Numerical Investigation on Detection of Prestress Losses in a Prestressed Concrete Slab by Modal Analysis

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Abstract. The paper presents numerical results of loss of prestress in the reinforced prestressed precast hollow core slabs by modal analysis. Loss of prestress is investigated by the 3D finite element method, using ANSYS software. In the numerical examples, variables initial stresses were introduced into seven-wire stress-relieved strands of the concrete slabs. The effects of span and material properties of concrete on the modal frequencies of the concrete structure under initial stress were studied. Modal parameters computed from the finite element models were compared. Applicability and effectiveness of the proposed method was investigated.

1. Introduction

In recent years, development of damage detection techniques based on modal parameters was extensively studied. It is possible to identify damage of structure by comparing typical dynamic properties of the damaged and undamaged structure. This method is being widely used because it is very simple in use. Many algorithms for damage detection were developed by many researchers over the three decades in the field of vibration based damage detection [1].

One of the main problems in the analysis of prestressed concrete is the estimation of the loss of prestress. It is known that the loss of the prestress force in tendon occurs due to elastic shortening and bending of concrete, creep and shrinkage of concrete, steel relaxation, anchorage take-up, and frictional loss between tendon and its surrounding materials. Also, the loss of the prestress force unexpectedly occurs due to damage or severing of prestress strands. Therefore, it is very important to estimate the prestress loss by considering the fact that a prestressed concrete should keep effective prestressing force during service life of structure [2].

The prestress forces lead to reduce deflections of prestressed concrete structures, and to add strength to the structures. Therefore, a substantial difference between the desired and the in-service prestress forces can lead to severe and critical serviceability and safety problems [3-5]. In this case, a prestressed concrete structure is considered as irreparable as it is seriously damaged on the condition of the prestressing strands [6]. The existing prestress force cannot be directly monitored and other alternative methods should be chosen. Based on previous research works, nondestructive methods using vibration monitoring can be used to estimate the prestress loss. One of the methods to detect a possible loss of prestress force in concrete structure is implementation of dynamic monitoring. Loss of prestress can change the stiffness of structure which causes changes of modal parameters and mode shapes. It is possible to identify loss of prestress of prestressed concrete structure by comparing
frequencies of reference structures and frequencies of structure with reduced prestress forces. The efficient application of this method was carried out by Finite Element Analysis.

The procedure for performing a modal analysis of prestressed concrete slab in finite element program ANSYS is concerned by the effect of initial stress on the dynamic response of concrete structure and include structural and modal analysis.

Structural analysis of prestressed concrete in finite element program ANSYS was successfully performed by Anthony J. Wolanski, [7]. In the thesis work, he studied reinforced and prestressed concrete beams using finite element program ANSYS to understand their load-deformation response. The results were compared to experimental data. Revathi and Menon [8] conducted finite element and experimental studies of concrete beams in ANSYS, to validate the potential of numerical simulation in predicting the nonlinear response of the elements. The numerical and test results were seen to compare well.

In this paper, a method to nondestructively detect the loss of prestress force in prestressed concrete slab using a modal analysis is presented. Modal analysis of concrete slabs are investigated by the 3D finite element method (FEM), using ANSYS software and obtained results compared. Loss of prestress was modeled as reduction of stresses in strand. The effectiveness of using percentage changes in modal frequencies as indicators of the loss of prestress was studied.

2. Numerical studies

In this section, a finite element model of the reinforced prestressed precast hollow core slabs was created and then initial stress with various values were introduced into the model, separately. The modal analyses were performed and the effects of initial stress on modal characteristics of the finite element model were studied to provide useful reference for further numerical studies.

2.1. Design of the reinforced prestressed precast hollow core slab

The cross-section dimensions of reinforced prestressed precast hollow core slab for the numerical studies are illustrated in figure 1. The slab is typically 1200 mm width with standard thicknesses 220 mm and span 12000 mm. The slab is prestressed by seven-wire stress-relieved strands of 15 mm diameter located 35 mm from the soffit and built by extrusion. The prestrressing force in prestressed concrete slab is commonly applied with prestressing strands. These strands are made from high-strength steel, and they are stressed before when the concrete should be hardened.

The concrete’s elastic modulus is $E_c = 27$ GPa; Poisson’s ratio is $\nu_c = 0.2$ and the density is $\rho_c = 2400$ kg/m$^3$. The steel’s elastic modulus is $E_s = 180$ GPa; Poisson’s ratio is $\nu_s = 0.3$; ultimate tensile strength is $f_{tu} = 1500$ MPa and the density is $\rho_s = 7850$ kg/m$^3$. Initial stress in steel strands is $\sigma_i = 1200$ MPa. The concrete slabs are simply supported at the two shortest opposite edges.

![Figure 1. Cross-section dimensions of reinforced prestressed precast hollow core slab (Dimensions in mm).](image-url)
2.2. Finite element modeling

The 3D finite element models of the reinforced prestressed precast hollow core slabs were simulated using commercial finite element software ANSYS16.0. Solid65 and link180 elements were selected to represent concrete and stress relived seven wires strands, respectively. Solid65 element was used to model concrete. This element has three dimensional concrete elements with eight nodes and three translational degrees of freedom at each node. The most important aspect of this element is the treatment of nonlinear material properties. Link180 is suitable for modeling stress relived seven wires strands. The 3D spar element is a uniaxial tension-compression element with three translational degrees of freedom at each node and translations in the nodal x, y, and z directions. Some model simplifications were done, namely side walls of slab was aligned. This gives the possibility to decrease the dimension of the finite element model. Fragment of FEM model is shown in figure 2.

Figure 2. Fragment of finite element model.

The procedure for performing a modal analysis of prestressed concrete slab in finite element program ANSYS is concerned by the effect of initial stress on the dynamic response of concrete structure. Firstly, a structural analysis is performed. Prestressing of concrete is simulated by INISTATE command. This command was used for applying an initial constant stresses to all selected elements of wires and resulting stress and strain fields are determined. Initial stresses are added in strands instead of prestressed forces.

Prestress effects were considered and the analysis was carried out for “Small displacement static conditions”. In the next step, these fields are then used and modal analysis is performed on the pre-loaded concrete structure.

Loss of stress in prestressed concrete slab was modelled by decreasing of initial stress in the strand that located in the center of prestressed concrete slabs. The models were analysed with its self-weight. Self–weight of the prestressed concrete slab was taken into account by providing the value of acceleration due to gravity (9.81m/s²).

2.3. Modal analysis and loss of prestress detection

Before numerical study and research of prestressed concrete slab with different values of initial stress and material properties, the finite element analysis was carried out to check validity of loss of prestress detection using modal frequencies. Figure 1 shows the first 4 mode shapes of prestressed concrete slab with reference initial stress of 1200 MPa.

The modal frequency percentage change is calculated using ratio of corresponding modal frequencies for prestressed concrete slab with reference initial stress 1200 MPa and with reduced initial stress.
\[ \Delta_f = \left| \frac{f_i - f_{1200}}{f_i} \right| \times 100 \] (1)

where, \( f_{1200} \) is the modal frequency of prestressed concrete slab with initial stress 1200 MPa and \( f_i \) is the modal frequency of prestressed concrete slab with reduced initial stress. The modal frequencies were compared using the first 3 vertical bending mode shapes.

| Initial stress [MPa] | Calculated First Mode Frequencies [Hz] | Difference [%] | Calculated Second Mode Frequencies [Hz] | Difference [%] | Calculated Fourth Mode Frequencies [Hz] | Difference [%] |
|----------------------|----------------------------------------|----------------|----------------------------------------|----------------|----------------------------------------|----------------|
| 1200                 | 1.45                                   | 0              | 10.21                                  | 0              | 24.11                                  | 0              |
| 1000                 | 1.50                                   | 3.4            | 10.23                                  | 0.2            | 24.14                                  | 0.1            |
| 800                  | 1.55                                   | 6.8            | 10.26                                  | 0.5            | 24.17                                  | 0.2            |
| 600                  | 1.59                                   | 9.9            | 10.29                                  | 0.8            | 24.19                                  | 0.3            |
| 400                  | 1.64                                   | 12.9           | 10.32                                  | 1.1            | 24.22                                  | 0.5            |
| 200                  | 1.68                                   | 15.9           | 10.35                                  | 1.4            | 24.24                                  | 0.5            |
| 0                    | 1.72                                   | 18.8           | 10.37                                  | 1.6            | 24.27                                  | 0.7            |

These results show that loss of prestress detection using modal frequencies better for first out of plane bending mode shape. Reduction of initial stress in strand leads to increase of frequencies. Further first bending mode shape was used for modal analysis of prestressed concrete slabs.

### 3. Results and discussions

The modal frequencies percentage change obtained for the 3 elastic modulus of prestressed concrete slab is calculated [9]. The variation of stress in strand with percentage change is represented in figures 4-6. The span of the prestressed concrete slabs is varied from 8 to 12 m. These results of percentage
change show that the modal frequency percentage changes differ significantly depending on the span used. The percentage change higher when elastic modulus of concrete is lower and increases almost linearly with initial stress.

![Figure 4](image1.png) **Figure 4.** Frequencies percentage change when $E_c = 27$ GPa.

![Figure 5](image2.png) **Figure 5.** Frequencies percentage change when $E_c = 29$ GPa.

![Figure 6](image3.png) **Figure 6.** Frequencies percentage change when $E_c = 31$ GPa.

It is assumed that frequency percentage change must exceed 5% to detect loss of prestress. If the difference does not exceed 5% detection is impossible. This is due to the fact that modal frequencies are small at each level of loading.

Table 2 shows calculated reduction of initial stress in strand required for loss of prestress detection with frequency change of 5%. The spans of 9 and 8 m had the smallest frequency change in comparison with other spans (less than 5%) and do not include in Table 2. It is seen that the prestressed concrete slab with minimal elastic modulus has more capability to detect loss of prestress with a much lower reduction of initial stress in strand than the prestressed concrete slab with greatest elastic modulus.
Table 2. Minimal detectable reduction of initial stress in strand, MPa.

| Span of prestressed concrete slab, m | $E_c = 27$ GPa | $E_c = 29$ GPa | $E_c = 31$ GPa |
|------------------------------------|---------------|---------------|---------------|
| 12                                 | 294           | 385           | 470           |
| 11                                 | 530           | 625           | 730           |
| 10                                 | 830           | 940           | 1065          |

4. Conclusions
This paper presents study on loss of prestress detection of the reinforced prestressed precast hollow core slabs by modal analysis. For the analysis of the model, prestress effects were taken into account and the finite element analysis was carried out. Parameter studies on the effects of loss of prestress on modal characteristics were investigated by the 3D finite element method (FEM) using ANSYS software. The present study shows that modal frequencies percentage change is dependent on the span of slab used for the loss of prestress measurement. The spans of prestressed concrete slabs were found for the percentage change of 5% required for an effective detection of prestress losses. The results obtained show that detection of loss of prestress is valid only for prestressed slabs with spans of 12, 11 and 10 meters. Additionally, the numerical results demonstrate the effectiveness to detect loss of prestress using modal analysis for prestressed concrete slabs with lower elastic modulus.

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