticipate all potential problems and constraints without overdesigning.

In the United Kingdom the C543 Bridge detailing guide published by CIRIA in 2001 has been widely adopted and included in the bridge design statement of the projects [3]. The guide aimed to improve the quality and standardisation of construction details with a focus on reducing the potential for water ingress into highway bridges and their maintenance problems. It was written with the best understanding and knowledge of the time in the UK and, although it does not cover all situations and needs, it is a recommended start which could be replicated in other countries. See examples in Fig. 3.

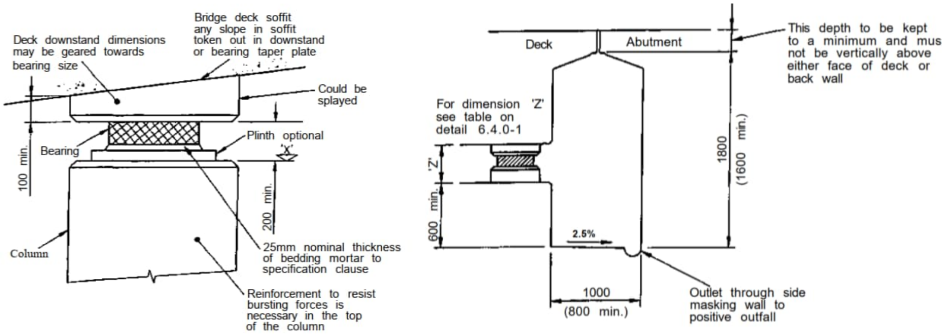

Fig. 3 (Left) Detail 6.4.0-4 from Ciria C543 [4] showing bearing plinth at discrete column guidelines. (Right) detail 6.5.0-2 from Ciria C543 showing recommended dimensions for abutment galleries.

3 CASE STUDIES

We present four case studies to illustrate how neglecting different aspects of maintenance, such as repairs and replacements, could impact the cost and carbon footprint of a structure at its maintenance phase.

3.1 Change of supports

The first case study is a tank for water already treated within a treatment plant. It is a cylindrical-shaped structure made of reinforced concrete. The tank is covered by a structure comprised of a lightened slab with a compression layer on top of concrete beams supported by columns (Fig.4). The dry connection between columns and beams resulted in most of the beams resting on the edges of the columns, causing both elements to break.

Fig. 4 Detail showing displacements, cracks and spalling at the corner.

The solution adopted consisted of the installation of steel brackets to unload the column and move the support area towards the centre of the span. Since the column was thin, there was no other option but to anchor the brackets using through-holes and tension bars (Fig. 5). This intrusive and delicate work requires knowing the condition of the concrete and the location of the reinforcement.

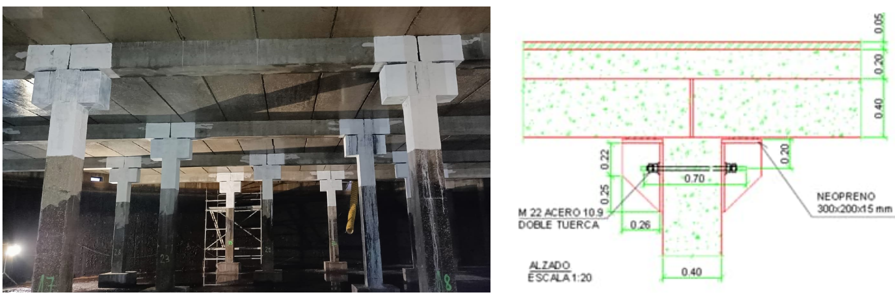

Fig. 5 Repairs being undertaken (left). Detail of the solution showing (right).

In addition, this repair was not considered during the design stage, and therefore, the structure was not prepared for the required change of supports. There was only a small access hole to introduce the necessary material and equipment inside the tank (Fig. 6). A creative system was required consisting of a bespoke small spider crane designed for the occasion (Fig. 7).

Fig. 6 (Left) Access hole; (right) the ancillary structure used during the works.

Fig. 7 Bespoke small spider crane designed for the works.

The design could have avoided these problems and defects for example, by installing elastomeric bearings at the columns. For the replacement of the bearings, the design should have left a larger access.

3.2 No room for jacking

The second case study is shown in Fig. 8. The bridge was not prepared for the replacement of the bearings at the abutments. It was necessary to embed some brackets made of steel beams (HEB and IPN) at the face of the abutment to take the reaction of the supports given their great magnitude.

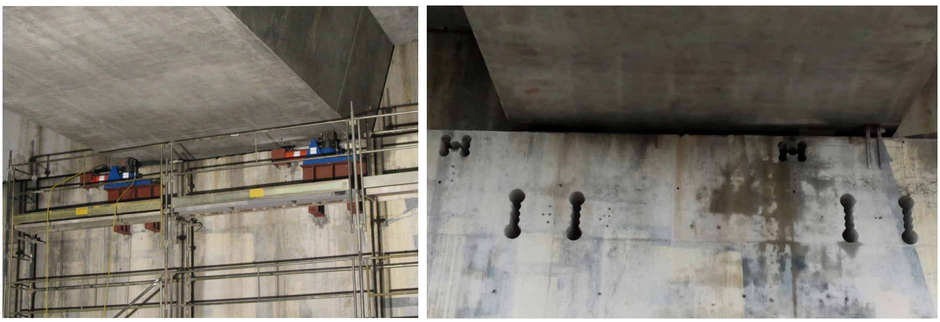

Fig. 8 (Left) Ancillary works. (Right) the trace left afterwards.

The design should have considered reinforced concrete cantilevers at the abutment or leaving enough room under the deck for the installation of jacks.

3.3 Failure to plan for bearing replacement

The structure in the third case study is a three-span highway bridge consisting of a reinforced concrete superstructure supported by two circular piers at each support location (Fig.9). It required a routine replacement of the bearings. Because a channel nearby did not allow excavation, it was impossible to build an ancillary tower, where to place the jacks, on top of the foundation of the piers. Furthermore, the jacks did not fit on the piers, nor could brackets be anchored to the double cylindrical columns as in the previous case, due to their small size.

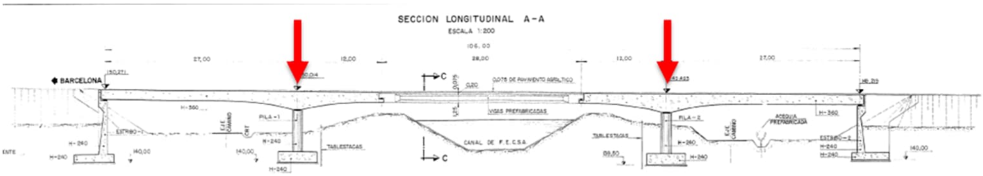

Fig. 9 Elevation of the bridge showing the resultant of the deck weight at the circular piers.

To lift the deck, two bespoke friction jacking collars were designed with a minimum design load of 1400 tons each. Each of these collars consisted of two cantilevered beams welded to a collar with a total steel weight of 10t (Fig.10). Just the change of supports cost 200,000 euros.

Fig. 10 (Left and right) Collars designed due to the lack of room for a routine jacking procedure.

The carbon footprint of this jacking collar is a huge addition to the usual embodied carbon for maintenance works. It was not calculated at the time and for this study is enough to compare the 10 tons of steel used for both collars and two elastomeric bearings. Table 1 shows the disproportional impact of the required solution. The steel alone, not including the embodied carbon due to assembly and welding, is seven times bigger.

Table 1 Comparison of embodied carbon between bearings and the amount of steel used for the jacking collars [5].

Element	$kgCO_2eq$	Comment
2 Elastomeric Bearings Vertical load (10000kN-20000kN)	1709	Modules A1-A3 + A4 + A5w [6]
10t of world average engineering steel	12700	ICE library data base

3.4 External prestress

The fourth and last case study is a viaduct carrying the high-speed train line between Madrid and Barcelona. It consists of twelve continuous spans with a concrete box superstructure with external prestress tendons within the box (Figs.11 and 12). An annual inspection of railway viaducts in Spain revealed a ruptured tendon, and subsequently, corrosion problems were detected in all of them.

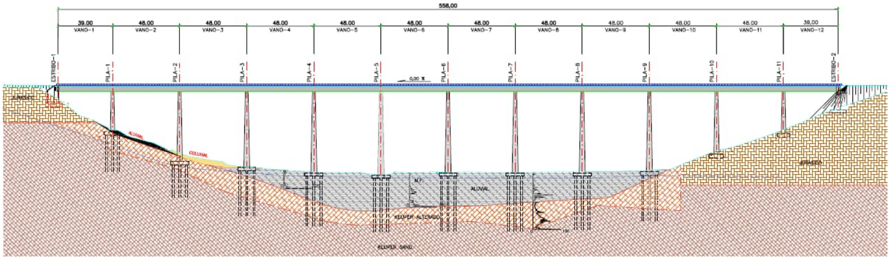

Fig. 11 Elevation of the viaduct.

The maintenance work consisted of replacing two families of external prestressing, raising the deck diaphragm at the fixed abutment by one meter, and concreting the interior of the box to anchor the new tendon.

Fig. 12 (Left) Cross section of the deck; (right) and picture showing the internal tendons.

External prestress technology became popular at the beginning of the twenty-first century in Spain due to the ease of replacement. The problem lay in the lack of the necessary means for replacement.

The machinery required to replace the tendons had to be transported within a 930 mm wide gallery with straight corners. A custom-made rail system with pulleys was installed to move through the confined space (Figs. 13 and 14).

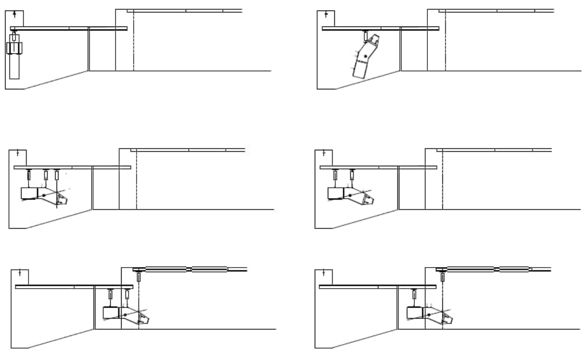

Fig. 13 Rail system with pulleys movements study.

Fig. 14 (Left) Gallery. (Centre and right) tendon anchor system being moved through the gallery.

Another challenge during the maintenance work was the necessary formwork. This had to be custom-made (Fig. 15). Currently, manufacturers and suppliers do not offer such small formwork, so the contractor had to build it with bolts, in a Mecano-style.

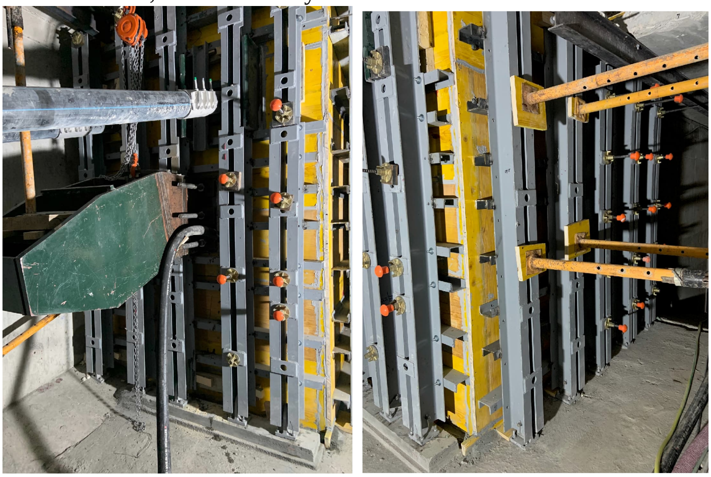

Fig. 15 Formwork of the anchor system

The cost of the complete work was 3.5 million euros. The design could have significantly reduced this cost with better access and a diaphragm at the abutment prepared to allocate the required anchors for cable replacement. In the new extension, some steel plates were installed to weld the next anchors in case more tendons need to be replaced in the future.

It is worth noting that the 930mm gallery, Fig. 14 (left), is wider than the 800mm minimum given in C543, Fig. 3 (right). Guidelines such as C543 may not consider the material needed for repairs and therefore, the use of the bare minimum should be challenged when necessary.

3.5 Carbon footprint

Special emphasis must be placed on the need for purpose-built equipment in the four case studies presented that could have been avoided during the design.

The carbon footprint of using construction equipment depends on several parameters, the most influential of which are: intensity of use (the amount of equipment required could be reduced by maximizing the utilization rate); equipment suitability (using the right equipment for the task); transportation (with the benefit of shorter distances and higher load factors); and maintenance. By optimizing equipment use, we could achieve reductions of between 30% and, in some cases, 50% [7]. The amortization cost of the machinery is considered obvious and will not be addressed in this study.

Therefore, manufacturing equipment specifically for a task that will not be repeated for years and that cannot be reused in other structures considerably increases the carbon footprint and the cost of the maintenance phase. This can be avoided at the design stage by considering the basic issues mentioned in section 2.2.

4 CONCLUSIONS

Four examples have been presented demonstrating that if repairs and replacements of elements with a shorter lifespan are not adequately considered during the design stage, they could be disproportionately costly and complex.

The design must include a maintenance plan. This should serve as a guide for the designer responsible for maintenance; for example, it should indicate where to place jacks or which areas are reinforced for future maintenance operations.

To develop this plan, we proposed including two steps in the early stages of the design. First, a visualization exercise of potential problems in the future. A broad perspective should be taken to identify all possible repairs and replacements. Second, a review of the design to ensure access and space for these works. Appropriate equipment should be considered, trying to avoid the need for purpose-built equipment as much as possible.

The design of the accesses should consider the need for small repair equipment in addition to maintenance personnel. Guidelines such as C543 may not consider all these aspects of repair, and if necessary, the use of the bare minimum should be questioned.

It is known that poor drainage and waterproofing design could result in a reduced lifespan. It was highlighted that care should be taken during any changes, such as extensions or repairs, to ensure they are not negatively affected.

Also, it was reminded that clients should implement appropriate archiving systems to retain as-built records throughout the lifespan of the structure and thus minimize the impact of intrusive works, if necessary.

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