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Effect of single and twin notches in prestressed concrete beams

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ABSTRACT

Main codes and standards offer sufficient provisions for the prestressing design of prestressed concrete members (PCMs). The designer must set the prestressing force and estimate the prestressing losses, so that the PCM meets its requirements over its service life. In addition, PCM can be instrumented during casting (e.g. vibrating wire strain gauges, magneto-elastic devices ...) with the aim of measuring parameters of interest for a real-time monitoring in service in a direct manner. In particular, a key parameter is the residual prestressing force at each time. However, there are many PCMs, which were cast without instrumentation, and consequently, the residual prestressing force can only be estimated indirectly. In these cases, additional complexity must be considered in relation to the initial prestress, the materials properties, their evolution, and the accounted short- and long-term prestress losses.

Regarding the indirect methods, they can be both destructive and non-destructive, the last including cases of reduced local damage susceptible of aesthetic restitution. A recent and promising non-destructive testing method is based on performing surface notches by saw-cutting the concrete. The key idea is to measure changes in stress/strain of the concrete accounted for after each introduced notch. Subsequently, a complex post-analysis is required to estimate the residual prestressing force.

Consequently, this paper focuses on the analysis of the effect of single and twin notches in prestressed concrete beams when the prestressing force is known. In this way, the information obtained may be used to simplify the corresponding post-analysis in the case of existing PCMs tested without direct control of the prestressing force. A finite element model to account for the effect of single and twin notches in PCMs is implemented. The main variables included in this numerical modelling have been: cross-section dimensions, eccentricity of the prestressing reinforcement, single notch or twin notches, notch depth, distance between each pair of notches, and length of basis for obtention of displacements between the corresponding nodes. Curves [average longitudinal stress dissipation] versus [notch depth] for several combinations of variables can be reproduced, which will serve to a better understanding of the testing technique and may help to protocolize the aforementioned post-analysis by calibrating curves suitable for case studies with unknown prestressing force.

Selection and peer-review under responsibility of the scientific committee of the International Conference on Advances in Construction Materials and Structures.

1. Introduction and objectives

The correct determination of the actual acting prestressing force, the residual prestress, is essential in the context of the assessment of existing prestressed concrete members (PCMs), as the effect of prestressing has a major impact on the stress–strain responses and capacities of such structures under both service and failure conditions [1–3]. For a large number of existing structures, the design service life has been or will be reached in the near future, as highlighted in FIB Bulletin No. 80 "Partial Factor Methods for Existing Concrete Structures" (2016) [4]. 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 [5–8] carried out on existing PCMs (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. It is therefore clear that there are difficulties in determining the residual prestressing forces using the models provided by the codes.

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Despite the above uncertainties, there are few empirical methods available to assess the actual condition of prestressing systems, and their application in complex conditions is not always feasible [9–10]. Furthermore, very few prestressed concrete structures have been built including instrumentation systems that allow the assessment of the residual prestressing by what is often referred to as a direct method of estimating the prestressing force. Consequently, the residual prestressing force can only be estimated in an indirect manner. In these cases, additional complexity must be considered in relation to the initial prestress, the materials properties and their evolution and the accounted short- and long-term prestress losses.

Regarding the indirect methods, it should be noted that they can be both destructive or non-destructive, the last including cases of reduced local damage susceptible of aesthetic restitution. A recent and promising non-destructive testing method is based on performing surface notches by saw-cutting the concrete [11–13]. The key idea is to measure changes in stress/strain of the concrete accounted for after each introduced notch (Fig. 1). Subsequently, a complex post-analysis is required aimed to estimate the residual prestressing force. In the saw-cut method, the residual prestressing force is calculated from the response of a concrete block formed by making surface cuts with a disc 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.

Consequently, this paper focuses on the analysis of the effect of single and twin notches in prestressed concrete beams when the prestressing force is known. In this way, the information obtained may be used to simplify the corresponding post-analysis in the case of existing PCMs tested without direct control of the prestressing force. A finite element model to account for the effect of single and twin notches in PCMs is implemented. The main variables included in this numerical model are cross-section dimensions, eccentricity of the prestressing tendon, single notch or twin notches, notch depth, distance between each pair of notches, and measurement base length. Curves [average longitudinal stress dissipation] versus [notch depth] for several combinations of parameters can be reproduced, which will serve to a better understanding of the testing technique and may help to protocolize the aforementioned post-analysis by calibrating curves suitable for case studies with unknown prestressing force.

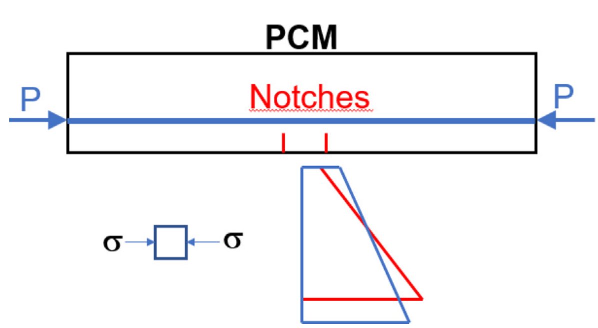

Fig. 1. Basic scheme of longitudinal stress dissipation in a prestressed concrete member after notching.

2. Finite element modelling of notches

The effect of performing notches in PCMs is addressed in this study by means of numerical modelling based on the Finite Element Modelling (FEM). The details on which the modelling is based are presented below.

The prestressed concrete beam modelled has a span-length of 2 m with a rectangular cross-section, 0.1 m width and 0.3 m depth. The modelling performed is 2D following a linear elastic material model based on a given concrete modulus (E_c) and a Poisson coefficient (ν).

The prestressed force is applied by means of an external straight tendon modelled as a truss element with a given prestressing force P anchored at both ends to 100x100x20 mm steel plates in order to apply the force in more distributed way. The beam is statically determined, and therefore, the boundary conditions have been included as a simple supported beam as shown in Fig. 2.

In the center of the beam a special modelling is required to perform the notches based on an adaptive meshing towards the position of the notches (Fig. 3). Moreover, specific nodes are introduced between notches in order to serve as virtual instrumentation to assess the mechanical behavior near the notches.

The effect of the notch can be achieved in this model thanks to implementation of a phased-analysis carried out according to the capabilities of the software Diana [14]. A phased analysis comprises several calculation phases, which enable the modeling of the notch to a desired depth. Between each calculation phase, the finite element model changes by removal of those elements affected by the saw-cut. A separate linear elastic analysis is performed in each phase, in which the results from previous phases are automatically used as initial values. In Fig. 4 it can be observed several phases of the numerical simulation.

3. Effect of notches

The study of the effect of single or twin notches on PCMs is important in order to establish the most robust experimental technology possible based on the saw-cut technique, and with the aim of preserving the non-destructive method of the saw-cut as minimally invasive as possible. In particular, it is analyzed the influence of single or twin notches on the longitudinal stresses dissipation (decompression) near the notch and the subsequent redistribution of stresses near the introduced notch.

3.1. Effect of single notch

In order to show the effect of a single notch, the normal stress dissipation on both sides of the notch is depicted in Fig. 5. The figure shows at the top the uniform distribution of compressive normal stresses induced by prestressing and at the bottom the dissipation effect produced after notching for the maximum depth of cut considered.

A significant redistribution of normal stresses can be observed in Fig. 5 (bottom). On both sides of the notch, stresses dissipate in a symmetrical triangular shape from the notch tip to almost zero or even moderate tensile stresses at the bottom of the beam. On the other hand, there is a very pronounced concentration of compressive stresses at the head of the notch. At the lowest border of the beam, the normal stresses recover as the distance from the position of the notch increases. It is important to mention that the normal stress dissipation is significantly variable and with a strong downward gradient in the positions closer to the notch location.

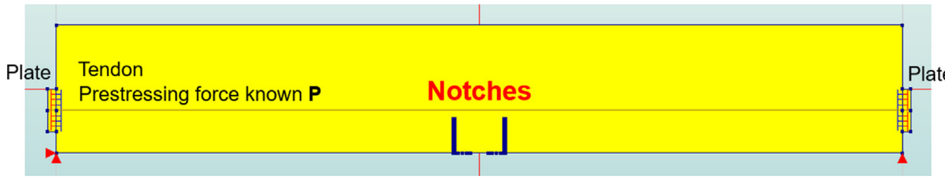

Fig. 2. Prestressed Concrete Beam details.

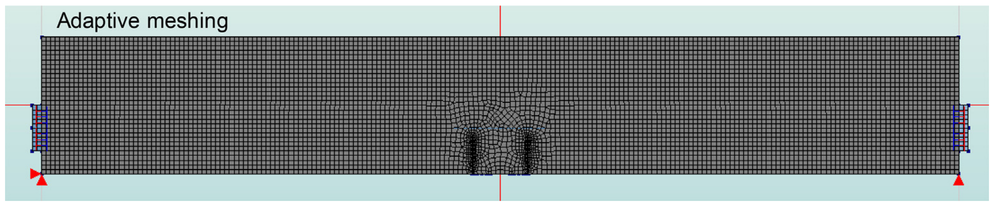

Fig. 3. Prestressed Concrete Beam mesh.

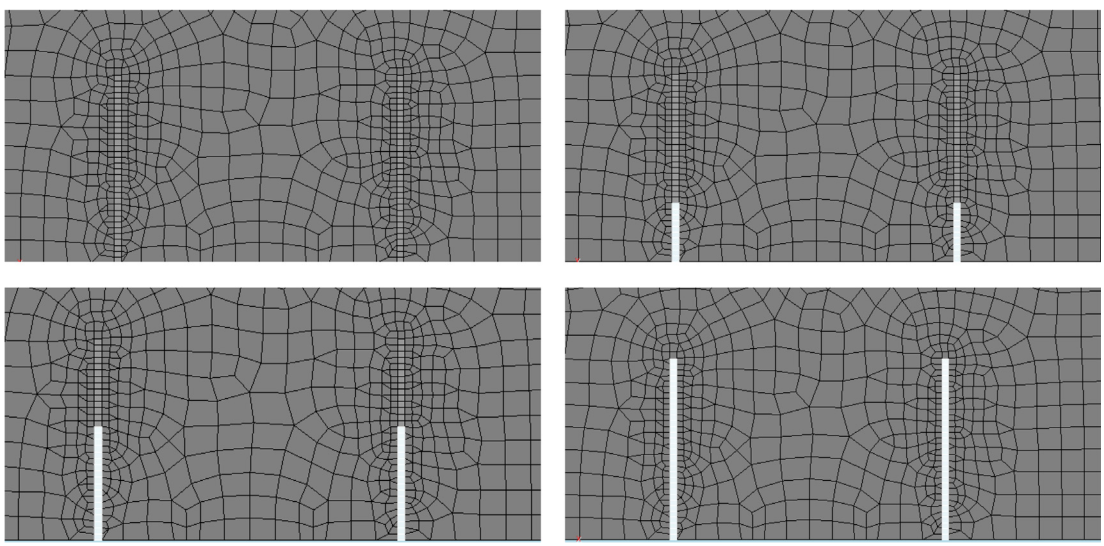

Fig. 4. Modelling of the evolution of the notches.

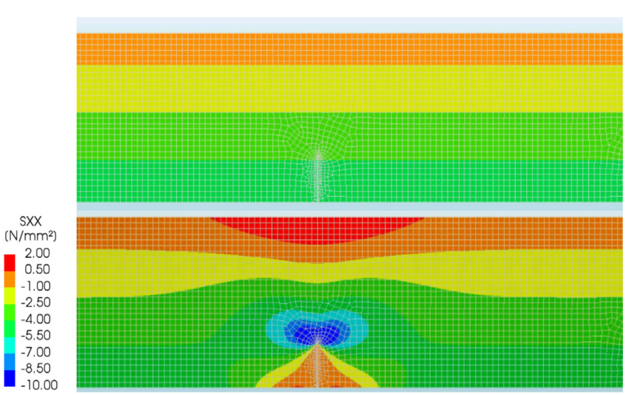

Fig. 5. Dissipation of normal stresses in a single notch.

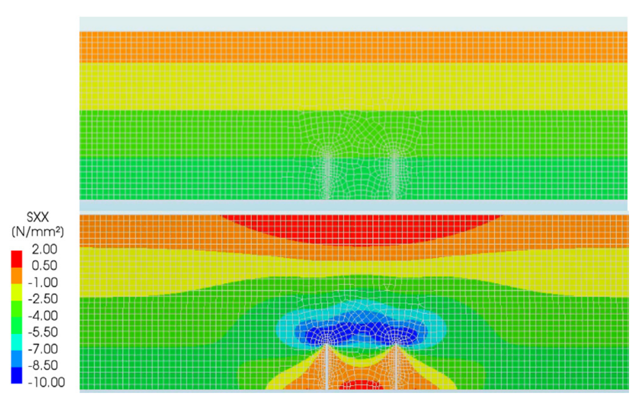

Fig. 6. Dissipation of normal stresses of twin notches.

3.2. Effect of twin notches

The effect of twin notches is shown in Fig. 6. In this case, two notches are cut with the same characteristics to those of the previous example and placed between them at a given distance D (120 mm in the example shown). The dissipation effect of the compressive stresses is superimposed, resulting in a clear intermediate zone with decreasing stresses depending on the notch depth.

It can be observed a much clearer dissipation zone compared with the first case. The stress level at the fibre in the bottom border within the region between the notches is variable, but stabilizes as the depth of the notches increases and the effects of the two notches overlap. Therefore, it results in a kind of isolated block of concrete, which can be generated in a controlled manner from different depths and distances between notches.

4. Characterization of the isolated block

In the case of twin notches, the concrete block that is going to be isolated in the prestressed concrete beam can be characterized by the following parameters: (a) cross-section dimensions; (b) prestressing force "P"; (c) eccentricity of prestressing reinforcement "e_p"; (d) distance between notches "D"; (e) notch depth; and (f) measurement base length.

With the numerical model, it is feasible to generate curves representing the isolation of the concrete block in compression between the notches. It is important to note that in this curves the y-axis represents the average dissipation of the normal stresses within the measurement base length considered. So given the specific data such as the cross section dimensions, the eccentricity of the prestressing reinforcement, the distance between notches and a measurement base length is possible to plot the response of the dissipation of the longitudinal stresses as a function of the notch depth, as shown in Fig. 7.

This is a curve that changes in terms of the values of the parameters considered but with a characteristic S-shape. This shape has three significant branches. In the first one, the rate of dissipation of normal stresses is exponential. Then an intermediate branch is generated with a relatively constant slope. Finally, in the last branch, the slope decreases to an almost horizontal plateau, which means that the complete isolation of the compression block in the concrete is reached (Fig. 7).

The average normal stress dissipation curves can be adapted to the type of saw-cut to be carried out in the PCM by providing appropriate values for the parameters. This dissipation of average normal stresses can be translated into dissipation of equivalent average strains by setting appropriate values of the constitutive properties of the concrete material (i.e. the concrete modulus (E_c) and the Poisson coefficient (ν), for the case of the numerical model implemented).

Furthermore, the calculated average strain dissipation vs. notch depth curve can be directly compared with the curve obtained by the saw-cut experimental method thanks to the use of suitable instrumentation allowing accounting for the change of strains along the measurement base length considered between notches. Finally, it will be possible to deduce by back analysis the value of the prestressing force P that best fits the experimental response. As a result, this will make it possible to estimate the residual prestressing force at every time the saw-cut is executed.

5. Example of application

In order to go more in depth into the results provided by the numerical model, the average normal stress dissipation curve of a particular case is shown in this section as depicted in Fig. 8. This correspond to a postensioned concrete beam with a span-length of 2 m with a rectangular cross-section, 0.1 m width and 0.3 m depth. The concrete modulus (E_c) and the Poisson coefficient (ν) considered are 38000 MPa and 0.2, respectively.

The beam is postensioned with a straight tendon with a section area of 100 mm^2 and with an eccentricity $e_p = -50$ mm for a given prestressing force (P). The two notches have been practiced at the center of the beam at a distance of 120 mm considering a thickness of 30 mm for each notch to take into account the concrete material removed by the saw when cutting the concrete.

Several curves have been obtained for different values of P ranging between 80 and 140 kN. This variability of the prestressing force could represent different level of prestress losses in a tendon of a real prestressed concrete specimen.

In these curves, a characteristic S-shape is obtained with a high rate of concrete stress release for low notch depths that gradually slows down for greater notch depths. It is important to outline that the curves are proportional to the level of prestressing force P considered.

Finally, it is worth noting that the measurement base length considered in this case is 60 mm, which could be representative of a typical strain gauge length usually employed for measurement of concrete strains. In any case, this measurement base length could be adjusted to the specific instrumentation device to be used in the saw-cut test.

6. Conclusions

It has been presented the implementation of a numerical model that allows studying the effect of induced notches in prestressed concrete members. This study is essential to support the evaluation of residual prestressing force using the indirect and non-destructive methodology known as saw-cut.

The following conclusions have been drawn from this study:

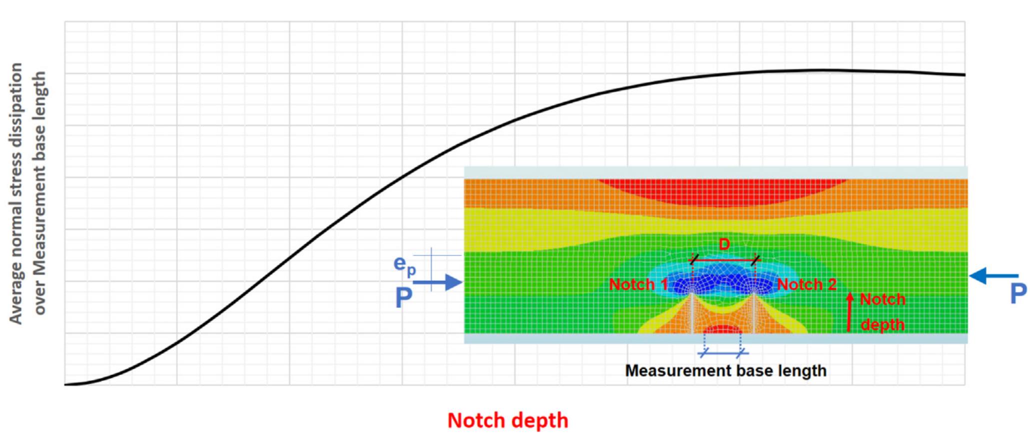

Fig. 7. Dissipation of normal stresses vs. notch depth.

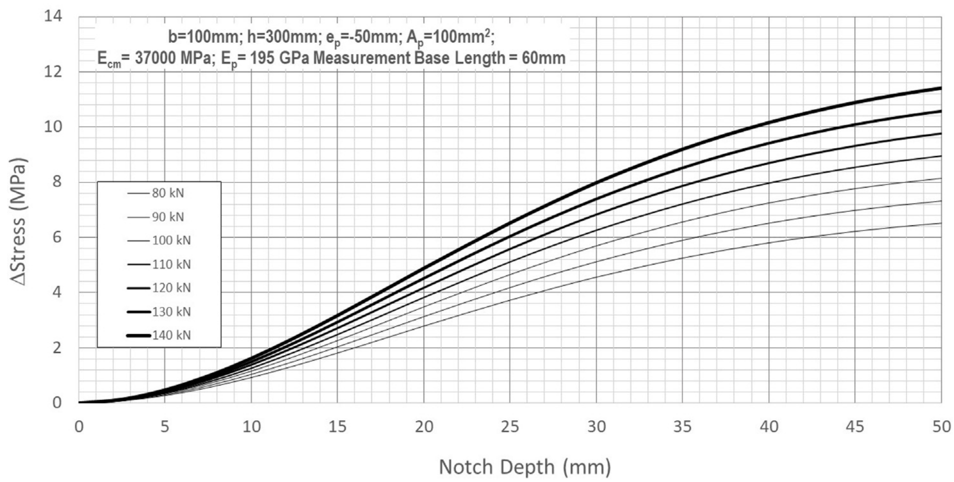

Fig. 8. Notched PCM (b = 100 mm; h = 300 mm; ep = 50 mm; D = 120 mm; BL = 60 mm).

- A numerical model capable of simulating the effect of dissipation of normal stresses produced by notches in prestressed concrete beam-type elements has been developed satisfactorily, and the effect produced by single or twin notches has been studied and compared.
- In view of the modelling results, the case of twin notches seems to be more suitable for determining the longitudinal stress dissipation, given that the isolation of the concrete is effectively achieved. An appropriate choice of the distance between notches is required.
- The numerical model with the simulation of the twin notches allows the determination of normal stress dissipation vs. notch depth curves for a given prestressing force P.
- These numerically obtained curves are potentially comparable with counterpart curves experimentally obtained that measure the effect of the notches over a measurement base length between the two notches.
- The prestressing force P that has to represent the experimental behavior can be adjusted by back analysis in the numerical model, which will result, in fact, an estimation of the residual prestressing force of the concrete member.

Finally, it is important to mention that the normal stress dissipation curves have been obtained in ideal working conditions that might differ in real practice application of the saw-cut technique. Moreover, the nonlinearity of the concrete behaviour might also have an effect after saw-cutting, which would require further refinements in the numerical model presented.

Data availability

No data was used for the research described in the article.

Declaration of Competing Interest

The authors declare that 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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