

Experimental Study on Smart Anchor Head

Young-Jun You, Ki-Tae Park, and Kyu-Wan Lee

Abstract—Since prestressed concrete members rely on the tensile strength of the prestressing strands to resist loads, loss of even few them could result catastrophic. Therefore, it is important to measure present residual prestress force. Although there are some techniques for obtaining present prestress force, some problems still remain. One method is to install load cell in front of anchor head but this may increase cost. Load cell is a transducer using the elastic material property. Anchor head is also an elastic material and this might result in monitoring monitor present prestress force. Features of fiber optic sensor such as small size, great sensitivity, high durability can assign sensing function to anchor head. This paper presents the concept of smart anchor head which acts as load cell and experiment for the applicability of it. Test results showed the smart anchor head worked good and strong linear relationship between load and response.

Keywords—SHM, prestress force, anchor head, fiber optic sensor

I. INTRODUCTION

THE prestressing of concrete are inter-related features of the modern building industry (see Fig. 1). Through the application of imaginative design and quality control, they have had an increasing impact on architectural and construction procedures since the 1930's. Prestressed concrete (PSC) can provide significant cost advantages over structural steel sections or ordinary reinforced concrete. Because PSC has steel reinforcements, PSC is subject to the same adverse effects of reinforcement corrosion as reinforced concrete members are. Documented cases of prestressed tension member failure as a result of corrosion make this a most pressing problem. Since PSC members rely on the tensile strength of the prestressing steels to resist loads, loss of even few wires or strands per member could result catastrophic [1]. There were some collapses of PSC structure in Europe. The Bickton Meadows bridge and the Ynys-y-Gwas bridge (Fig. 2), both in UK; and a bridge over the River Schelde in Belgium collapsed without any warning. Because that the application of PSC technology in civil structures is relatively recent, the existing PSC members are still relatively healthy. The corrosion and the concrete deterioration problems in PSC members have become clearly evident only in the early 1980's and the interest on structural health monitoring for PSC girder bridges has been emerged as a recent issue.

It is important to investigate present residual prestress force for evaluating the state of PSC member. A few techniques used to determine condition states of prestressing steel wires

include: (1) Utilization of x-ray methodologies, (2) Application of remnant magnetism methodologies, and (3) a sound print acoustic monitoring system [2]. The surest method is to attach strain gages to the strand or to install a load cell in front of anchor. However, they are not practical due to difficult installing, cost, maintenance, and so on.



Fig. 1 Marina bay sands hotel (Singapore)



Fig. 2 Sudden collapse of Ynys-Y-Gwas bridge (UK, 1985)

Fiber optic sensors have been emerging as a promising sensor in civil engineering field due to various advantages such as small size, high durability, greater sensitivity, electrical passiveness, freedom from electromagnetic interference, wide dynamic range and both point and distributed configuration over the conventional electrical resistance strain gages [3].

These special features of fiber optic sensor can successfully assign sensing function to anchor head. This paper presents the concept of smart anchor head which acts a role of load cell for PSC members and experiment programs for investigating the applicability of it. Test results showed the smart anchor head worked good and strong linear relationship between load and response.

II. SMART ANCHOR HEAD

A. Load cell

A load cell shown Fig. 3 is a transducer for measuring force with converting physical quantity such as force into electric signal. It consists of an elastic body which deforms linearly in

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proportion to the increase of external load and generally four strain gages which convert deformation into electric signal.

When a force is applied to a load cell so that the elastic body deforms, strain gages attached to the body measure the quantity of deformation. The deformation measured by strain gage is the quantity of electrical resistance and it is converted into voltage by a "Wheatstone bridge" and the value is expressed into a force.

Therefore, the elastic body which is the one of the most important components and decides the performance of a load cell should deform uniformly for the applied load and the strain should change linearly in proportion to the load. The linear relationship between load and strain is the most important requisite to dominate the reliability and accuracy of a load cell.



Fig. 3 Load cell

B. Fiber optic sensor

Over the past decades many product revolutions have taken place due to the growth of the optoelectronics and fiber optic communications industries. An offshoot of fiber optic technology was to use optical fibers in sensing systems, which led to the sensing devices and components [4].

Fiber optic sensors can be used to monitor various different parameters such as strain, temperature, vibration, deformation and acceleration. Optical sensors have other advantages over conventional sensors including: greater sensitivity, electrical passiveness, freedom from electromagnetic interference, wide dynamic range and both point and distributed configuration.

There are many types of fiber optic sensors such as Fabry-Perot, Polarization, Bragg Grating, Mach-Zender, and so on. Among of these optic sensors, Fiber Bragg Grating (FBG) has some attractive special characteristics. It has ability, so called multiplexing, to merging data from several channels into 1 channel and acts as an "absolute" strain gauge so that the FBG provides an absolute measure of strain, which can be connected to optoelectronics at any time for real time measurements. This kind of absolute measurement is not available with standard foil type strain gauges [5].

C. Anchor head load cell

Anchor head is a device which settles prestressed strands and transfers prestressing force to a structural member. Generally it is made of SMC 45C steel in Korea. At the stage of prestressing concrete members, a load cell is installed in front of anchor

head to manage introduced force to strands when it needs to be checked. This load cell has to remain permanently even though its price is not so cheap and be always connected with data acquisition device due to signal type.

That anchor head is made of steel may mean it could have linear elastic material property same with that of load cell body. If anchor head deforms uniformly by compressive force, prestressing force can be managed by attaching conventional strain gages onto the surface of anchor head. But it does not deform uniformly because it has many holes, the arrangement of holes is asymmetry, and force is transferred indirectly by wedge. This was checked in following section about FEM analysis. Consequently it is unsure that strains measured from gages attached to the later surface of anchor head indicates real or exact deformation state. One solution for this problem is to measure strain of the closest position possible to the hole into which strand settles. But the space between holes is narrow and gages should be installed inside the anchor head to measure the strain in the direction of applied force.

Developed anchor head load cell is designed taking advantage of elastic material property to act a role as elastic body which is a component of general load cell. Small size of fiber optic sensor makes this possible. Due to this special feature, fiber optic sensor can be embedded inside a structure without influencing the mechanical properties of the host material [6]. Anchor head load cell is manufactured by inserting FBG fiber optic sensor into bored small hole between strands settlement holes and grouting (see Fig. 4).



Fig. 4 Anchor head load cell

III. FEASIBILITY OF SMART ANCHOR HEAD

A. Preliminary FEM analysis

In a narrow sense of the word, a structure having sensors in itself is called as a smart structure. So anchor head which can act a role of load cell by sensors could be smart. In this paper, smart anchor head means anchor head load cell that consists of anchor head and fiber optic sensors and performs two roles of structural element and sensor.

Analysis by finite element method was performed to observe this behavior before investigating the feasibility of smart anchor head. ANSYS 13 was used for analysis. Anchor head has a diameter of 180 mm and 65 mm depth. There are twelve wedge holes in anchor head with 29 mm diameter on upper side (wedge insert face) and 17 mm on lower side (contact face

between structural member and anchor head). Analysis was performed for the case that one strand in a hole among three in center was tensioned. Fig. 5 shows an FEM model mesh and analysis result example about deformation to the direction of depth.

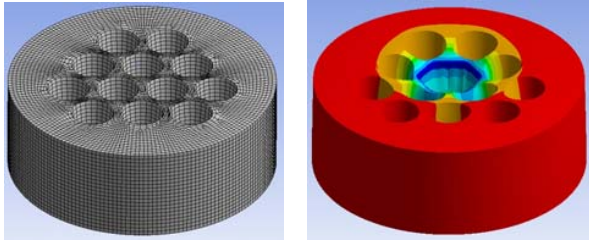


Fig. 5 FEM model mesh and analysis result (deformation)

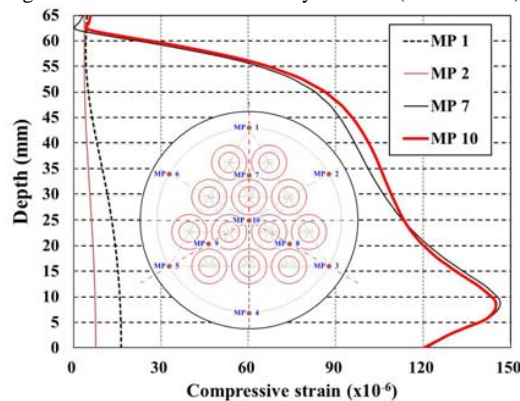


Fig. 6 Strain distribution along depth

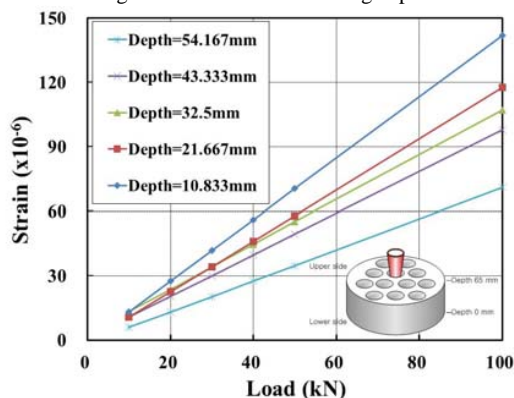


Fig. 7 Strain vs. increased load at same depth

Compressive strain distribution was plotted along the direction of depth in Fig. 6. As stated early, anchor head has many holes and they have a shape of cone. This leads non-linear compressive strain distribution along the depth of it. Besides it was checked from FEM analysis that the compressive strains were different according to measuring points even at same depth. This results from the different area which resists compressive force. At point of MP10 in Fig. 6, the area which external force acts on is smaller and the change rate of area along the depth is also higher than MP 2.

Although compressive strain distribution along the depth is non-linear, there is a noticeable feature due to the elastic

material property. If one surface from upper or lower side of anchor head is decided first to measure strain, in other words, if a depth to install sensor is decided, strain of any point on that surface increases linearly according to the increase of load as shown in Fig. 7. This is an important condition to make anchor head into load cell.

B. Laboratory test

The final aim of smart anchor head is to provide engineers with a way to control prestressing forces introduced into strands individually. For achieving that, the feasibility of making anchor head load cell is investigated first with one strand at this beginning stage.

Tensile test of a strand was performed to observe the behavior of the designed anchor head load cell. The objective of this test is to confirm the linear relationship of response of anchor head load cell which is the most important property as a sensor.

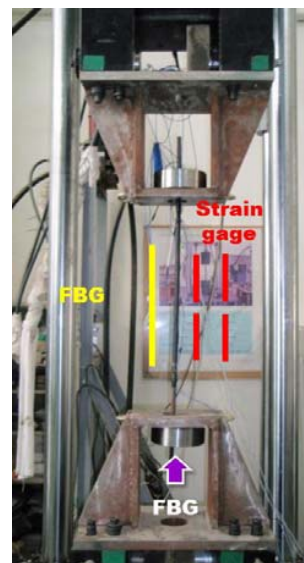


Fig. 8 Tension test for PS strand and anchor head

Before test, a few of sensors were installed to obtain responses of behavior of strand and anchor head. Four conventional strain gages and one FBG sensor were attached to the strand to measure strain and compare their responses each other. One FBG sensor was inserted in a bored hole placed at the center of anchor head (MP 10 point in Fig. 6).

A strand settled by with a pair of anchor head was tensioned using UTM (Universal Testing Machine) with a capacity of 1,000 kN. Load was applied up to 50 kN by five stages with 10 kN and this process was repeated four times. Fig. 8 shows set-up of experiment. Test results were shown in Fig. 9-Fig. 11. It was observed that responses of electrical resistance strain gages attached directly to the strand showed linear behavior as seen in Fig. 9. Linearity can be said by R-squared value (coefficient of determination). With linear regression, the results showed strong linearity due to the high R-squared value over 99%. Maximum and minimum R-squared values of each gage were 99.81% for Strain gage 4 and 99.96% for Strain gage

3. For FBG sensor attached to the strand showed higher R-squared value of 99.99%. This means that test was performed successfully and FBG sensor worked well.

Fig. 11 shows the compressive behavior of anchor head according to the increasing load. The response of FBG sensor embedded in anchor head. This sensor also showed strong linearity with high R-squared value of 99.93%. This means that the anchor head deformed elastically and FBG could measure well the deformation of anchor head, consequently anchor head with embedded FBG sensor behaved as a load cell successfully.

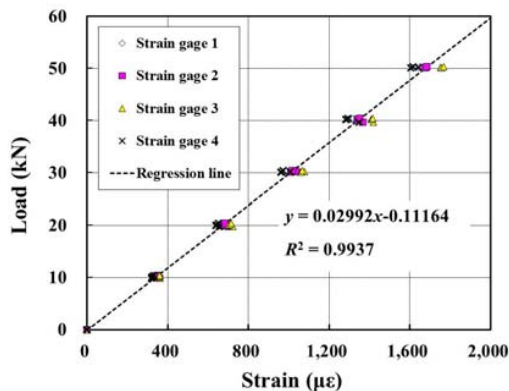


Fig. 9 Load vs. responses of strain gages on strand

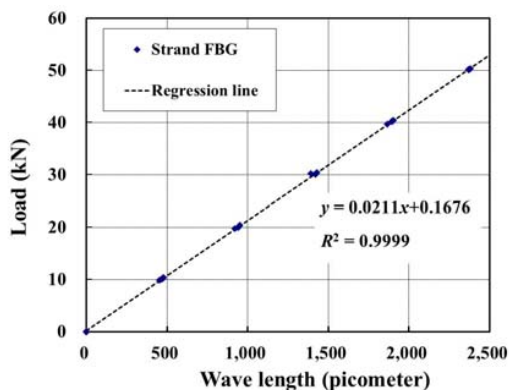


Fig. 10 Load vs. response of FBG on strand

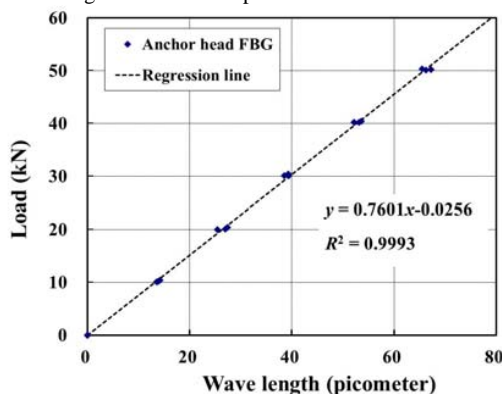


Fig. 11 Load vs. response of FBG in anchor head (lab.)

C. Field test

A test for observing the in-situ applicability of anchor head load cell was performed. The considered structure was a PSC I type girder with a length of 60 m (see Fig. 12). To investigate the prestressing force, a conventional load cell was installed in front of anchor head. FBG sensors were attached to a strand and inserted in anchor head.

It is true that conventional load cell is a good device to measure load but it could indicate wrong value according to installed condition. To make it to work well in-situ condition, it is very important to arrange a load cell right way such as close contact between faces of structure and load cell, good agreement of hole centers of anchoring plate and load cell. When load is applied on load cell, it could show inexact value due to the eccentricity otherwise. However these works scarcely are done in field.



Fig. 12 Field test of anchor head load cell

Fig. 13 shows the relationship between measured force by load cell and the response of FBG sensor embedded in anchor head. R-squared showed high value of 99.66% but it was observed that the relationship showed a little non-linearity graphically in Fig. 13. Another statistical value for goodness-of-fit test to check whether measured values are proper is "standard error of estimate". This value expresses the scattered variation of measured values from regression line. The bigger standard error of estimate is, the more scattered measured values are. If all measured values are on the regression line, standard error of estimate is zero. Even though this result showed high R-squared value but standard error of estimate was 1.091 while 0.035 for that of FBG sensor attached on strand. If regression analysis is performed with a second order equation, R-squared changed to 99.97% but this is not proper behavior as a sensor because the inclination of regression line generally is used as a coefficient to calibrate sensor. This non-linear response behavior was observed too for FBG of strand.

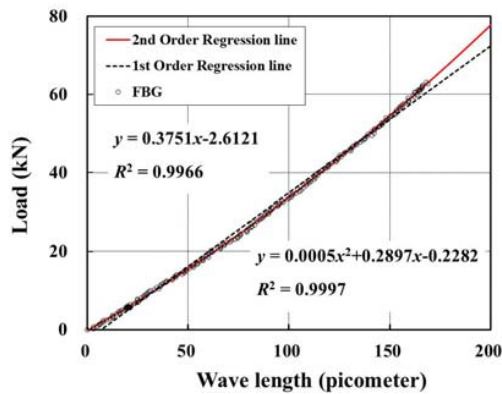


Fig. 13 Load vs. response of FBG in anchor head (field)

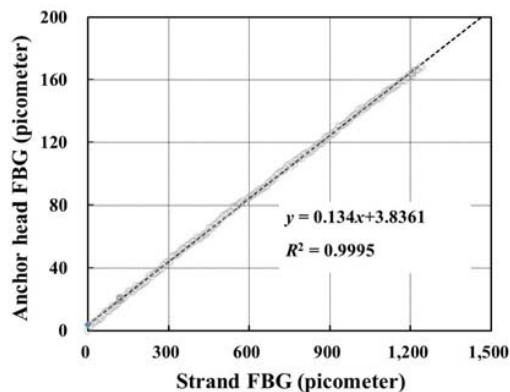


Fig. 14 Relationship between strand and anchor head

However, the relationship between FBGs of strand and anchor head showed strong linearity as shown in Fig. 14. The fact that non-linear behavior between load cell and FBGs and linearity between FBGs were observed implies that there could be installing error of load cell as early mentioned. From these graphs, it might be considered there was a problem for load cell but it is not easy to find out the reason due to various in-situ conditions.

The strong linearity between the responses of strand and anchor head in Fig. 14 proves that present prestress force of a strand is able to be estimated by measuring the strain of anchor head. With further investigation, two equations could be obtained. One is y (load) = $a_1 x$ (response of strand) and another is y (response of anchor head) = $a_2 x$ (response of strand). With these equations, the strain of strand and present prestress force can be estimated from the response of anchor head.

IV. CONCLUSIONS

In this paper, a simple method to manage prestressing force for PSC members was introduced. The basic concept is to use the elastic material property of anchor head as that of conventional load cell. Some special features of fiber optic sensor make this possible.

It is an easy way to attach conventional electrical resistant strain gages on the later surfaces for measuring compressive

strain of anchor head. However, it was investigated from FEM analysis that the compressive strain distribution showed non-linear behavior along the depth and measured values from strain gages attached to the surface could be impractical or inexact because strains of each interesting points were different even at same depth. At decided depth, any points of anchor head showed linear behavior according to increased load.

From laboratory and field tests, the performance of anchor head load cell was verified. For linearity which is a key property of sensor, anchor head load cell showed strong behavior for load and strain of strand while non-linear behavior was observed for responses between conventional load cell and FBGs. It is well known that conventional load cell is a good device to measure load but need of careful attention for installing and high price are the obstacle to apply this to monitor present prestress force.

It was studied that anchor head may be smart with fiber optic sensor and with low cost. With further study, it is expected that prestressing forces introduced in every strain settled in anchor head could be managed.

It provides some advantages as followings; 1) it is very simple and does not require extra load cell for measuring prestressing force. 2) it could be possible to manage strand with easy installing work and low cost. 3) manager can check present prestress force with data acquisition system when needed due to the attractive property of FBG optic sensor which indicates absolute readings.

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