Proceedings of the IMAC-XXVIII
February 1–4, 2010, Jacksonville, Florida USA
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Experimental investigation of the pre-tension effects on the modal parameters of a slender pre-tensioned concrete beam

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ABSTRACT

Slender pre-tensioned concrete structures are nowadays of common use, due to their unique features. Slender beam can be used to sustain large structures and important loads leaving the architects a lot possibilities in the structure design. The health of such structures is strictly related to the conditions of the tendon that, in many cases, are not accessible. Visual inspection is the most used technique to assess the tendon condition even if in many cases access to the inspection points is very difficult or impossible. This paper investigates the possibility of detecting a pre-stress loss or a tendon failure by means of modal analysis. A pre-stressed concrete beam has been built and tested under laboratory conditions, varying the applied pre-stress and the number of active tendon. Modal analysis has been performed in each of the experimental condition and attention has been focussed on the variation of all identified modal parameters, frequency, damping and mode shapes. Furthermore a set of damage indexes have been computed to highlight the most sensible magnitude able to identify a change on the structure. Obtained results showed that an accurate analysis is needed in order to identify a change in modal parameters due to variations in the pre-stress, while tendon failure leads to more important changes in the identification results. The performed study are the starting point in order to properly tune a numerical model of the beam useful to accurately interpreter structural changes.

INTRODUCTION

A large amount of slender concrete structures are nowadays built using prestress techniques. This technique allows to build slender structures sustaining large weights, and thus giving the architects a number of additional degrees of freedom in the design process. Another important achievement is the amount of space left to be used due to the reduced thickness of floors and walls.

The prestress condition is obtained by means of steel tendon which provide the compression that allow to increase the structural performances reducing the positive (elongation) strain and stress. The health of prestressed concrete structures is thus strictly related to the conditions of the tendon that, in many cases, are often included in the concrete and there is no way to directly inspect them.

One of the main problem of prestressed concrete is therefore the tendon conditions which may deteriorate due to corrosion, or exceptional loads. To this aim many non-destructive diagnostic techniques have been proposed [1,2] but it has to be considered that these techniques are always difficult to apply and their results are often affected by a high level of uncertainty. In the last decades a lot of papers have been written concerning structural health monitoring via modal analysis, the structure condition is assessed by its modal parameters that are considered representative of the actual structure dynamic behaviour. A change in these parameters identify an evolution in the dynamic behaviour and a possible ongoing damage [3,4].

The latter approach pushed forward to the exploitation of the possibility to consider the relationship between prestress conditions and dynamical behaviour of a structure in assessing the tendon conditions and therefore the health of prestress concrete.

The tendon presence and the prestress load influence the structure dynamical behaviour, therefore a reliable identification of the modal parameter of a structure could offer the opportunity to monitor the prestress condition. This sort of monitoring is really attractive: it is non destructive and can be performed continuously during normal life of the structure if operational modal analysis is considered.

Different researches have been developed in this direction but the connection between damage and modal parameter changes has not been completely cleared up yet[5,6,7,8]. One of the main aspects is the entity of the modal parameter change due to tendon damage: in many cases it can be of the same order of magnitude

T. Proulx (ed.), *Dynamics of Civil Structures, Volume 4*, Conference Proceedings of the Society for Experimental Mechanics Series 13,
DOI 10.1007/978-1-4419-9831-6_15, © The Society for Experimental Mechanics, Inc. 2011

of the modal parameter estimation uncertainty. A deeper investigation in this field is therefore necessary to pursue damage detection by means of modal parameter analysis.

In a previous paper [2] a first approach has been developed: other researches results have been analyzed and a numerical analysis (FEM Modelling) has been performed to investigate the possibility to detect prestress changes by means of dynamic behaviour identifications. The obtained results were encouraging and therefore an experimental campaign has been designed and a test specimen has been built to perform extensive tests in laboratory controlled conditions.

As one of the goal of this research is the investigation of the relationship between damage and dynamical behaviour modifications the test structure has been designed to allow the simulation of different sort of known tendon damages. Furthermore the possibility to apply different damage entities allows to test the performances of different techniques: in this paper the first results will be presented: they have been obtained analyzing the relationship between natural frequencies, Mode Shape Area and Flexibility Matrix changes with different damage levels. At first the test specimen and the measurement campaign are illustrated putting into evidence the simulated damage conditions, then the main results are shown and finally some concluding remarks are given.

In the next paragraphs the test specimen, the measurement set-up and the performed experiments are described.

THE TESTED BEAM AND THE MEASUREMENT CAMPAIGN

As the aim of the experimental campaign is to investigate only the prestress effects on the beam dynamic behaviour the measurement set-up has been kept simple. Tests have been carried out in laboratory controlled conditions on the post-tensioned concrete beam depicted in Figure 1. The specimen is a single span (6 m long) beam with a constant rectangular section (20 cm x 30 cm). The concrete used to build the specimen has been prepared according to the European standard [9,10]. The beam is post-tensioned by means of a single straight unbounded tendon, being in the simplest framework of ungrouted post-tensioning. The tendon, located in the middle of the beam section, at 6 cm from the lower side of the beam, is made of three strands whose characteristics are assumed to be in agreement with the prEN10138 norm. The adopted diameter is about 15 mm (0,6”), the elastic modulus Es=209000 N/mm2. The steel structure connect the strands and the beam, those structures are equipped with 3 ring load cells that allow to measure the load of every strands (Figure 2). The beam is simply supported by 2 steel round beams which diameter is 5 cm (Figure 3).

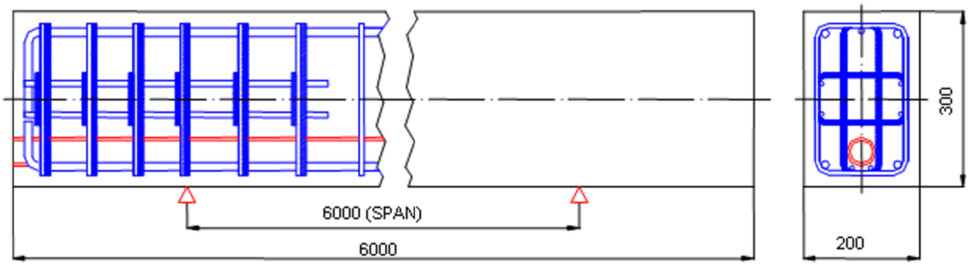


Figure 1 Layout of the concrete beam object of the analysis

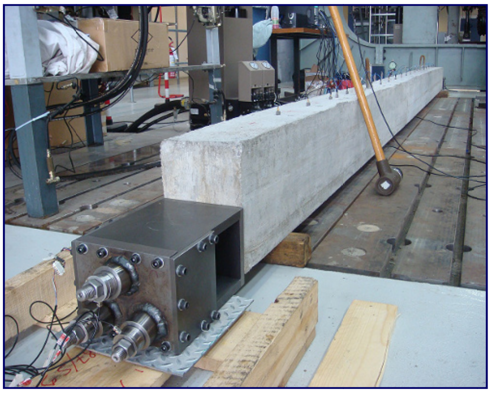


Figure 2 The concrete beam in the laboratory with the accelerometers and the impact hummer.

Figure 3 Detail of the constraints

The choice to build the single tendon with 3 strands has been taken to grant the possibility to simulate different damage kinds: it is possible to apply different loads with the same number of strands, the stiffness of the strands remain the same, and, on the other side, apply the same load with different number of strands. The first case is used to study the effect of a prestress loss while in the second case a damage of the tendon can be studied. In Figure 4 the test matrix resuming all the possible damages scenarios is shown.

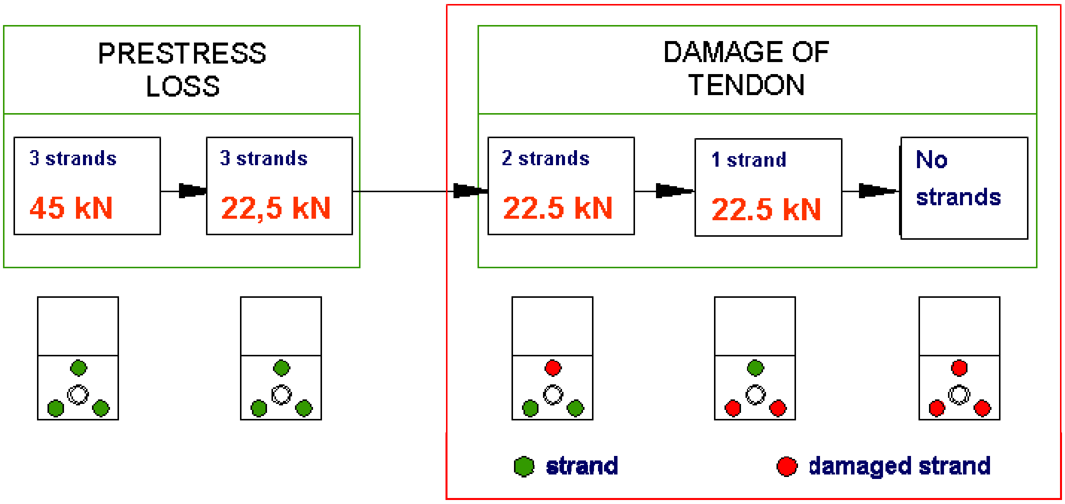


Figure 4 Different configurations of the 3 tendon allow to simulate different sort of damages

As the idea of this paper is to detect prestress changes by means of dynamic behaviour analysis a series of indexes have to be chosen in order to give a quantitative index of the beam conditions starting from the identified modal properties, frequencies, damping and mode shapes. Due reasons that are well explained in literature [11] the damping value is the index affected by the highest uncertainty in the identification and therefore is not considered in the study.

Starting from the other modal parameters, frequency and mode shapes, 3 different indexes have been related to the damage level [4]: natural frequencies themselves, mode shape area and the flexibility matrix.

The first index is self explaining, while the other two are defined as:

$$MSA_i = \int_{X=0}^{X=L} \left| X(\omega_i) dx \right|$$

where x is the position on the beam, i is the considered vibration mode and $X(\omega_i)$ is the modal shape of the considered mode.

$$\text{FlexMatr} = [F] = [\Phi]\left[diag\left({}^{1}\!/_{\omega_i^2} \right)\right][\Phi]^T$$

where $[\Phi]$ is the matrix of the modal shapes and ω_i are the eigenfrequencies.

All these properties are calculated starting from the identified modal parameters, the latter have been estimated using the Polyreference least square frequency domain identification algorithm [12,13]. It has to be pointed out that natural frequencies and mode shape area are properties of the whole structure, on the other hand every element of the flexibility matrix gives local information. As the simulated damages are related to the whole structure (a prestress load loss interest all the beam) a synthetic index related to changes in the flexibility matrix has been considered: in particular the index that has been chosen is the standard deviation between the matrix evaluated when the beam is in nominal preload condition and the one evaluated when the beam is in damaged condition.

In the next section the measurement set-up is described.

THE MEASUREMENT SET-UP AND FIRST RESULTS

In order to provide a deep knowledge of the beam dynamic behaviour the measurement set-up was made of 20 piezo-accelerometers placed on the symmetry plane on the upper surface of the beam; Measurement points have been equally spaced along the upper surface.

Excitation has been given by means of an impact hammer and the response has been measured in the 0 – 200 Hz range. A first set of measurements has been taken to ensure that the impact had the needed energy in the considered frequency range. All subsequent analyses have been carried out averaging ten impacts and always checking coherence information.

The first condition that has been tested is the simple beam without any preload, results are shown in Figure 5 (blue line). The first four in plane vibration modes are clearly visible in the frequency response function at 12,5 Hz, 51,1 Hz, 109,1 Hz and 175,1 Hz. Then preload has been applied and the same analysis have been repeated.

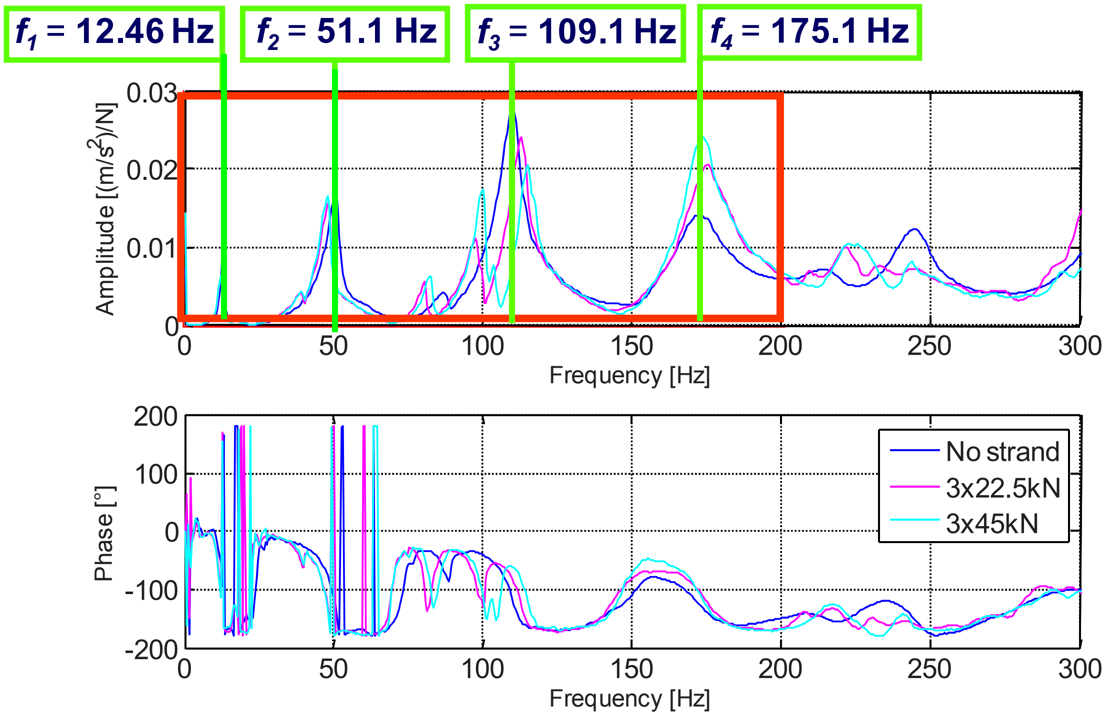


Figure 5 Frequency responses measured at 1/3 of the beam span with different tendon configurations

The analysis of the accelerometer signals showed that other natural frequencies appear when preload is applied (Figure 5, light blue and violet lines). A new series of tests has been carried out measuring also the out of plane vibrations. This analysis showed that the new natural frequencies that appear when a preload is applied are related to torsional and lateral mode shapes, probably due to a non perfect symmetry of the applied prestress load.

In the following analyses only the “in plane” mode shapes will be considered postponing the other results to a further step of the research. The results obtained simulating a prestress loss will be presented in the next section.

PRESTRESS LOSS

This section considers the results obtained applying different preload levels by means of the same number of strands. The test is carried out to investigate only the effect of the preload force on the modal properties of the beam not taking into account any other damage: as the tendon section remains the same his stiffness does not change.

The first set of experiments has been carried out with 3 strands and different preloads: 45 kN, 22,5 kN and 0 kN on every strand. The results, in terms of natural frequencies and mode shapes (1st and 2nd natural frequency), are shown in Figure 6.

Increasing the preload level from 0 to maximum leads to a decrease in the identified frequency values as shown in the left graph of Figure 6.

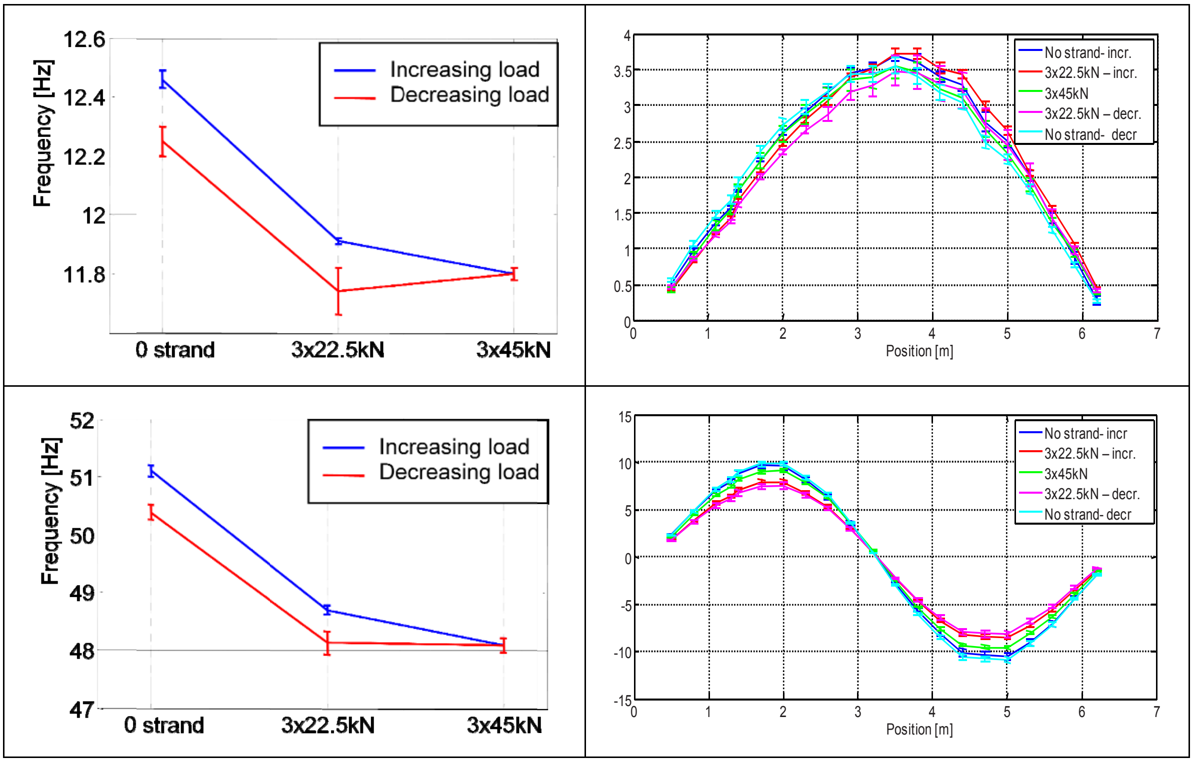


Figure 6 Natural frequencies and modal shapes (1^{st} and 2^{nd} mode) measured increasing and decreasing the preload (1^{st} application of the load)

Looking at mode shapes in the right side of Figure 6 a unique trend in shape changes due to the pre-stress value cannot be detected. Even worse than this, if the results pertaining to the prestress decrease are looked at, it can be seen that the same frequency value and shape modification can be attributed to different pre-stress levels. At the end of the test the obtained values showed a difference if compared to the ones obtained at the test start, and this had to be investigated deeper.

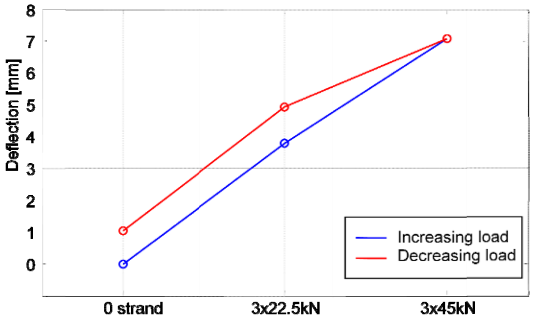


Figure 7 Deflection measured on the beam at the span centre

One of the reason could be identified in the different static equilibrium conditions measured on the beam, Figure 7 shows the centre span deflection measured in the different tested conditions, as can be seen a residual deflection is evidenced at the end of the first test session.

It has then been decided to repeat the cycle using only one tendon, to assure that the preload was applied symmetrically. This new test, highlighted a different beam behaviour (Figure 8). After having removed the preload stress the beam returned to the same static equilibrium position of the beginning. As can be noticed the deflection at full load is in the order of magnitude of $1/3^{rd}$ of the previously obtained as the total preload is given by $1/3^{rd}$ of the strands. No residual deformations have been evidenced as the preload has been removed. In this situation too natural frequencies and mode shapes have been extracted and results are shown in Figure 9.

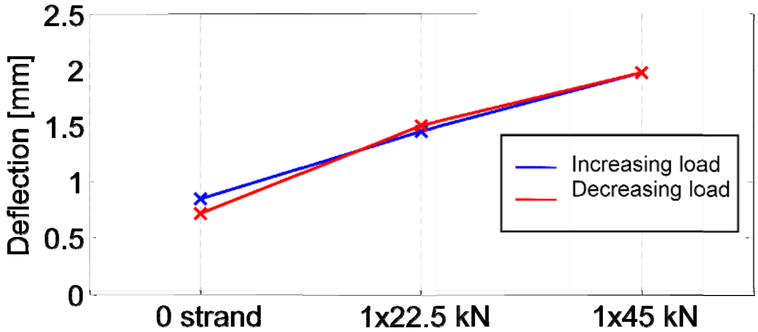


Figure 8 Deflection measured at the center of the beam span

Looking at the graph in Figure 9 it is possible to notice that a decrease in the estimated frequency values is still present as the prestress load increases. Moreover the magnitude of this decrease is in the same order as the one observed in the first test, where the applied load was three times bigger. Looking at mode shapes it is still not possible to identify a clear dependence between mode shape changes and prestress value.

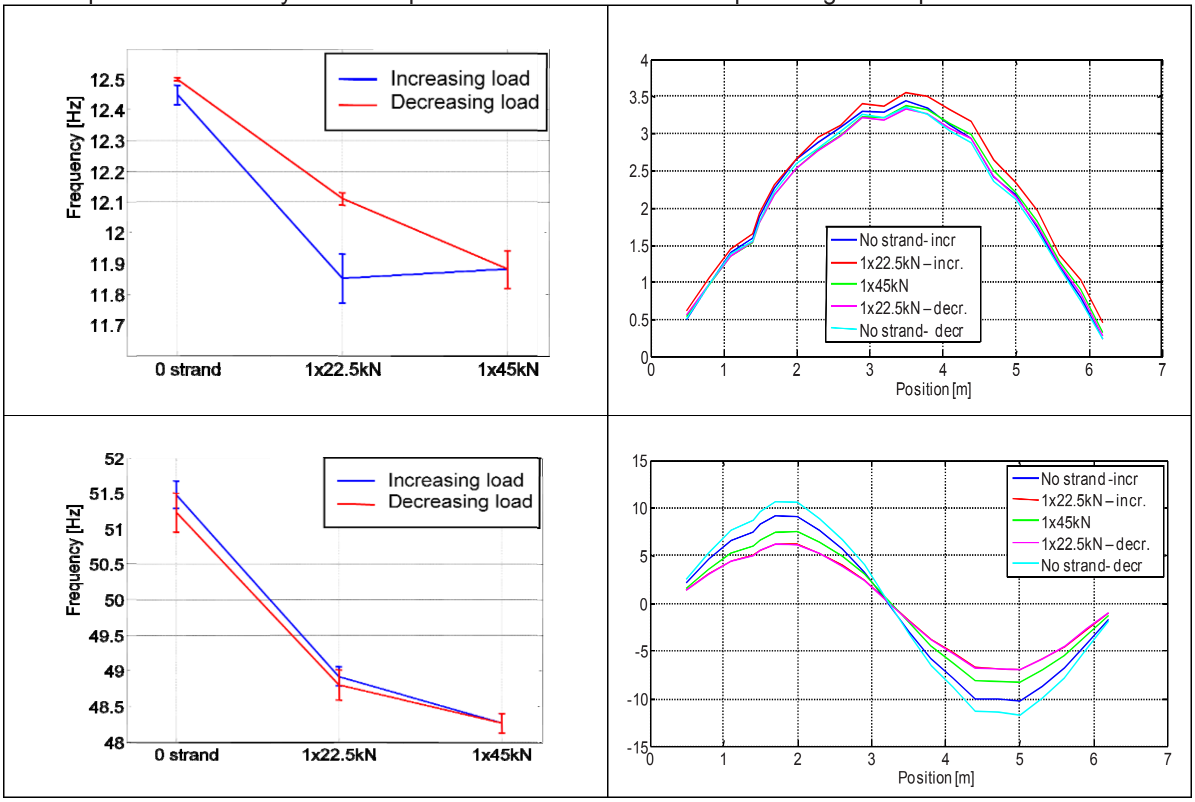


Figure 9 Natural frequencies and modal shapes (1st and 2nd mode) measured increasing and decreasing the preload (2nd application of the load)

Results given form this first test series did not put into evidence a straight relationship between the beam dynamic behaviour and the prestress value. Moreover some of the obtained results deserve a deeper investigation, a totally different load values lead to the same variations in the identified beam eigenfrequencies. A series of hypothesis have been made, but these are still to be verified. A reason could be that friction can affect the prestress distribution on the beam, or that due to imperfections on the beam surface the load is applied differently from one test case to the other. All these possibilities will be further investigated and a numerical model will be developed to better understand the results.

The next investigated kind of damage is the loss of a tendon and the results for this case are shown in the next section.

DAMAGE OF THE TENDON

Another series of tests have been performed to investigate a different sort of scenario, while in the previous section a loss of prestress has been studied, in this section the attention will be pointed on a loss of stiffness that could be due to tendon corrosion. Figure 10 shows how natural frequency and modal shapes (1st and 2nd) change as a function of the number of strand while the preload on each strand remains the same.

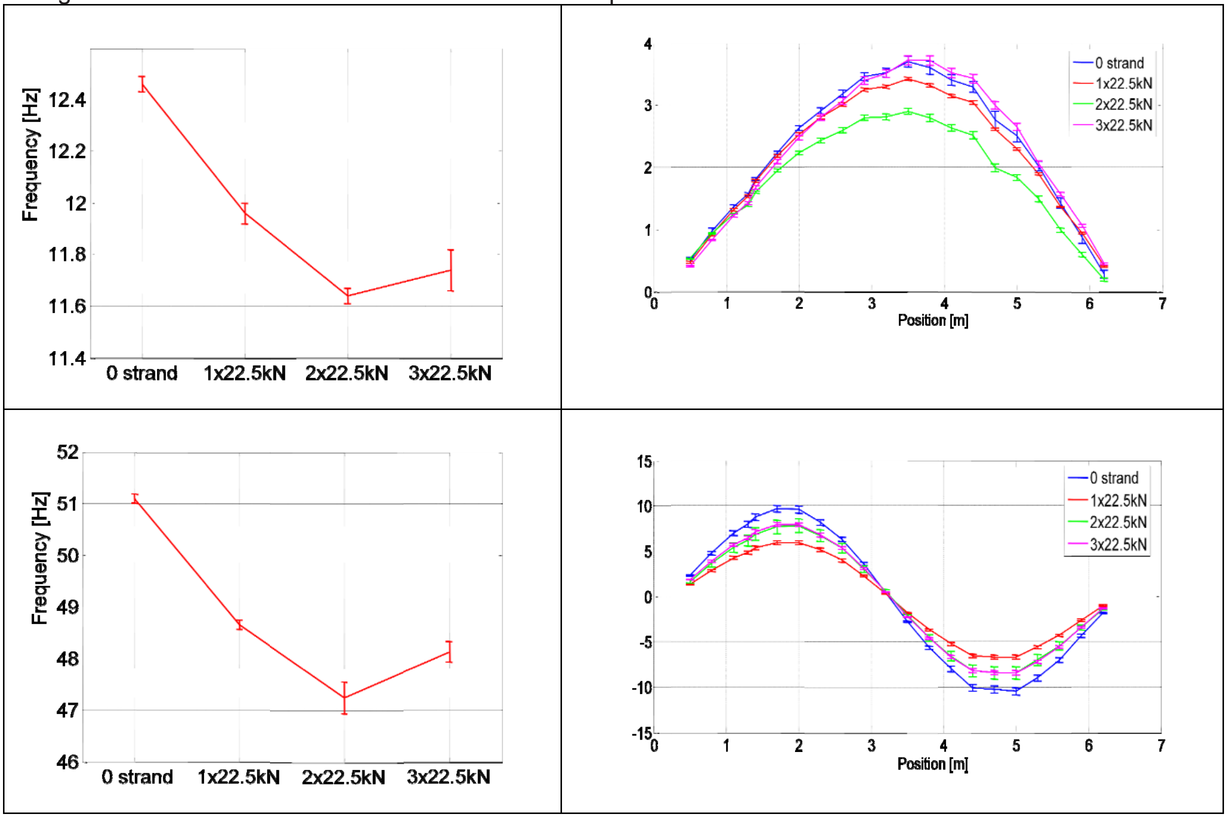


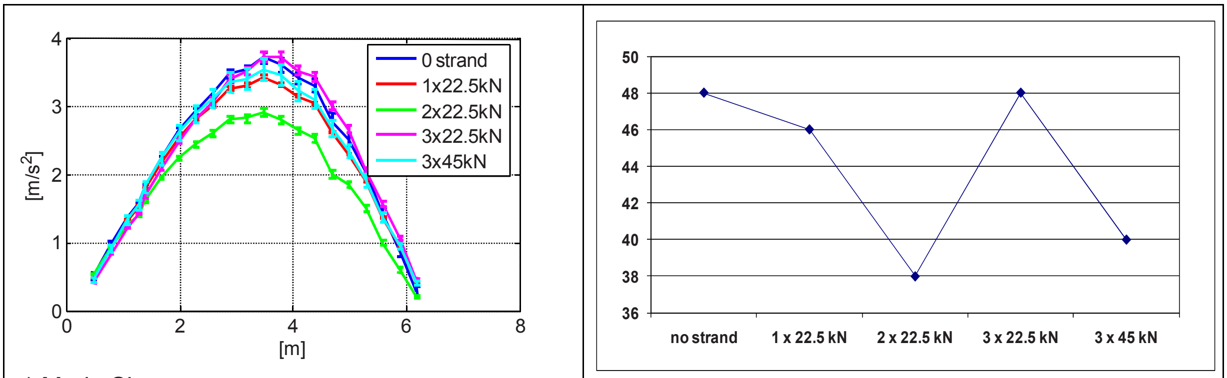
Figure 10 Natural frequencies and modal shapes (1st and 2nd mode) measured in different preload conditions (2nd application of the load)

Looking at the results a clear relation between natural frequencies and number of strands installed cannot be detected: while a meaningful decrease of the natural frequencies has been measured increasing the number of strands from 0 to 2, a further increment to 3 strands involved an increment of the identified natural frequencies. The same behaviour has been detected for the 1st and 2nd mode. This situation is in good agreement with the previous section results, in which the same frequency value was identified with substantially different prestress values as shown in Figure 6 and Figure 9.

If mode shapes are considered some meaningful differences are identified as the number of strand varies but a clear trend is not yet identified. Different simulated damages leads to similar mode shapes, as is the case of 2/3 strands for mode 2 (green and pink curves in Figure 10).

This idea is confirmed by the analysis of the Mode Shape Area. Figure 11 summarizes the results obtained for this damage index: the mode shapes measured with different damage scenarios (different preload conditions and different number of strands are considered) and the correspondent calculated mode shape area are shown.

As can be seen in the left side of Figure 11 different pre-stress conditions lead to changes in the mode shapes, but again an uniform trend is not detected. This is confirmed if the graph on the right side are analyzed. The computed Mode Shape Area is different as prestress and number of strands changes but a straight law connecting its value to the tension value is not detectable.



a) Mode Shapes

b)Mode Shape Area

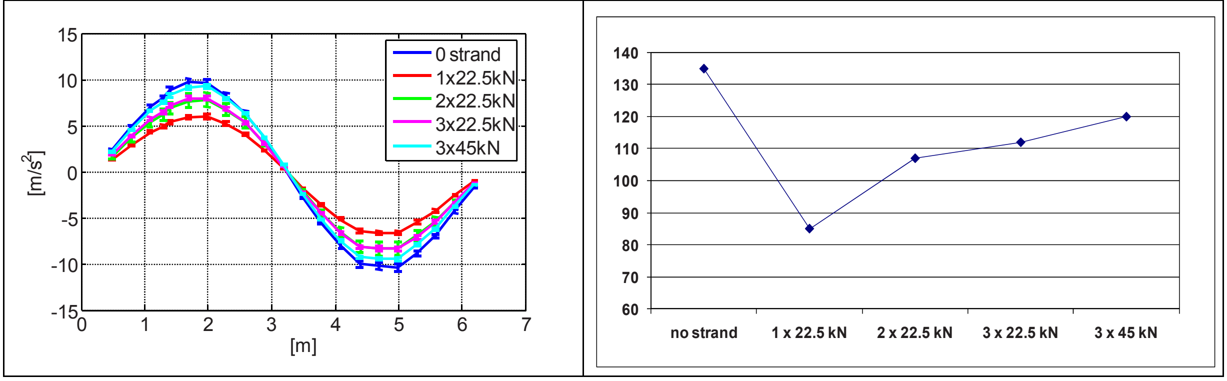


Figure 11 Modal shapes (1st and 2nd modes) and mode shape area index (1st and 2nd modes)

Considering what has been found so far a straight relation between the beam dynamic behaviour and the prestress condition has not been found yet, even if the beam modal parameters are affected by meaningful changes as the prestress is varied. This situation pushes forward to consider a damage index that is related to all frequencies/mode shapes, so that all the information can be exploited at one time. This will be shown in the next section.

FLEXIBILITY MATRIX

As the results obtained considering Natural Frequencies and Mode Shapes alone did not identify a straight relationship between prestress value and parameter evolution, here the possibility to resume all indexes into changes in the Flexibility Matrix have been investigated.
Recalling the definition of flexibility matrix [F]:

$$\text{FlexMatr}=[F]=[\Phi]\left[diag\left(1/\omega_i^2\right)\right][\Phi]^T$$

It can be seen that all modal residues and eigenfrequencies contribute to the final value. It has to be considered that every element of the Flexibility Matrix gives local information while the damages considered in this research are global.
In Figure 12 the squared difference between the matrix in reference conditions and with no preload is presented. Changes are evident and moreover all matrix elements are affected indicating that changes are generalized to the whole structure.

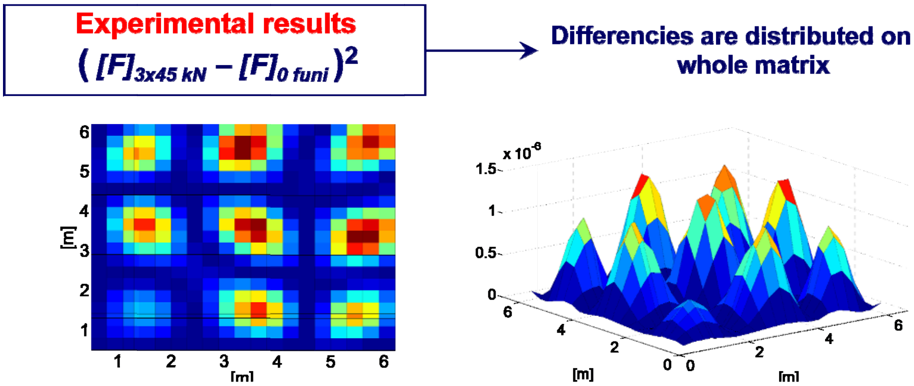


Figure 12 Changes in the flexibility Matrix from 3x45 kN condition, to 0 kN prestress

An index resuming all changes has been therefore adopted: the flexibility matrix in undamaged condition (3 strands installed with the a preload of 45 kN) has been evaluated and used as reference, the same matrix has been evaluated in damaged conditions and the standard deviation between the two matrix has been computed. In Figure 13 the behaviour of the computed Standard Deviation is shown versus the preload condition.

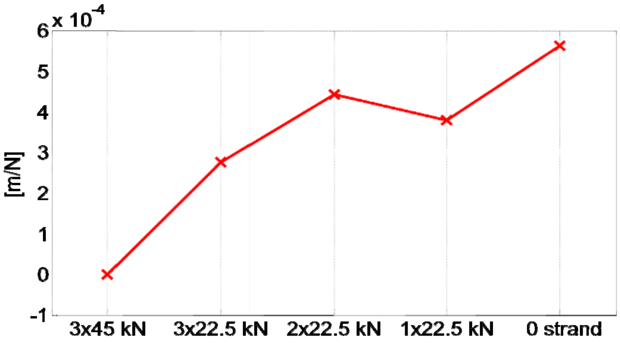


Figure 13 SQM of the flexibility matrix in different conditions

Looking at the graph in Figure 13 an uniform trend in the SQM evolution is evident as the preload situation evolves from nominal to 0. From this index it seems that there is a possibility to detect changes in the beam prestress conditions starting from the modal parameters identification.

CONCLUDING REMARKS

This paper presents a resume of the first results obtained analyzing the prestress influence on the dynamic behaviour of a concrete beam. The idea was to exploit modal identification to assess the prestress condition of the beam. A simple test specimen has been built and analyzed in laboratory controlled condition, so that all the other possible influencing magnitudes have been kept under control. A series of different experiments have been carried out to simulate different damage kinds, at first a loss of tension in the strands and then the total loss of one or more strands have been reproduced. In each of the tested conditions the beam modal parameters have been estimated. The obtained results showed that is really difficult to extrapolate a straight rule linking the prestress condition to single modal parameters, while the use of a global index, considering all modal parameters together seemed more promising. These results are being used to tune a numerical model that will help to interpreter changes in the modal properties.

ACKNOWLEDGMENTS

Authors would like to acknowledge Eng. Mario Scrosati for the help given in building the test specimen.

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