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Research Basis on The Potentials of The Saw-Cut Technique Applied to Prestressed Concrete

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Abstract

In the prestressing design, the designer must set the prestressing force introduced to the concrete member and estimate both the short- and the long-term prestress losses, so that the structure meets its requirements over its service life. Since construction practice has commonly not considered the use of devices for monitoring after casting, prestress losses are usually unknown, and therefore the residual prestressing force. Hence, this paper presents the basis of a research project motivated by the need to formulate reliable assessments in the field of existing prestressed concrete structures (EPCSs. The project aims the implementation of a specific methodology for the diagnosis of the residual stress-deformational state of EPCSs, and is based on the potential synergy of the Isolated Concrete Block Method (ICBM) as an empirical basis and a multi-level structural modelling strategy following the latest trends. With a schedule developed through six tasks, it is intended to follow a working methodology that integrates the design/modelling and experimental aspects, so that there is an almost continuous feedback between both. According to the expected impact of results, the ICBM, which has a clear potential to become a reference non-destructive, practical, economical and reliable method, is suitable to promote an active approach to EPCSs maintenance.

1. Introduction

The accurate determination of the residual prestressing force is essential within the context of the assessment of existing prestressed concrete structures (EPCSs), since the effect of prestressing has a major impact on the stress-deformation responses and capacities of such structures under both serviceability and ultimate conditions. The de-sign of concrete prestressing is usually approached under stress criteria (allowable stresses in the elastic-linear re-gime) in accordance with the limitations imposed by codes and regulations, taking into account both geometrical limitations, derived from the minimum tendon cover requirements, and technological constraints (e.g. prestressed or post-tensioned reinforcement, internal or external prestressing, ...) and the subsequent variations of the prestressing force throughout the service life of the structure.

The prestressing of concrete by means of reinforcement requires the reinforcement to be stressed. The need to con-form to the design and the regulatory requirements for quality control require that the value of the "prestressing force" is known and documented, usually from the measuring devices (pressure sensors) of the hydraulic actuators used. Afterwards, with the transmission or introduction of the prestressing into the concrete, either by detensioning in the case of pre-stressed reinforcement or by anchoring in the case of post-stressed reinforcement, the resulting tensile force in the active reinforcement is the so-called "prestressing force", a force which is not usually known and which has different values both along the tendon and over time. Thus, "prestressing loss" is defined as the difference between the “prestressing force” and the "residual prestressing force" (prestressing force in a section of the structural member at a given time). Prestressing losses can be of different origin, and are usually classified as follows:

- Instantaneous: by penetration of anchor wedges, by elastic shortening of the concrete, and also, in the case of post-stressed reinforcement, by friction with the sheaths, and in the case of pre-stressed reinforcement, by re-laxation of the reinforcement, by thermal expansion and by shrinkage of the concrete up to the instant of pre-stress transfer.
- Deferred: by shrinkage and creep of the concrete and by relaxation of the active reinforcement.

In the design of the prestressing, the designer sets the prestressing force and makes an estimate of the prestressing losses, so that the final value of the prestressing force is equal to or greater than that required for the structure to meet its requirements throughout its service life. However, prestressing losses are not usually known, and therefore neither is the residual prestressing force, since the usual construction practice to date has not considered the incorporation of measuring devices in concrete structures to monitor them over time. Therefore, there is a great deal of uncertainty when it comes to assessing the extensive stock of EPCSs, as it is increasingly necessary to have information on the condition of the structures: maintenance plans, service life prediction tools, decision-making criteria in the event of extraordinary events, etc., are undoubtedly elements that enhance sustainability in the field of infra-structure management.

For a large number of existing structures, the design life has been or will be reached in the near future, as highlighted in FIB bulletin no. 80(2016) [1]. This is because a large part of the existing structures was built in the 1960s, and may need a comprehensive assessment from a risk and reliability point of view. In this context, several studies [2-5] carried out on EPCSs (in service between 25 and 40 years) have found an appreciable deviation between the measured prestressing losses and the losses predicted by the models provided in the codes. Thus, it is clear that there are difficulties in determining the residual prestressing forces using the models provided by the codes. These difficulties are related to factors including (among others) assumptions about the characteristics of the prestressing system and time-dependent phenomena, as well as the possible development of degradation processes. Uncertainties associated with prestressing have on occasion led several prestressed concrete bridges to structural collapse [6,7]. Consequently, and as stated in the Strategic Plan 2020-2023 of the World Road Association (PIARC) [8], the scientific method and state-of-the-art knowledge for the assessment of existing structures should be promoted.

2. Current status

Despite the above uncertainties, there are few empirical methods to assess the condition of prestressed members, and their application is not always feasible. Destructive methods include [5]:

- Cracking moment (crack initiation).
- Concrete decompression (crack re-opening).
- Tendon cutting.

Destructive methods inevitably cause structural damage and are therefore unsuitable for application to in-service structures, hence the interest in developing non-destructive methods (or with conditions that only require aesthetic restitution) such as:

- Tendon deformation (exposed tendon) [9].
- Hole drilling [2].
- Saw-cuts [10].

On the other hand, although reliability-based assessment of existing concrete structures has been the subject of research over the past decades, a coherent structural assessment framework and a practical approach compatible with Eurocodes and applicable to existing concrete structures is currently lacking. Trends point towards multilevel structural modelling strategies [12-13]. The idea is as follows: with different design expressions and methods, the higher the level of approximation and the more sophisticated the analysis, the more realistic the safety estimation will be and the more possibilities there will be to find "hidden" structural capacities, so that the likelihood of avoiding overly conservative assessments and of incurring unnecessary costs resulting from decisions taken after assessment will also be higher.

The Model Code [14] has taken an important step in providing safety formats to be used in connection with non-linear finite element analysis. These safety formats define safety factors for material properties and overall structural strength. However, the development of specifications on how to perform the analyses has not kept pace with the development of the safety formats. There is no doubt that results using non-linear finite element analysis can be substantially influenced by the model and human factors arising from the skill of the analyst. In this respect, the recent (2020) guidelines promoted by the Dutch Ministry of Infrastructure [15] constitute a very advanced body of documentation that allows clear and common criteria for the analysis of existing structures to be established. Multilevel structural modelling strategies usually work by applying different degrees of modelling refinement, e.g. [12]:

- Level I: simplified linear analysis
- Level II: linear finite element analysis
- Level III: 2D non-linear finite element analysis
- Level IV: 3D finite element non-linear analysis, with perfect bond
- Level V: 3D non-linear finite element analysis, with bond constitutive laws.

With all this, the evaluation strategy using multilevel structural modelling must be "fed" with experimental results, with the saw-cut method [10] being the one addressed in this Project, as it is still far from being developed and validated for a reliable application. With this method, the residual prestressing force is obtained from the response of a concrete block formed by making surface cuts with a circular saw. These cuts are made perpendicular to the prestressing direction, defining a concrete block between two cuts which is isolated from the effect of the prestressing; the concrete in the block is decompressed. The deformations on the surface of the isolated block are obtained by comparison with the pre-cut state. Once the deformations are known, the stresses are computed and entered into a calculation model to determine the residual prestressing force.

Among the few documented realisations of this method it can be found a study carried out with beams from the Logan Canyon Bridge (Utah, USA) [16], and the evaluation of the Kiruna Bridge (Sweden) [10]. In both cases the method was used in conjunction with other destructive methods, and in neither case was the prestressing force monitored, so the residual prestressing force estimate was obtained from indirect measurements. Consequently, it is of the utmost interest to carry out an experimental investigation to materialise the saw-cut or isolated Concrete Block Method (ICBM) with prestressing force monitoring, in order to know the sensitivity of the method to different parameters (e.g. strip width between cuts, cut depth, stress level, ...) and to be certain about the actual prestressing force acting.

3. Justification for the proposal

Existing infrastructure and the built environment represent approximately 50% of national wealth in most developed countries [12], and the costs associated with their maintenance constitute about 50% (and tending to increase) of the total construction sector [17]. In Spain, the State

Road Network has more than 15,000 crossing structures with spans of at least 10 m in length, technically known as "bridges". Given these orders of magnitude, it is necessary that the decisions to be taken regarding the potential actions to be carried out for the adequate preservation of a structure (e.g. repair, reinforcement, limitation of actions, ...) are supported by adequate diagnoses, which will be all the more accurate to the extent that they are based on an adequate determination of the stress-strain state of the structure. In turn, the stress-strain state must be properly contextualized in the life cycle of the structure, in order to take into account for the interrelationships between the phases that make up this cycle, taking as initial reference the project phase (e.g. design methods and values), the specificities inherent to the construction phase (e.g. properties of the materials supplied) and the "clinical history" (e.g. previous inspections) corresponding to the service life phase.

Therefore, the need to formulate reliable diagnostics in the field of the assessment of existing prestressed concrete structures, in a context of a regulatory vacuum that makes it necessary to advance at the frontier of knowledge with the support of recently published reference documents, together with the large number of structures susceptible to assessment, justify this R&D&I Project based on the synergy of a new non-destructive method as an empirical basis and a multilevel strategy for structural assessment.

4. Research objectives

The general objective of the Project is to implement a specific methodology for the diagnosis of the residual stress-strain state of existing prestressed concrete structures. This general objective involves achieving the following specific objectives:

- To develop prediction models of the residual stress-strain state.
- Set up a guide for the application of the ICBM.
- To develop a modelling tool for structural assessment based on the residual state.
- To establish a guide to the application of multilevel structural analysis based on the residual stress-strain state.

5. Work packages

It is intended to follow a work methodology that integrates the aspects of design/modelling and experimentation, so that there is almost continuous feedback between the two throughout the development of the project. All the elements (beams and slabs) under study will have an initial design, as well as a pre-modelling and a post-modelling of their behaviour in a computer laboratory. The pre-modelling will be the simulation carried out with the available data before the element is tested in the experimental laboratory, while the post-modelling will correspond to the simulation incorporating the information obtained from the observation and the results obtained in the experimental laboratory. Under this premise, the development by stages, and additionally the sequential study foreseen in Stages 1 and 2, will allow progressing towards a progressive refinement of the pre- and post-modelling. In this way, the pre-modelling of element "i" will incorporate the aspects already known and introduced in the post-modelling of element "i-1"; in turn, once element "i" has been tested in the experimental laboratory, it will be post-modelled and the advances obtained will be incorporated into the pre-modelling of element "i+1". Based on this concept, the work plan is detailed, which includes the following tasks and milestones:

5.1. Task 1. Design and modelling of elements to be tested (beams and slabs).

The initial design will be approached according to simplified methods usually applied to prestressed concrete structural elements, for different combinations of parameters (concrete strength, prestressing force, prestressing eccentricity, cross-section, and distribution of transverse reinforcement). It is estimated that elements of 3-4 m length and rectangular cross-section will be optimal in terms of representativeness of the phenomena to be studied, consumption of resources and equipment required. Preferably, Y 1860 S7 prestressing steel strands will be used. All the elements designed will be pre-modelled in 2D with non-linear behaviour, using the DIANA FEA software.

A collection of designs shall be available from:

a) In the case of beams:

- 2 class of concrete (HP-40 and HP-70).
- 3 levels of prestressing force (75%, 60% and 50% of the maximum prestressing force allowed by the Spanish Structural Code and Eurocode 2).
- 2 depth (cross-section).
- 2 eccentricities (sectional positioning of the prestressing force).
- 2 transverse reinforcement distributions.

It should be noted that the combination of 2 concretes, 3 prestress levels, 2 depths and 2 eccentricities results in 24 different stress-strain states.

b) In the case of slabs: a single combination of concrete type-prestressing force, varying the distance between prestressing tendons. The aim is to see how the spacing between tendons affects the strip width between cuts, for different cut lengths and with different degree of interception in terms of number of tendons.

Milestones:

- 1.1. Design of the structural elements to be tested.
- 1.2. Initial behavioral models.

5.2. Task 2. Characterisation of materials (concrete and prestressing reinforcement): mechanical and bonding properties.

Obtention and characteriation of standard concretes based on the design of the corresponding mixtures; the compressive and flexural strengths and deformation moduli of the concretes to be used in the manufacture of the elements will be determined, analysing the evolution of these properties with age.

With regard to the prestressing reinforcement, the characteristics certificate shall be requested from the supplier, and tensile samples shall be tested.

The bonded concrete-strand interaction shall be studied by determining the transmission lengths. Note that the ICBM should be applied in region B (Bernouilli) of the structural element, as shown in Figure 1:

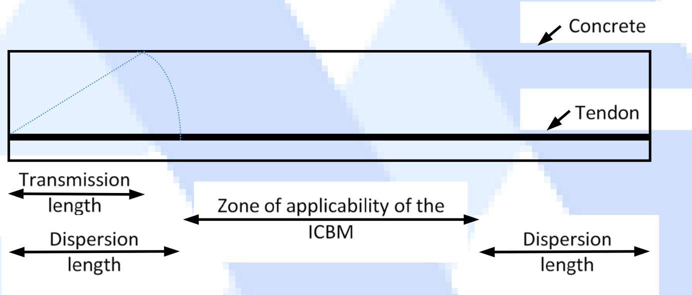

Figure 1. Idealisation of the zone of applicability of the ICBM

Milestones:

- 2.1. Test results of mechanical properties of concrete.
- 2.2. Results of tendon mechanical properties tests.
- 2.3. Definition of the area of applicability of ICBM.

5.3. Task 3. Development of Stage 1: ICBM tuning in beams.

Starting from the designs and models resulting from Task 1, with the materials characterised in Task 2, the ICBM will be developed through the sequential study of 5 type beams.

BEAM 1: positioning of cuts. The area of application of the ICBM will be instrumented on its most stressed face with strain gages arranged longitudinally (in the pre-stressing direction), foreseeing the practice of 6 cuts (Figure 2). To set the positions of the cuts (1 to 6), the simulation of the response will be based on the pre-modelling of the beam including the effect of the cuts, and the length of the strain gage to be used (estimated at 5-6 times the maximum size of the aggregate) and the spacing of the guard so that the instrumentation is protected from the cuts will be determining factors. For the same cutting position, the cut will be made progressively, advancing in steps (tentatively with a depth of 5 mm). First, cuts shall be made at positions 1 and 6, and the response detected by the strain gage assembly shall be observed. It will be crucial to analyse how the prestressing develops in the vicinity of the cuts. Once the maximum depth of cut at positions 1 and 6 has been exhausted, the same procedure shall be followed for positions 2 and 5, and then for positions 3 and 4.

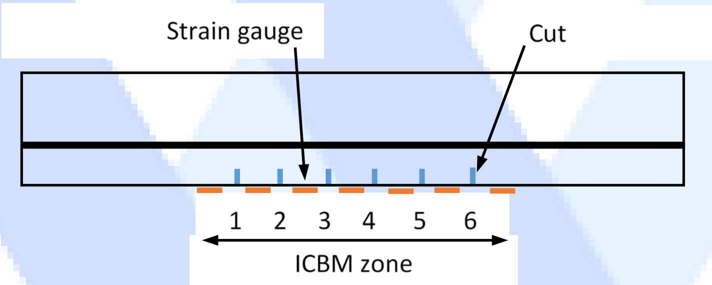

Figure 2. Layout of cuts and strain gauges in BEAM 1

BEAM 2: repositioning of the neutral fibre. Based on the results of BEAM 1 and a new modelling, another 6 shear positions will be set, in this case to form 3 ICBs that will be analysed: ICB 1-2, ICB 3-4 and ICB 5-6 (Figure 3). The most stressed face will be instrumented in the same way and strain gages will also be placed along the edge of the beam to analyse the effects of the cuts on the deformation profile.

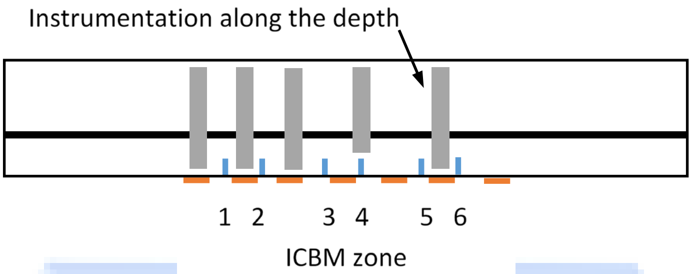

Figure 3. Layout of cuts and strain gauges in BEAM 2

BEAM 3: influence of transverse reinforcement. The starting point will be a beam design incorporating transverse reinforcement, so that given its spacing, the response of ICBs positioned in correspondence and in alternation with respect to the transverse reinforcement distribution will be analysed. The instrumentation scheme shall follow the guidelines of BEAM 2.

BEAM 4: sensitivity to stress Level-I. All the knowledge acquired with regard to ICBM will be used and a new BEAM 1 will be studied, in this case by instrumenting and cutting the less stressed face.

BEAM 5: sensitivity to stress level-II and pilot destructive test. A beam similar to BEAM 1 will be studied, with a different edge, which will have the most advanced pre-modelling in this Stage; it will be instrumented in an optimised way in terms of the number of ICBs (1 or 2) on the most stressed face, avoiding cuts in the central section of the ICBM zone with the idea of carrying out a pilot destructive test of great interest for Stage 3. This destructive test will be carried out in a 4-point load/reaction configuration, so that experimental information will be obtained on the cracking moment, the extent of the cracked zone and the exhaustion. These results will be used to contrast with traditional empirical methods (crack initiation and crack re-opening) and post-modelling of BEAM 5 will provide an excellent starting point for pre-modelling and possible revision of Stage 3 beam designs.

Milestones:

- 3.1. Characterisation of the extent of stress release in ICB concrete in beams (ICB length = element width).
- 3.2. Definition of the ICB: width, depth and shear progression, and positioning with respect to the transverse reinforcement.
- 3.3. Sectional impact of the ICB.
- 3.4. Additional recording of deferred losses in beams.
- 3.5. Pilot destructive testing.

5.4. Task 4. Development of Stage 2: application of ICBM on slabs.

The study of 2 slabs will be carried out. The prestressing will be introduced differently in each slab by varying the distance between prestressing tendons. Isolated concrete blocks (ICBs) of different lengths, intercepting a certain number of tendons as well as differentiated zones of influence of the tendons (Figure 4 shows some examples). Strain gages shall be arranged in and around the ICBs, considering coincidence and alternation of tendon positions. Based on the arrangement and configuration of the different ICBs in the 2 slabs, the possible effects due to the spacing between tendons will be analysed and the requirements to be met in terms of ICB length will be determined, as well as the convenience of forming a ICB by means of 4 parallel cuts two by two.

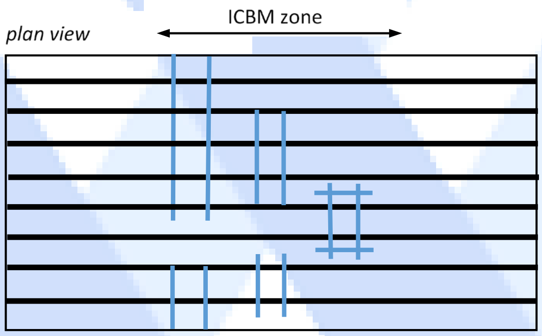

Figure 4. Layout of proposed cuts in a slab

The slabs will be placed under different environmental conditions in order to obtain records of the evolution of deferred prestressing losses.

Milestones:

- 4.1. Characterisation of the extent of stress release in ICBs in slabs (ICB length ≤ element width).
- 4.2. Definition of the ICB to be tested: length and transverse positioning.
- 4.3. Additional recording of deferred losses in slabs.

5.5. Task 5. Development of Stage 3: diagnosis of beams with ICBM.

In this task, a study campaign will be carried out with the 24 stress-strain states defined in Task 1. The initial designs may be subject to revision, and the highest possible multilevel structural analysis representing the detected effects of greatest impact will be applied. The computer laboratory and experimental laboratory work will go hand in hand for each element: (1) pre-modelling, (2) application of ICBM and diagnosis of the residual stress-strain state, and (3) post-modelling. The pre-modelling will focus on the prediction of the residual stress-strain state, while the post-modelling will focus on the reproduction of the diagnosis obtained. The different prestress levels introduced in the beams will be representative of 3 time instants that will be contextualised in the lifetime of the structure. The guidelines on instrumentation, positioning and materialisation of the ICBs will be in accordance with Task 3.

Milestones:

- 5.1. ICBM application protocol.
- 5.2. Prestressing loss recording.
- 5.3. Prediction of diagnostics in computer laboratory.
- 5.4. Obtaining diagnostics in experimental laboratory.

5.6. Task 6. Pilot testing and implementation of guidelines for structural assessment.

Based on the scientific-technical knowledge gathered throughout the Project, the drafting of documents will be undertaken that include the guidelines, recommendations and contextualisation of both the potential application of ICBM in the field of maintenance and assessment of prestressed concrete structures, and the suitability of considering approaches based on a multilevel structural modelling strategy in this field. Likewise, possible proposals for adjusting the design methods related to the estimation of prestressing losses will be implemented, in order to finally carry out pilot tests for the application of ICBM and multilevel structural modelling on beams manufactured on a real scale by a precast prestressed concrete company in the area.

Milestones:

- 6.1. ICBM application guide: diagnosis of the residual stress-strain state.
- 6.2. Guide to the application of multilevel structural analysis of the residual stress-strain state.
- 6.3. Review of prestress loss estimation design methods.
- 6.4. Pilot testing of real beams under controlled conditions.

6. Schedule

Figure 5 summaries the schedule for the Project Work Packages.

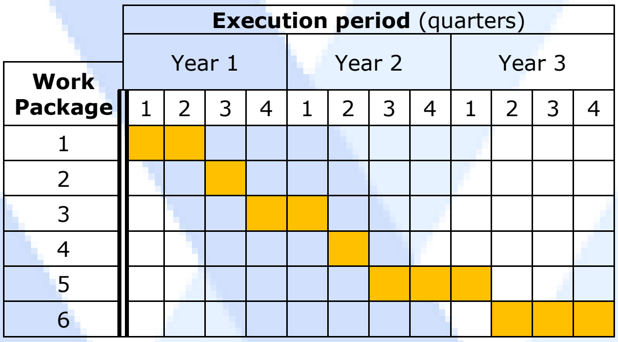

Figure 5. Schedule for the Project Work Packages

7. Conclusions, expected impact of results

The results of the Project will represent a significant advance in the frontier of knowledge, which will have a scientific-technical impact that will be reflected in:

- Promotion of the scientific method and state-of-the-art knowledge oriented to the evaluation of EPCSs.
- Contribution to overcoming the existing regulatory vacuum in the field of the assessment of EPCS.
- Technological, competitive and functional improvement, with the development of a new non-destructive test method capable of providing more reliable diagnostics of the stress-strain state of EPCSs.
- Development of advanced specifications on how to perform structural analysis with varying degrees of modelling refinement.
- Updating of design methods for estimating prestressing losses by reducing uncertainties in the determination of the residual prestressing force, which will allow the design of more resilient structures in the future.

Regarding the socio-economic impact, it is noted that:

- The Project has a preventive impact, in order to avoid or delay the appearance of problems that, if postponed, would be more complicated and costly to solve.
- The potential practicality, cost and reliability of the ICBM make it a non-destructive method of reference for the evaluation of prestressed concrete structures, which will make it possible to "popularise" the carrying out of a greater number of evaluations.
- The Project contributes to the Sustainable Development Goals: SDG 9 "Industry, Innovation and Infrastructure", SDG 12 "Responsible Consumption and Production" and SDG 13 "Climate Action", as the experimental and modelling tools resulting from the Project for the development of diagnostics will support decision-making criteria on the extension of the useful life of structures.

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Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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