

Nonlinear Numerical Simulation of Prestressed Concrete Beam and Wireless Sensor Node Design for Reinforcement Corrosion Monitoring Based on ANSYS

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Received: 15 November 2013 / Accepted: 22 December 2013 / Published: 30 December 2013

Abstract: This paper puts the finite element method into the nonlinear analysis of prestressed concrete beam, reveals the regularity and bearing capacity behavior in different stages of the concrete structure. The result finds that Solid65 is the unit provided by the ANSYS for analyzing the structures of reinforced concrete, to some extent, it can reflect the cracking and crushing of concrete, and it can truly represent the characteristics of the structures' typical destruction of reinforced concrete; This article also completed the node design of wireless sensor for steel corrosion monitoring. Further work will focus on wireless sensor network study including multiple-node wireless communication, related communication protocols, multiple-hop self-organizing network, aggregation node and human-computer interaction function, to achieve real intellectualization and the purpose of online real-time monitoring. *Copyright © 2013 IFSA.*

Keywords: Finite element method, Prestressed concrete beam, Steel corrosion monitoring, Wireless sensor.

1. Introduction

In China and worldwide, ANSYS software has become the mainstream of the CAE simulation analysis software in civil construction industry. Using ANSYS economically and quickly has great significance to the civil engineering structure's numerical simulation calculation, to improve the design level and quality of the whole civil engineering industry and to increase comprehensive economic efficiency of the project.

Linear elastic analysis of reinforced concrete finite element has been matured, nonlinear analysis is developing rapidly, and it has made many achievements applied in practical engineering [1]. ANSYS has been applied in many large projects at home and abroad, on the analysis of prestressed

concrete and reinforced concrete beam, absolutely most are linear elastic analysis, only a few analyses refer to the ultimate load calculation, analysis method is not yet mature [2]. This article aims to further perfect nonlinear numerical simulation method of prestressed concrete and reinforced concrete beam by ANSYS.

At the same time, this paper adopts the method put forward by the university of Texas of combination of effective content detection (steel wire) and radio-frequency technique. Among which, the embedded sensors are designed through model analysis and adopted LC circuit. In order to gather resonant frequency change information of the embedded sensor and make long distance transmission and summary of that information, this paper designed the external circuit with its main

processing chip of MSP430F149 based on DDS and wireless data transceiver chip NFR905.

2. Nonlinear Numerical Simulation of Prestressed Concrete Beam

2.1. Theoretical Basis

When analyzed with ANSYS, finite element model of reinforced concrete structure are mainly two kinds which are disconnect-type and integral type [3]. The model of integral type use directly the SOLID65 with tendon unit to simulate, simple modeling, high efficient analysis, it is easy to converge when solve, but the result is relatively rough, it does not apply to the area that reinforcement distribution is uneven, and it is more difficult to has reinforced internal force. Disconnect-type model choose a different unit according to different mechanical properties of concrete and reinforcing steel bar. Using the space bar element LINK8 or spatial unit PIPE20 to establish reinforcement model, and share common node with the concrete unit SOLID65. Its advantage is that it can be arbitrary arranged reinforcing steel bar and get internal force of reinforcing steel bar directly, it considers the actual situation of bond and slip between steel and concrete, the results are more reliable, but the complex modeling, it is difficult to converge when solve; Need to consider the common node position, and it is easy to appear the stress concentration problem.

Constitutive relation of concrete material can apply multiple linear strengthening models MISO, multiple linear servo reinforced model MKIN, and DP; Steel can adopt bilinear follow-up reinforced model BKIN and bilinear strengthening model BISO, etc. When it doesn't input the constitutive relation, before concrete cracking and crushing, ANSYS uses the default constitutive relation, the concrete and steel bar adopt linear constitutive relation. To input the constitutive relation of concrete, first determine what kind of uniaxial compressive stress-strain relationship is to be adopted. The relationship has many expressions, you can refer to relevant information or make normative selection, it is recommended to apply the GB50010-2002 recommended formula or Hong Nestad formula [4].

2.1.1. Finite Element Model of Prestressed Concrete Beam

Finite element model of prestressed concrete beam disperses reinforced concrete beam into two nodes, and uses Timoshenko beam that considering shear effects. External loads have influence on the beam element node, the distance between the nodes depends on the form of load and the shape of prestressed reinforcement. Prestressed reinforcement is dispersed into planar truss two nodes unit that

corresponding to beam element and only under the axial force, the distance between the truss element node and the corresponding beam element node is the eccentricity of prestressed reinforcement [6]. Set short rigid arm in the place that between the truss element node and the corresponding beam element node, to ensure the eccentricity of prestressed reinforcement stays the same throughout the loading history. Detailed modeling process can reference the relative literature [7], this paper emphatically describes the incremental iterative method [8] adopted when tracking the whole process of beam's nonlinear response.

2.1.2. Constitutive Model

In compressive zone, concrete uses the rise of the quadratic parabola and decline period of stress - strain curve of straight line suggested by Hognestad. In tensile zone, concrete uses the stress-strain relationship suggested by Vecchio and others. Material parameters:

$$\gamma = 0.16, \varepsilon_0 = 0.002, \varepsilon_u = 0.0034, E_c = 42.2 GPa, \\ f_t = 5.6 MPa, \alpha_1 = \alpha_2 = 1.0.$$

Prestressed reinforcement applies three line stress - strain relationship, material parameters:

$$\sigma_e = 1500 MPa, \sigma_{0.2} = 1660 MPa, f_{pu} = 1785 MPa, \\ \varepsilon_{0.2} = 0.015, \varepsilon_{pu} = 0.035.$$

However, the non-prestressed reinforcement uses elastic-plastic stress-strain relationship.

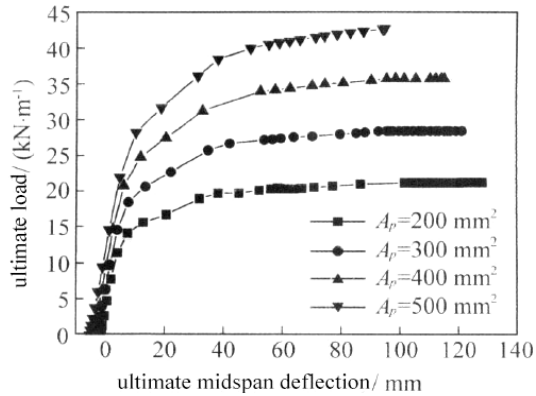
2.2. Instance Analysis

2.2.1. Model Specification and Numerical Simulation of Prestressed Concrete Beam

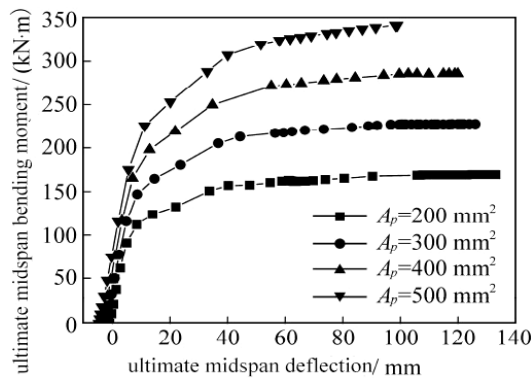
In order to study material strength effect on prestressed concrete beam performance, the embedded prestressed concrete beam which can bear the even load is designed. Linear prestressed tendon is designed with strength of extension 1860.5 MPa, elasticity modulus 195.5 GPa. Compressive zone structure without tendon area is $A'_s = 300 mm^2$, the yield strength $f'_y = 350 MPa$. And the cross section's lower part is equipped with non-prestressed reinforcement of tensile region, and its area is $A_s = 300 mm^2$, its yield strength is $f_y = 530 MPa$, its elastic modulus value of non-prestressed reinforcement is 200 GPa, compressive strength of concrete's axis $f_c = 35.5 MPa$.

2.2.2. Results and Analysis of Calculation

1) The influence of prestressed reinforcement's area. Regarding the area of prestressed reinforcement A_p as variable, the range of the variable is $200-500\text{mm}^2$, $\sigma_{pe}=1200\text{MPa}$. Fig. 1(a) and Fig. 1(b) are the load – mid-span deflection ($p \sim \delta$) and mid-span moment – mid-span deflection ($M \sim \delta$) curve that different prestress under the effect of uniformly distributed load of concrete beam.



(a) The impact that the area of prestressed reinforcements on the load – deflection curve.



(b) The effect that the area of Prestressed reinforcements on bending – deflection curve.

Fig. 1. The influence that the area of prestressed reinforcement on load, bending moment – deflection curve.

From the curves ($p \sim \delta$) and ($M \sim \delta$), we can see that the bigger the area of prestressed reinforcement, the bigger the arch deflection that the beam under the effect of pre-tension and gravity load, the bigger the cracking load and cracking bending moment of beam. For a specified load level, the smaller the area of prestressing tendons, the bigger the beam's deflection. When the beam is broken, from the Fig. 1 (a) and Fig. 1 (b), we can see that along with the rising of the prestressed reinforcement's area, ultimate load and the ultimate bending moment of beam remarkably increase, and the mid-span ultimate deflection decreases. When the

area of prestressed reinforcement increase from 200mm^2 to 500mm^2 , ultimate load of uniformly distributed load from $21.36\text{KN} \cdot \text{m}^{-1}$ to $43.01\text{KN} \cdot \text{m}^{-1}$, it is increased by 101.35 %; The mid-span ultimate bending moment increases from $170.28\text{KN} \cdot \text{m}$ to $342.42\text{KN} \cdot \text{m}$, it is increased by 101.09 %; The mid-span ultimate deflection from 132 mm to 98.2 mm, it is decreased by 25.61 %.

2) The influence of the effective prestress

Regarding the effective prestress σ_{pe} as a variable, the variable range is $600-1200\text{MPa}$, $A_p = 400\text{MPa}$. Fig. 2(a) and Fig. 2 (b) are the load – mid-span deflection curve ($p \sim \delta$) and the mid-span bending moment – mid-span deflection curve ($M \sim \delta$) of different prestress of beams under the effect of uniformly distributed. From the curves ($p \sim \delta$) and ($M \sim \delta$), we can see that the bigger the effective prestress, the bigger the arch value of beam out load, the bigger the cracking load and cracking beam bending moment of beam. For a specific load level, when the deflection of the beam is smaller, effective prestress is relatively large. When the beam is broken, from the Fig. 2(a) and Fig. 2(b), we can see that with the increase of effective prestress, beam's ultimate load and the ultimate bending moment almost have no change, and the mid-span ultimate deflection decreases gradually. When the effective prestress increases from 600MPa to 1200MPa , the ultimate deflection uniformly distributed decreases from 158 mm to 119 mm, it is decreased by 24.68 %.

2.3. Brief Summary

Through the finite element model, tendon area, effective prestress effect on bearing capacity of prestressed concrete beam are analyzed, draw the following conclusions:

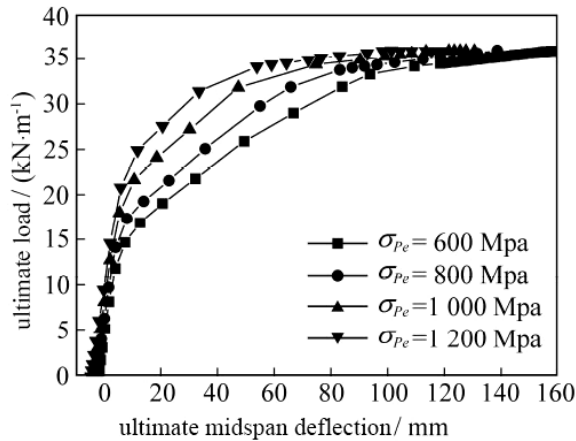
- 1) Increase the reinforcement ratio of tendon can significantly improve beam cracking load, bending moment, ultimate bearing capacity and the nominal bending strength, but the ductility dies down.
- 2) With the improvement of effective prestress, beam cracking load and bending moment are significantly improved, but ultimate load and ultimate bending moment stay almost the same.

3. Node Design of Wireless Sensor for Steel Corrosion Monitoring in the Concrete

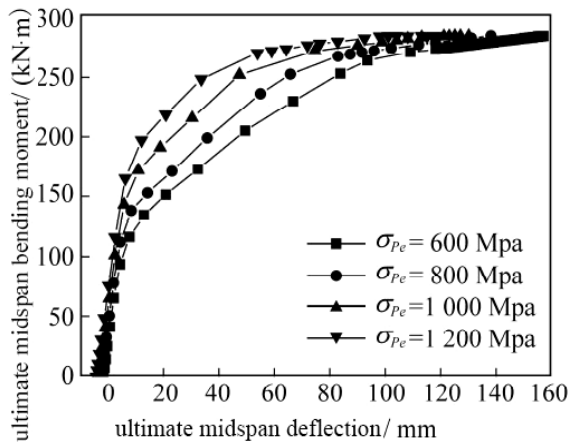
3.1. Hardware Design of Wireless Sensor Node

The node hardware structure consists of two parts: Embedded sensors and external circuits. Embedded sensors are LC oscillating circuits based

on effective content such as steel. An external circuit is divided into external detection circuit and wireless transceiver circuit. The main function of the external detection circuit is to provide excitation frequency sweep for LC oscillation circuit and collect the signal which reflects the condition of steel corrosion. Wireless transceiver circuit is responsible for maintaining communication between nodes and between aggregation nodes and nodes. The overall structure of the node is shown in the Fig. 3.



(a) The effect that the effective prestress on the load – deflection curve



(b) The effect that effective prestress effects on bending deflection curve

Fig. 2. The effect of effective prestress on load, bending moment – deflection curve.

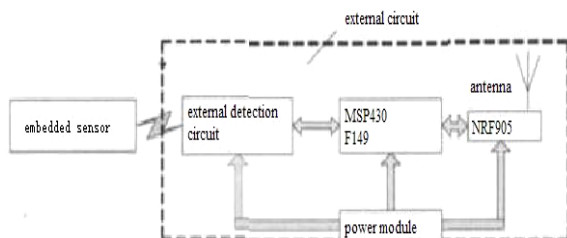


Fig. 3. The overall structure of the node.

3.1.1. Embedded Sensors

Resonant circuit is the basis of the embedded sensor. Inductive coupling resonance circuit is shown in figure 4. The resonant frequency is drawn by formula $f = \frac{1}{2\pi\sqrt{L_2C(1-k^2)}}$. Among which, L_2 and

C are respectively the inductive inductance and total capacitance. k is the coupling coefficient between inductance and inductive inductance.

As shown in Fig. 4, the right half is embedded sensor circuit, buried near the steel to be monitored in the concrete construction after sealed. The left part is the external detection circuit, fixed in the concrete structure surface, and used to measure the resonant frequency of the transducer. When the steel corrosion occurs in the concrete, steel wire of the embedded sensors in turn disconnects, its performance in the circuit is switch disconnection in turn. The resonant frequency of the external detection circuit changes correspondingly. So as to realize the wireless transmission of steel corrosion signal both inside and outside the concrete structure. Moreover, sensor within the concrete structure can realize long-term monitoring without power supply. The sensor possesses the advantages of wireless, passive and cheap [9].

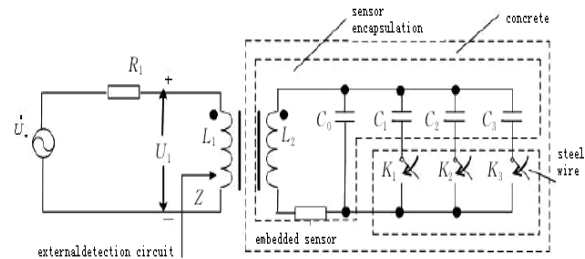


Fig. 4. Basic circuit diagram of steel corrosion monitoring.

3.1.2. External Circuit

External circuit is mainly divided into external detection circuit and wireless transceiver circuit. Collect resonant frequency change information and send it out by means of wireless communication. External detection circuit is mainly composed of MCU single chip, DDS ac frequency sweep excitation source and peak detection circuit. Wireless transceiver circuit mainly consists of MCU and wireless data transceiver chip NRF905. Their power supply all come from unified power supply module.

3.2. Software Design of Wireless Sensor Node for Steel Corrosion Monitoring

Wireless sensor node software design are mainly used for measuring L_1 , reading the voltage amplitude frequency characteristics on both ends of

the inductance. Calculate the resonant frequency of the circuit and realize wireless radio communication between nodes. The software adopts modular design structure, each functional module making independent writing and debugging and finally connects each module into a system. So it's very good for the optimization design, debugging and maintenance of program code. Due to the wireless sensor node in the monitoring area is sensitive to power consumption, Software design of the system sensor nodes makes it do job rotation between the working status and dormant state (low power mode). And do maximum working in a dormant state. The main program flow chart of nodes is shown in Fig. 5.

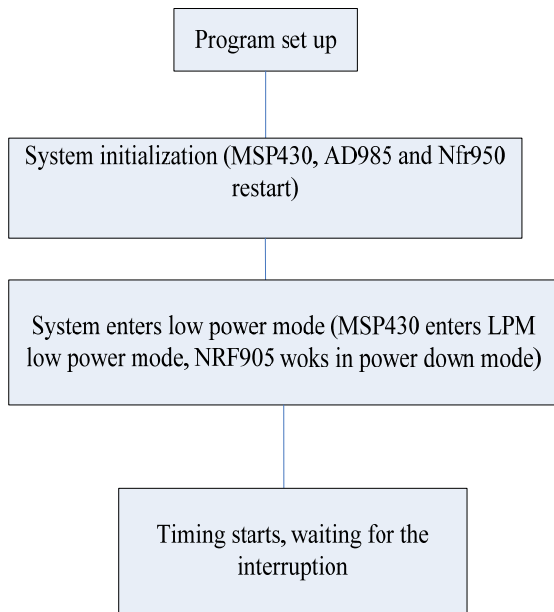


Fig. 5. Main program flow chart of nodes.

3.3. Experimental Results and Analysis

Based on the circuit of Fig. 4, conduct simulation experiment based on steel corrosion of embedded sensors using an external circuit, of which, $R_1=50\ \Omega$, $R_1=0.5\ \Omega$, $C_0=1\ \text{pF}$, $C_1=1\ \text{pF}$, $C_2=20\ \text{pF}$, $C_3=100\text{pF}$. A magnet ring with its outer ring diameter of 5.8 cm and inner ring diameter of 4 cm is selected as the skeleton of L_1 . Winding 10 circle of enameled wire with radius of 0.5 mm along its diameter. The inductance is 19.3 mu H. Another magnet ring with its outer ring diameter of 5 cm and inner ring diameter of 3 cm is selected as the skeleton of L_2 . Winding 27 circle of enameled wire with radius of 0.3 mm along its diameter. The inductance is 107.6 mu H. When the distance of identity, i.e. the circular interval between L_1 and L_2 is 5 cm, the voltage amplitude frequency curve is shown in Fig. 6.

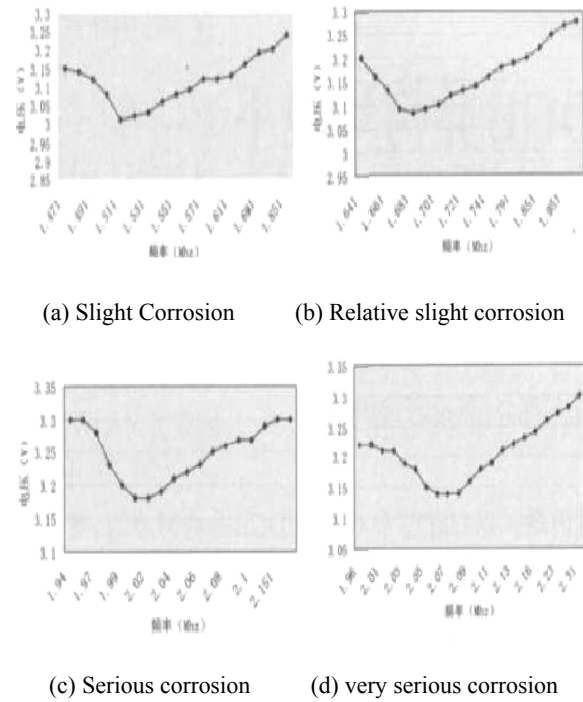


Fig. 6. The amplitude-frequency curves under different corrosion condition.

By the figure, it can be concluded that the method can reflect the degree of different steel corrosion in concrete. This paper also designs the external circuit which applies external detection circuit based on MSP430 and AD9850 and wireless transceiver circuit based on NRF905. With characteristics of low power consumption, long transmission distance, stable data transmission, etc. Through experimental tests, the external circuit cost is low and it can automatically collect steel corrosion information instead of using various kinds of expensive equipments and provides a data basis for health monitoring of construction.

4. Conclusion

Through the finite element nonlinear analysis of reinforced concrete beam, the result find that: the Solid65 is the unit provided by the ANSYS for analyzing reinforced concrete structures, it can reflect the cracking and crushing of concrete to a certain extent, and it can truly represent the characteristics of reinforced concrete structures' typical damage; Using ANSYS to do numerical simulation, before the concrete cracking ,it converges easily, after cracking it is very difficult to converge. Then it can adjust the grid density and sub-steps, and change the convergence criteria to speed up the convergence. Improper handling of constraint of bearing place and load method and parameter selection will lead to larger calculation error.

Through nonlinear numerical analysis of prestressed concrete beam by ANSYS method, the result finds that improving the reinforcement ratio of

prestressed reinforcement can significantly increase the capacity of the beam's cracking load and bending moment, ultimate bearing capacity and nominal bending strength, the ductility of the beam gradually reduces. With the improvement of effective prestress, cracking load and cracking bending moment of beam increase significantly, but the ultimate load and the ultimate bending moment have almost no change.

This article also designed the embedded sensor based on LC resonance circuit. Through on and off situation of steel wires of different thickness can reflect different degree of corrosion of reinforcement in concrete structure. The circuit has the characteristics of wireless, passive, cheap and easy for engineering implementation, etc. And compared with traditional corrosion monitoring, the method can also reflect the degree of different steel corrosion in concrete.

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