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Actual Prestress Force Detection of Tendons in Prestressed Beams Based on Static Responses Using Genetic Algorithm

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ABSTRACT

Researchers' attention has recently been focused to the measurement and tracking of prestressing force in the tendons of prestressed concrete (PC) constructions. Older structures need non-destructive testing techniques to evaluate these forces, even if modern structures are fitted with sensors to monitor prestress losses. This work presents a new approach that uses static displacement data under experimental loads to determine the real prestress force in the tendons of a prestressed concrete beam. This approach offers a more economical alternative by doing away with the requirement for destructive tests or pre-installed sensors. A genetic algorithm (GA) is created to precisely calculate the prestress force of tendons. Laboratory testing shows that the proposed method can detect prestress losses with excellent accuracy, even in the presence of intentional measurement mistakes of up to 10%..

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Indexes

F= Force

K= Stiffness

U= Displacement

NLC= Point Number

U_m & Δ_m = *Measured Displacement*

U_a & Δ_a =*Analytical displacement*

f= Fitness

ω= Objective Function

e= Convergence Criterion

p_r= *Damage Index*

p_0= *Initial Force*

p= Residual Force

1. Introduction

Prestressed concrete structures, whose prestressing forces gradually reduce over time, are fundamental infrastructural elements. Ensuring the safety and serviceability of tendons and strands requires close monitoring of their actual degree of prestress force **[1]**. Particularly important to a nation's transportation network are large bridges, which can fail for a variety of reasons over their useful lives, one of which being a decrease in prestressing force.

In recent decades, various methods have been developed to assess the health of bridges, with a focus on non-destructive techniques due to their cost-effectiveness and feasibility **[2, 3]**. Visual inspection is a common method for detecting damage on the outer walls of bridge decks, while sound-based methods such as ultrasonic and magnetic field techniques are used for monitoring the inner surfaces of structures **[4]**. This study aims to explore non-destructive methods for monitoring the health of engineering structures, specifically beams, with a focus on assessing prestressed concrete bridges. By evaluating the effectiveness of these techniques engineers can ensure the longevity and safety of critical infrastructure components **[5]**. In the field of civil engineering, various measurement instruments such as GPS, radar, and GPR mechanisms are used to control displacements caused by changes in the geometric and mechanical coordinates of bridges **[6, 7]**. However, these methods are expensive, time-consuming, and do not provide a clear judgment on the remaining prestressing force in bridge tendons. As a more efficient and cost-effective alternative, analytical failure detection methods like finite element models can be utilized to detect failures in structures.

Many studies have been conducted in this field over the past few decades due to the importance of estimating the residual force in prestressing tendons. When Abraham et al. developed an algorithm in 1995 that could identify decreases in prestressing force in concrete beams with a single tendon, it was one of the first major research projects **[8]**. When it comes to identifying different damage levels in concrete beams with many embedded tendons, this method is not very effective.

Other methods for measuring modal strain energy and changes in frequency and periodicity due to structural geometric variations have been proposed but fail to distinguish among different types of failures **[9-11]**. In 2018, a technique involving measuring the curvature of a bridge under load was introduced as a means of detecting prestressing damages **[12]**. This approach is not as good at differentiating between internal forces in beams with many tendons, but it works well for detecting single tendons. Methods have been developed to detect prestressing loss when only one tendon is present. These methods involve examining static and dynamic responses arising from beam excitation by loading or shifting loads and comparing them with intact beam responses. These advancements highlight the ongoing efforts to improve damage detection techniques in civil engineering structures **[13]**. Overall, the evaluation of existing methods and techniques for monitoring force reduction in prestressed structures highlights the limitations in terms of accurately determining the location and extent of force reduction in individual tendons. While advanced equipment and sensors such as fiber optic and FBG sensors have been developed for long-term monitoring, they are costly and not feasible for use in older structures **[14-19]**. The proposed method in this paper offers a promising alternative by utilizing simple tools and measuring static displacements under various loading scenarios. By incorporating an artificial intelligence algorithm based on genetic algorithm, this method aims to provide accurate results in identifying force reduction in all tendons separately. In comparison to current methods, more investigation and testing will be required to confirm the efficacy and dependability of this suggested approach. If successful, this strategy might provide a cost-effective way of monitoring on prestressed structures and ensuring their integrity and safety throughout time.

2. Theoretical bases of the method

In any linearly elastic structure, the following relationship can be established between the point loads, **{F}**, and joint displacements, **{U}**, matrices

$$\{F\} = [K]\{U\} \quad (1)$$

Where the elements of the stiffness matrix, denoted by the [K], are determined by the physical characteristics of the material. The stiffness matrix will now contain unknown properties if the material's physical attributes have been selected as the damage criterion, and the force vector will include unknown values if one or more external forces are indicated as damage. Therefore, the problem can be defined as a multivariate problem by placing unknown variables in the force vector and stiffness matrix. In the present study, the problem of prestressing force loss is defined as an unknown parameter, therefore, with the variables related to the physical properties of materials and displacement, this problem is a reverse engineering problem and can be analyzed mathematically. This paper seeks to discover the values of prestressing forces in tendons by studying the static displacement of the structure. In this regard, the first question that must be answered is whether the displacement of the structure is a function of the amount of prestressing of the tendons or not? To investigate and answer the above question, a simple concrete beam consisting of a tendon with a single loading scenario, as shown in **Figure 1**, is modeled in the finite element structural analysis program and the displacement of an arbitrary point is measured and recorded. Then, without making changes in the geometry and loading scenario, only by applying changes in the amount of prestressing force, the displacement of the same point is measured by the number of different values of prestressing. The graph below shows the displacement of the structure inversely proportional to the amount of prestressing. Therefore, knowing that the displacement of the structure is a function of the amount of prestressing, the displacement can be considered as a criterion for studying and measuring prestressing force.

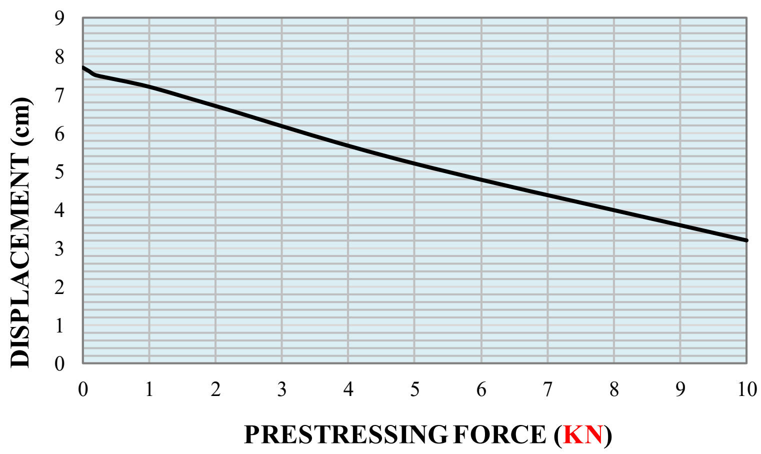

Fig 1: Prestressing force-displacement relationship monitoring

The suggested approach is based on measurements made in a lab and a comparison of the results of two prestressed concrete beams that have the same geometry, loading, and tendon arrangement. The intended prestressing forces are first applied to a certain prestressing beam created in the lab, and then these forces are decreased in some of the tendons that are the subject of the investigation. This deliberate change in prestressing values is considered as failure and the technique presented in this paper tries to discover the quantity and locality of failure of the beam. Next, the defective beam is subjected to a specific loading scenario and the displacement of some points of the beam is measured and recorded. Here, the displacement values are available as the only information from the response of the defective vector, and the proposed algorithm utilizes a computer program based on artificial intelligence in the **PYTHON** program environment to detect this failure. **[20]** In the first step, the computer program assigns random prestressing values to the 3 desired tendons with an initial guess and issues the analysis command of the proposed beam with the same geometry and loading scenario as our prototype called the proposed beam. The suggested beam is analyzed, the displacement of peer-to-peer points with the control beam is measured, and the algorithm is provided by the SAP2000, **[21]**, which is connected to the AI program used in this study—an evolutionary search algorithm. By comparing the suggested beam's responds with those of the laboratory beam, the program determines how accurate the proposed beam is. Clearly, the probability that the initial proposed beam corresponds to that of the laboratory beam is very small, therefore, the program changes the random prestressing forces by proposing changes to its initial conjecture and proposes another beam. This method continues until the suggested beam's response equals that of the control beam or reaches a reasonable and insignificant approximation. The last suggested vector with the preload values for which the program is estimated is introduced as the "answer beam" at this point, and the command to end the program is given. Now, by comparing the prestrerssing values of the answer beam with the control beam, we can comment on the robustness of the technique used·

2.1.Problem Formulation

This section presents a technique that can be used to quantify and identify damage to the entire structure, including the prestress losses of tendons and the structure's shape. The displacement vector in a structure showing linear elastic behavior can be described as follows and is a function of the force vector acting on the structure:

$$\{U\} = [K]^{-1}\{F\} \tag{2}$$

Where $\mathbf{[K]^{-1}}$ is the inverse matrix of the structural stiffness in the damaged state. In the finite element model of a two-dimensional beam, which is ignored by its out-of-plane displacements and identified by **N** points, the number of degrees of freedom for each point of the beam is 3, and the partial stiffness matrix of each point will be 3 × 3. Each element is such as length, cross section and modulus of the Yang and is expressed in the following equation:

$$[K] = [A][P][A]^T \tag{3}$$

Where **[A]** refers to the transformation matrix of the geometrical characteristics of the structure and the diagonal matrix **[P]** contains the stiffness information of the structure. Now, if the damage in the geometry of the beam is studied, we can comment on the measurement of stiffness matrix elements in the finite element points and address the changes in the elements of this matrix in the form of the following relation to identify the geometric damage of the beam:

$$\{U_d\} = [K + \Delta K]^{-1}\{F\} \tag{4}$$

Where, $\{U_d\}$ refers to the displacement resulting from stiffness changes in the damaged beam. Now, with a similar argument, if the changes in the prestressing force are examined, it can be concluded as the following equation:

$$\{U_d\} = [K]^{-1}\{F + \Delta F\} \tag{5}$$

Where, $\{U_d\}$ indicates the displacement observed in the studied structure.

What can be seen from the above equation is the proposed technique has the ability to detect the damaged prestressed beam and by solving multivariate equations, identifies the damage caused by prestressing reduction and beam geometry simultaneously. However, since the present study focuses on damage due to prestressing force loss, and in order to reduce the amount of calculations, the geometry and stiffness of the structure are assumed to be undamaged and the basic equation based on the calculations will be **Equation 5**.

Next, if the beam is loaded in the form of several different scenarios and each time the displacement of the desired points of this beam is measured and recorded, it can be said that the displacement of a point of the structure is in scenario "**i**" and the index "**m**" to the studied structure, which we call an unknown structure. It is also possible to indicate the vector of forces acting on the structure and the index "**i**" will vary from one to the number of loading states. The vector $\{U_m\}_i$ consists of the displacement of points on the beam, each of which is denoted by Δ_{mj}. On the other hand, the displacement of peer-to-peer points in the control beam with Δ_{aj} is shown and the aim of this study is to find an vector in which the difference between the displacement of peer-to-peer points such as the control beam and the unknown beam is small. To put it simply, we are searching for a beam utilizing artificial intelligence search algorithms that yields consistent static responses even though its geometry and computer-generated loading match those of a laboratory beam. The outcome of the previous explanations can now be summarized into the following equation when the displacement of multiple peer-to-peer points of the two beams in a particular loading situation is taken into consideration:

$$\{U_m\}_i – \{Ua\}_i| = \{\varepsilon\}_i \tag{6}$$

The answer to the above equation will be zero in the ideal scenario, which is the case when two vectors have exactly the same static responses. However, since there is very little chance that this will happen in the field of artificial intelligence, a minimum criterion for this equation is taken into consideration, and if it is satisfied, the problem is considered solved. The following section will address how the user's diagnosis and the problem conditions impact the minimal value, also referred to as the convergence criterion.

When analyzing reverse engineering challenges, it is preferable to examine the problem as several loading situations in order to ensure the accuracy of the solution. Consequently, it is proposed that the following generalization of Equation 7 to the potential for re-examinations be made:

$$\text{Minmize } \psi_1 = \sum_{i=1}^{NLC} \sum_{i=1}^{n} \left|\Delta_{mij} - \Delta_{aij}\right| = \sum_{i=1}^{NLC} \sum_{j=1}^{n} \varepsilon_{ij} \quad (7)$$

where the number of points whose displacement is measured is denoted by "NLC." This relationship shows that the convergence to the optimal solution increases as the above expression's value decreases. Furthermore, taking into account the application of the genetic algorithm discussed in the following section, every answer (proposed beam) in every generation of answers need to have an opportunity to exist in subsequent generations based on the level of convergence they have achieved. "Fitness," denoted by f_i, is the degree to which each response converges to the ideal response. The following equation provides the definition for this index:

$$F_i = \frac{\sum_{i=1}^{n} \left|\Delta_{mi} - \Delta_{ai}\right|}{\sum_{j=1}^{k} \sum_{i=1}^{n} \left|\Delta_{mi} - \Delta_{ai}\right|} \quad (8)$$

Where "**k**" is the number of responses that are evaluated simultaneously at each stage. This equation shows that as the convergence of a response increases, the f_i index value decreases. Therefore, in order to harmonize convergence and fitness values, the following equation, which we call the fitness index, is suggested:

$$\omega_i = \frac{1}{F_i} \quad (9)$$

This equation is called "*Objective Function*" in reverse engineering problems and is a suitable indicator to measure the evaluation of each response.

2.2. Procedure of actual prestress force detection

Nowadays, plenty of engineering problems that demand for optimization and the search for the optimum solution in discontinuous environments use artificial intelligence as an effective tool **[22, 23].** The genetic algorithm can simply be called a search engine that is based on observations of the characteristics of the offspring of successive generations and the selection of offspring based on the principle of survival of the fittest. The genetic algorithm on the offspring of a generation (one-step problem answers) mimics the laws of genetics and uses them to produce better-characterized offspring (answers closer to the problem goal). In each generation, with the help of a selection process commensurate with the value of the answers and the reproduction of the selected children (answers), better approximations of the final answer are obtained. This process makes the new generations more adaptable to the problem conditions. This competition between genes and the dominance of the dominant gene (selected by the algorithm for subsequent reproduction) and the elimination of recessive genes (problem-away answers) is an efficient way to solve complex and difficult problems. The mechanism of the algorithm used is shown in **Figure 2**.

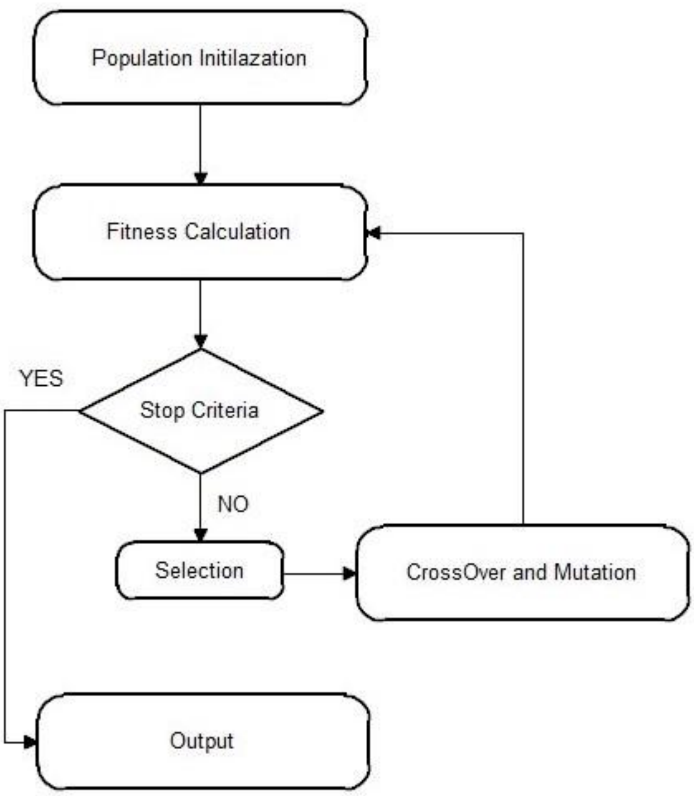

Fig 2: Schematic of the proposed error function minimizing technic

2.3. Convergence Criteria

Convergence criteria are important in civil engineering because they help assess the reliability and efficiency of optimization algorithms. According to the conformity-based assessment of responses called Fitness, consistent responses have a higher chance of producing generations with greater validity in the future. How long will future generations continue to produce is the question that emerges. Until the result of the last search phase is sufficiently consistent with the ideal response, the search process is repeated. Adequate compliance, defined as a number indicating the convergence interval, is crucial in this process. In this study, the convergence interval is set at 0.01 cm, but it may vary depending on the problem and user discretion. The convergence criterion can be determined by comparing the best and worst response of the last generation **(Equation 10)** or by comparing the best response with the average of all responses obtained in the same generation **(Equation 11)**. This criterion ensures that the optimization algorithm converges towards an optimal solution effectively.

Convergence criteria are essential in the development of optimization algorithms, to sum up, in order to ensure the generation of legitimate and consistent solutions for future generations. Through the development of suitable convergence intervals and criteria, engineers can attain optimal outcomes in their processes of design and analysis.

$$\psi_2 = \frac{\omega_1 - \omega_m}{\omega_1} \leq \varepsilon_2 \quad (10)$$

$$\psi_3 = \frac{\omega_i}{\frac{1}{m}\sum_{i=1}^{m}\omega_i} \leq \varepsilon_3 \quad (11)$$

Here, “**m**” refers to the number of responses per generation, and the values e_2 and e_3 are defined depending on the problem conditions and the user. It should be noted that, none of the above convergence criteria is superior to the others and each of them or a combination of them can be introduced as a condition to end the search to the algorithm and the desired answer as the final answer.

3. Experimental Program

To determine the status of prestressing force in each tendon and at the beam's bearing points, an analysis was conducted on a prestressed concrete beam with certain dimensions and tendon arrangement. Two distinct loading situations were applied to the beam, and the displacements of certain places were measured. For verification, strain gauges were inserted into each tendon after an artificial intelligence algorithm identified a beam with similar physical properties (240 cm in length and 25 by 35 cm in cross-section). The steel tendons used in the beam had an ultimate strength of 4200 kg/cm^2, a specific weight of 7870 kg/m^3, and a diameter of 1.2 cm, which are placed in the tensile zone of the beam by observing the concrete cover. The normal concrete (NC) used in the beam was cast using general purpose (GP) Portland cement (Type II) with specific surface area specifications. Natural river gravel and sand were used as coarse and fine aggregates, respectively.

Standard cylindrical specimens were prepared and tested for compression and Brazilian tensile strength at different curing durations **[24, 25].** The concrete mix design used and the test results are presented in **Tables 2** to **3**.

Figures 3 to 4 display the geometry, tendon arrangement, actual model of the tested beam, and photos of the measurement and preparation processes. Through actual testing, this work aims to evaluate the accuracy of the suggested method and offer helpful details about the behavior of prestressed concrete beams under various loading situations.

Table 1: Physical and chemical properties of the cement

Material	Chemical analysis (%)									Specific surface (cm^2/g)
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	Na_2O	K_2O	$L.O.I$	
Cement	21.8	4.85	3.53	63.43	1.52	2.13	0.36	0.56	2.4	3050

Table 2: Mix compositions

Concrete Type	W/C	Water (kg/m^3)	Cement (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	Slump (mm)
NC	0.4	160	400	728	1092	63

Table 3: Compressive and tensile test results of concrete at different times

Concrete Type	Compressive strength (MPa)			Tensile strength (MPa)		
Days	7 days	28 days	90 days	7 days	28 days	90 days
NC	20.94	31.54	35.87	2.85	3.62	3.96

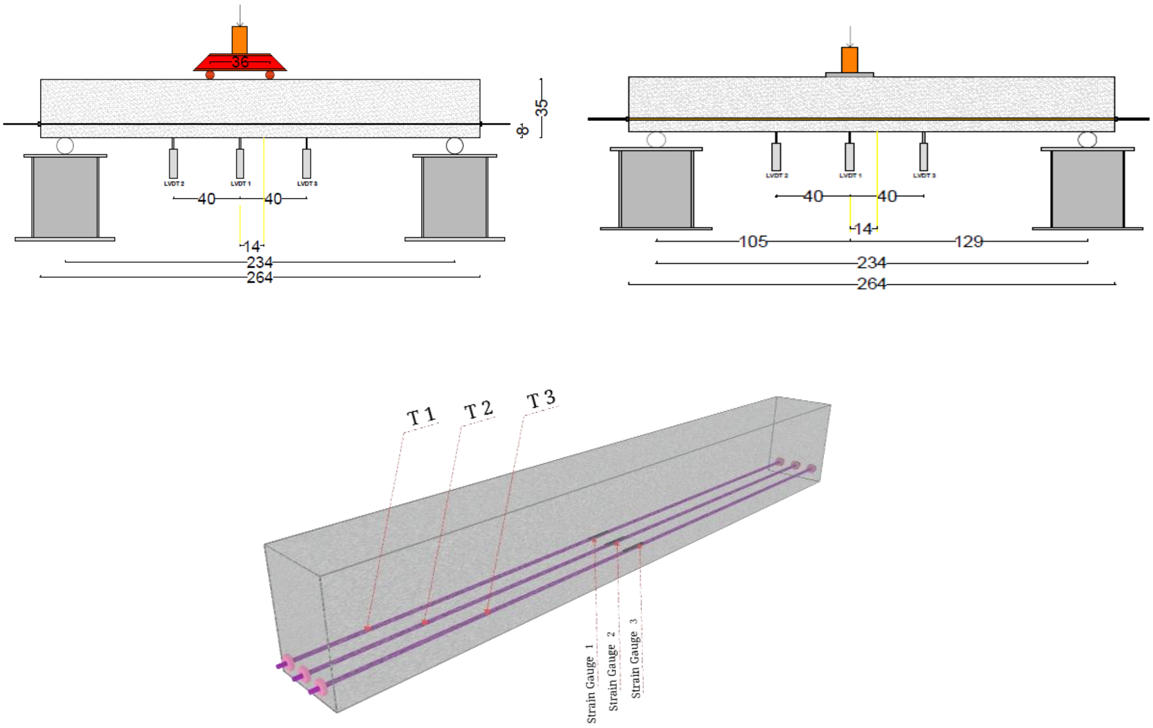

Fig 3: Schematic view of the case study

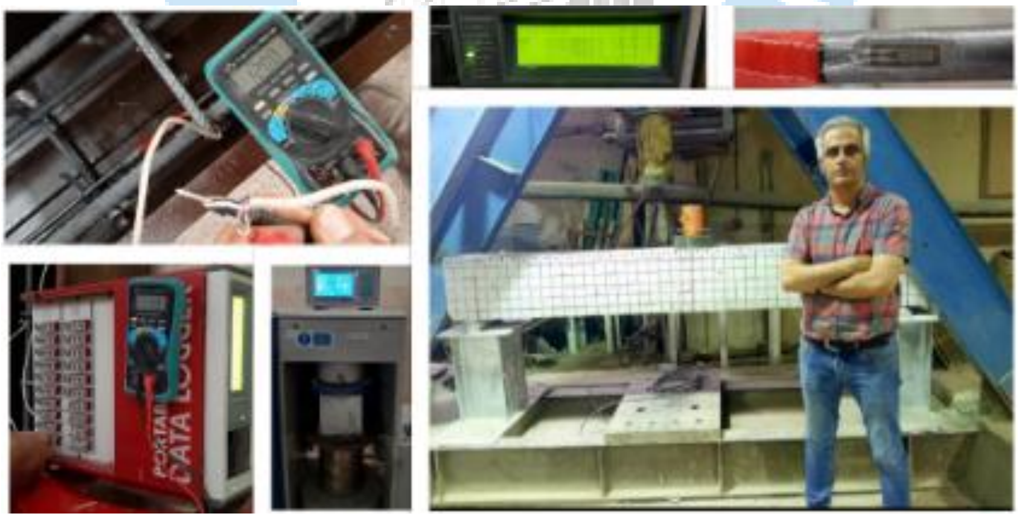

Fig 4: The real model and measuring equipment

As was previously noted, one may determine the internal force of each tendon by observing static structural changes like strain and displacement and applying transformation equations. As a result, we applied static loading to the tested beam and then increased the load gradually to detect the displacement of specific puts on the beam as well as the momentary strain of each tendon. **Figures 5** to 8 show some graphs that illustrate how strain and beam displacement vary with the amount of load under various loading situations.

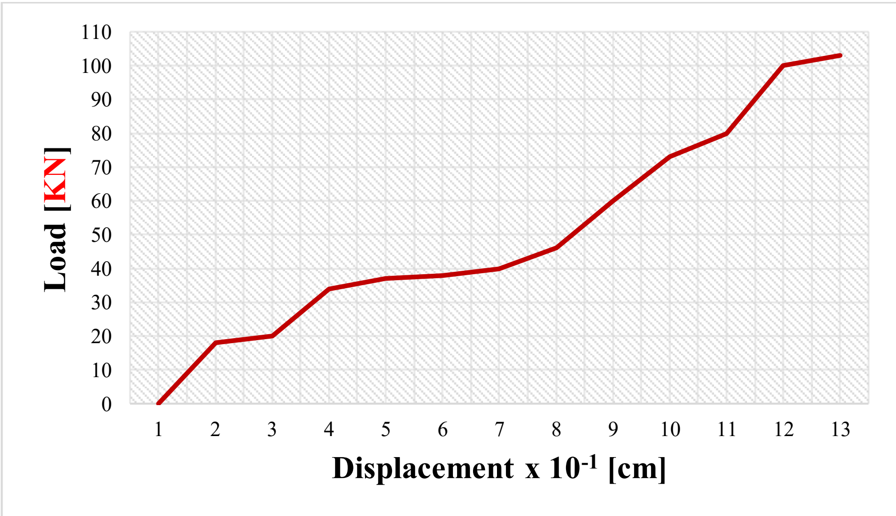

Fig 5: The 3-point load-displacement relationship measured from LVDT 1

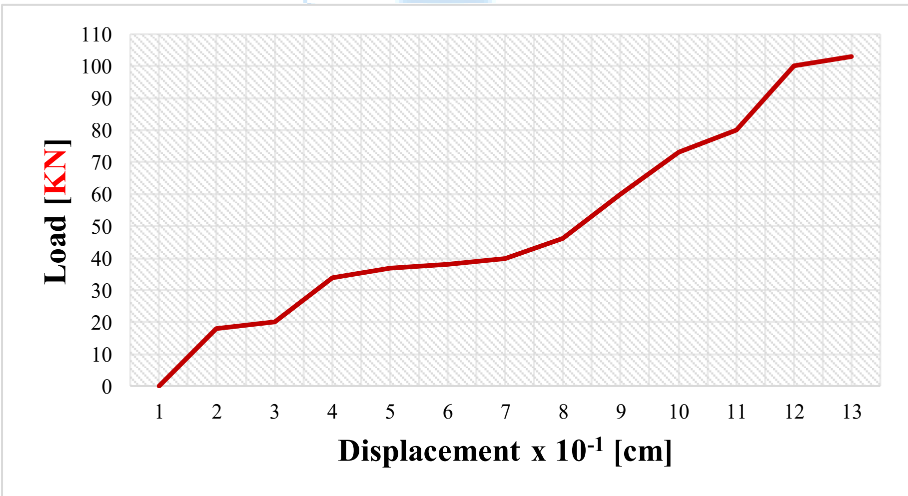

Fig 6: The 5-point load-displacement relationship measured from LVDT 3

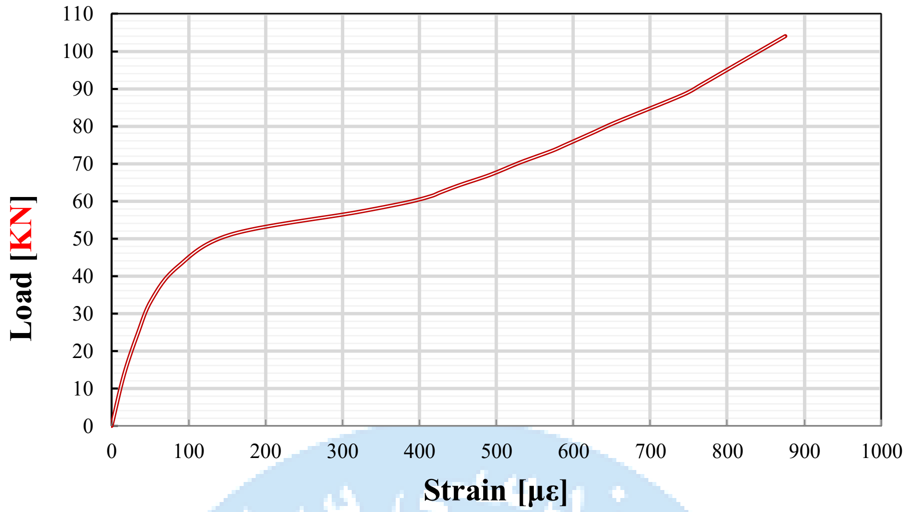

Fig 7: The 3-point load-strain relationship measured from Strain Gauge 1

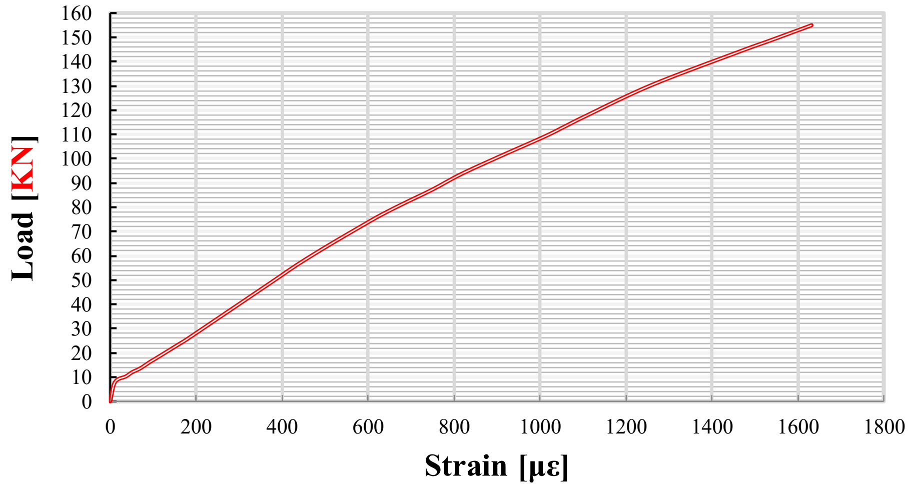

Fig 8: The 8-point load-strain relationship measured from Strain Gauge 2

3.1 Program running

Here, we test the proposed technique by dividing the finite element of this beam into five nodes, including two end supports, three midpoints at a quarter of the opening from the abutment and the midpoint of the beam, and applying a 7-ton tensile force to the three tendons of the tested beam. We also intentionally damage some of the tendons by reducing the prestressing force. The following values of prestress reduction are defined and coded as guessing choices since they need to be specified:

Table 4: Severity of possible failure in the 3 tendons

Remaining Force (KN)	Damage Number (decimal)	Damage Code (binary)	$F_r = \frac{F_0 - F}{F_0} \times 100\%$
70	0	0000	0
65	1	0001	7
60	2	0010	14
55	3	0011	21
50	4	0100	28
45	5	0101	36
40	6	0110	43
35	7	0111	50

30	8	1000	57
25	9	1001	64
20	10	1010	71
15	11	1011	79
10	12	1100	86
5	13	1101	93
0	14	1110	100

In table 4, $\mathbf{F_r}$ is the damage index and refers to the percentage of prestressing force loss. As shown in **Table 1**, the number of cases studied is limited to 15. Now, considering that 15 failure states are searched in three tendons, the total number of probabilistic space states can be defined as 3^{15}. Obviously, this number refers to a large range of possibilities and the technique used will be able to find the answer by examining a small space of the total probability space. In the following, an arbitrary intentional failure case that includes prestressing reduction in parts of the control beam is defined according to the table below and in the beam analysis program, the displacement of other points is measured and recorded under a loading scenario. The reduction in prestressing in each of the three tendons is displayed in the table below. The artificial intelligence program then attempts to determine the location and amount of failure using the mechanism mentioned and an initial guess.

Table 5: Locality and quantity of prestressing force in the 3 tendons

Tendon Number	Tendon 1	Tendon 2	Tendon 3
Force (KN)	60	70	55

Note: Some values of prestressing force of the laboratory sample have been deliberately reduced. These values are considered as failure indicators and the proposed algorithm tries to calculate them.

4. Evaluation of the proposed algorithm and results

This study provides consumers with useful information by thoroughly examining the proposed method and conclusions. It is advised to run the program multiple times under different loading conditions and to adjust the mutation factor rate in order to increase the dependability of the results. By comparing and finding common ground between the results at each program level, users can arrive at the final solution with more confidence. The sensitivity analysis conducted by introducing intentional displacement measuring errors is a good way to evaluate the robustness of the algorithm. The results obtained in **Figure 9**, **Figure 10**, and **Figure 11** demonstrate that the algorithm was able to accurately identify the position and amount of prestress force loss in three tendons. The use of convergence criteria such as ψ_1 and ψ_2 also helped in reducing response time. Overall, by following the evaluation methods and recommendations provided in this study, users can ensure that reliable and accurate results are obtained from the proposed algorithm. Further research could focus on testing the algorithm on more complex structures or comparing it with other optimization algorithms to assess its performance further.

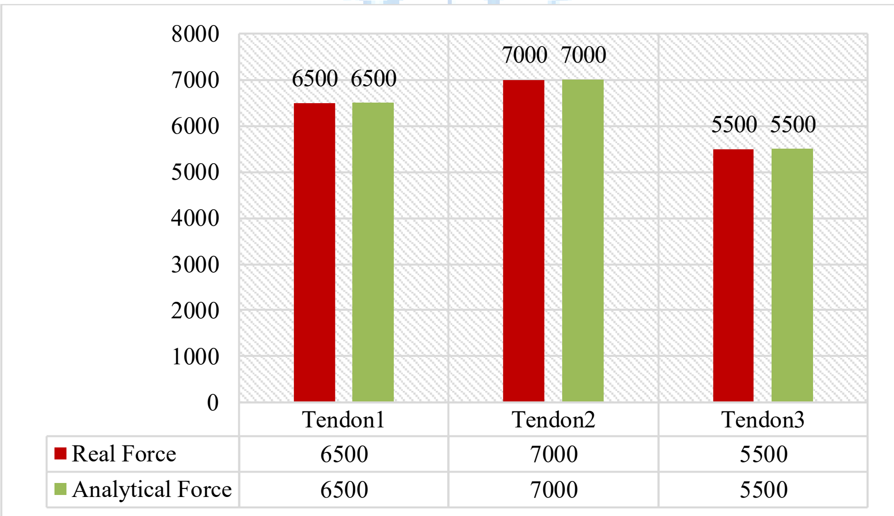

Fig 9: Comparison diagram of real and analytical prestressing forces

Fig 10: Convergence diagram, considering ψ_1 as the only convergence criterion

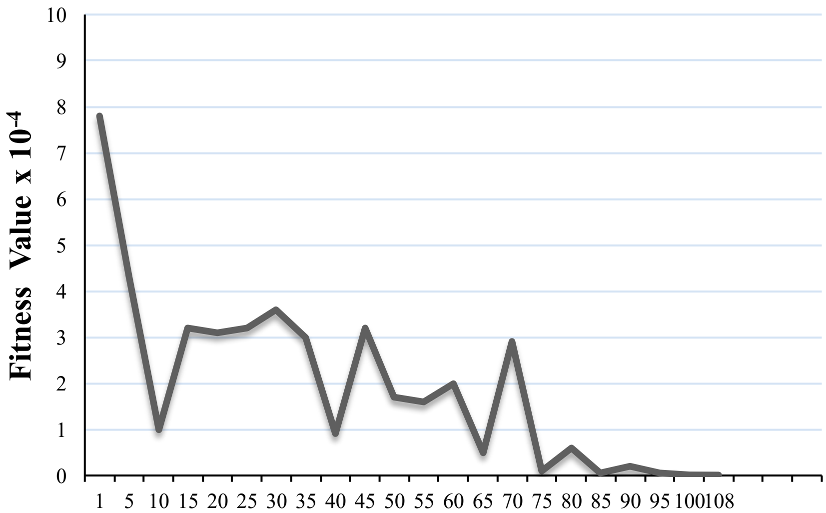

Fig 11: Convergence diagram, considering ψ_1 and ψ_2 as convergence criteria

The search operation is then repeated to see how sensitive the suggested method is to measurement error, looking for 10% and 20% of the deliberate displacement measurement error, which could be caused by a user's reading mistake or a measuring device's inaccuracy. As Figure 12 demonstrates, the suggested method can identify the right response with 93% accuracy even with a 10% deliberate displacement measurement error. However, the suggested algorithm becomes invalid when a measurement error of 20% is used, as shown in **Figure 13**.

Fig 12: Comparison diagram of real and analytical prestressing forces, applying 10% Measurement error

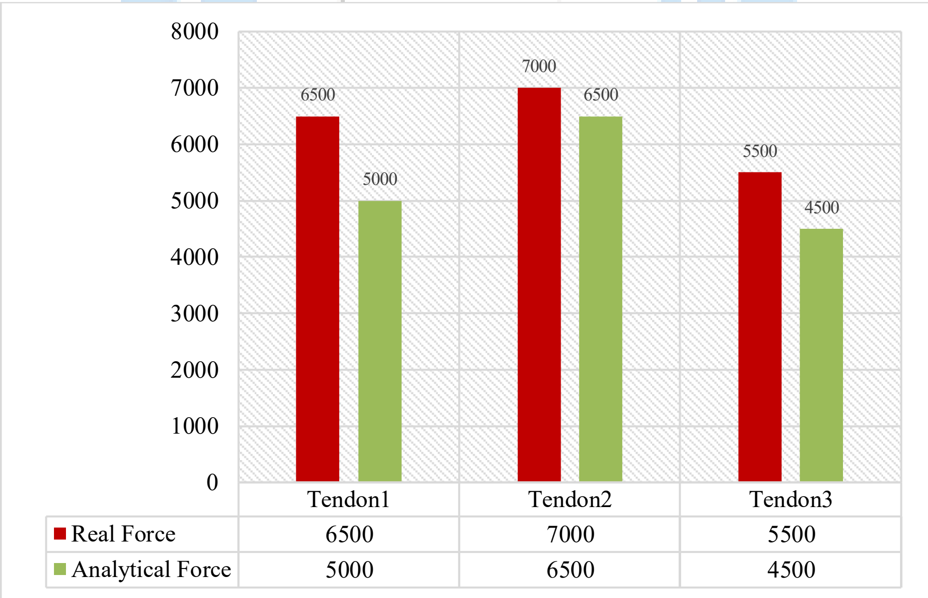

Fig 13: Comparison diagram of real and analytical prestressing forces, applying 20% Measurement error

5. Conclusions

In this study, we aimed to develop a non-destructive method for measuring static displacement under load to calculate the prestressing force in prestressed concrete beams. This approach is particularly beneficial for structural health monitoring (SHM) applications, as it allows for the continuous assessment of prestressing loss without the need for destructive testing. The findings of this research can be summarized as follows:

1. Displacement as an Indicator: The initial analysis demonstrated that variations in prestressing force significantly affect static displacement, establishing a clear relationship between these two parameters. It was confirmed that measuring static displacement can effectively serve as a criterion for identifying reductions in prestressing force, particularly within reverse engineering contexts.

2. AI-Based Prestressing Force Reduction Assessment: The application of an artificial intelligence-based search method, specifically a genetic algorithm, allowed for precise determination of the degree of prestressing force reduction. Genetic algorithms require significantly less data compared to other artificial intelligence-based search techniques. Therefore, it is possible to explore solutions even with limited loading scenarios and measurements.

3. Laboratory Validation: A laboratory experiment conducted on a concrete beam validated the proposed technique, confirming its practical applicability and effectiveness, using a finite element analysis modeling. A detailed finite element model of a prestressed reinforced concrete beam with three steel tendons exhibiting different prestressing forces was successfully developed and analyzed under various static loading scenarios.

4. Optimization Convergence Rates: As another innovation, the study highlighted that applying different convergence criteria, at the same time, can enhance convergence rates in optimization problems related to structural assessments. In this context, by logically selecting empirical values for the mutation and crossover operators, the amount and location of force reduction were identified with an accuracy of 93%, even in the presence of a 10% intentional measurement error.

5. Future Research Directions: This technique holds promise for future studies aimed at simultaneously evaluating both prestressing reduction and potential concrete failure in beams, paving the way for more comprehensive structural health monitoring solutions.

Overall, this research contributes valuable insights into non-destructive testing methods and their application in maintaining the integrity and safety of prestressed concrete structures.

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