Strain Response of Tunnel Anchor Using Rayleigh Scattering-based Optical Fiber Sensing Technology in the Field Test

Wang Shuai, Zhang Yihu, and Hu Wei

Key Laboratory of Geotechnical Mechanics and Engineering of Ministry of Water Resources, Yangtze River Scientific Research Institute, Wuhan, China, 430010

Abstract. Tunnel anchor is a relatively new type of anchor for suspension bridges. Loading tests on a scale model in site are generally considered to be the most direct way to evaluate the bearing capacity of the tunnel anchor system. The response of the anchor body has received minimal attention and involves only a few or no measuring points, because the anchor plug does not undergo elastoplastic failure in a model test. This article intends to explore the relationship between the strain response of the anchor and the state of the surrounding rock. Optical fiber strain sensing technology based on adjustable wavelength optical time domain reflectometry (i.e., TW–COTDR) was applied to the scale model test of Baotaping Bridge tunnel anchor. The strain distribution and evolution of the entire anchor body were determined by optical measurements during overload. In the elastic and plastic stages of the anchor system, the strain around the anchor body linearly decreased from back to front, except for the top arch and the bottom plate at the end. The anchor strain–load curve was nonlinear, similar to the displacement–load curve, but unrelated to concrete damage, which signaled that plasticity began to appear in the anchor system. Therefore, the strain response of the anchor body can be used as an alternative to determine bearing capacity of the anchor system, especially when the displacement is too small to observe.

1. Introduction
The tunnel anchor is one of the anchorage structures of suspension bridges built in the mountains. Relying on its special inverted wedge shape, the anchor body can maximize the strength of the surrounding rock to bear tens of thousands of tons of load [1]. Given the discontinuity, heterogeneity, and anisotropy of the surrounding rock, accurate evaluations of the bearing capacity of the tunnel anchor system are difficult [2]. Although the tunnel anchor was first proposed in foreign countries, there are few public reports on this aspect abroad [3]. The scaled model test on site with rock mass conditions similar to engineering was first proposed by Chinese scholars [4]. It was considered to be the most direct and effective method compared with numerical simulation, limit equilibrium analysis, and other techniques. Among many projects in China such as Egongyan Yangtze River Bridge [5], Siduhe Bridge [6,7], Guanshan Bridge [8], Puli Bridge [9], Jijiang Yangtze River Bridge [10,11], and Taihong Yangtze River Bridge [12], on-site scale tests of tunnel anchors were carried out. The deformation inside and outside the model was the main test item in the experiment. The nonlinear characteristics on the load–deformation curve are usually used as basis for judging the bearing capacity of the tunnel anchor system. However, measurements of the micron-sized deformation during initial loading are extremely difficult. Considering that the accuracy of the surficial deformation test is affected by temperature, no regular surficial deformation data were obtained in the model test of the tunnel anchor of the Egongyan Yangtze River Bridge [5]. For this reason, the model testers [10,11] of the Jijiang Yangtze River Bridge project built a constant temperature chamber, and available deformation data were obtained by a dial indicator, which increased linearly under the sevenfold equivalent design load. They
also found that the displacement meter is not sensitive to the initial loading due to the insufficient stiffness of the measuring rod. Its data were less than previously reported and increased nonlinearly under small loads. Besides, the closure of the joints during initial loading may also make the displacement–load curve nonlinear when the model is established on rock slope surface with relatively well-developed open joints [7]. In most trials, the model did not break even under the maximum load [6,8,9]. Whether the nonlinearity on the incomplete curve is caused by the initial compaction of the joints or caused by plastic failure of the surrounding rock is difficult to assess. Evidently, there are certain shortcomings in the analysis of the bearing capacity of the anchor system only from the displacement. Additional responses of the interaction between anchor and rock should be considered.

During the overloading process, the tunnel anchor interacts with surrounding rock in a highly complex manner. When pushed, the anchor back can transfer the load into the nearby surrounding rock, resulting in local damage to the surrounding rock. The damaged rock cannot bear the load, which forces the anchor to undertake such load. As the load advances from the anchor back, the rock around the anchor is gradually damaged. Whether the anchor stress will change in a nonlinear way when the surrounding rock is under the nonlinear elastic–plastic state, and whether the two behaviors are related to each other remain unclear. To answer these problems, the adjustable wavelength optical time domain reflectometry technology [13] (TW–COTDR) was used to measure the strain of anchor. The stress distribution curve and strain–load curve of anchor was used to analyze the response of tunnel anchor under the overloading process. The displacement curve was also collected for comparison. After the correlation between the response of surrounding rock and anchor body was confirmed, a novel index was introduced to identify the bearing capacity of the tunnel anchor system.

2. Principle of TW–COTDR-based distributed optical fiber sensing

When light travels across the fiber, it will continually produce backward Rayleigh scattering. The Rayleigh scattering power is directly proportional to the light resource. In addition, the light power will gradually attenuate during transmission due to the light loss. Therefore, the Rayleigh scattering signals contain different loss information, which can verify where the scattering occurs. When the scattered light returns to the original input position, some parameters such as temperature and bending moment can be measured by Rayleigh scattering power [14]. The power of Rayleigh scattering is larger and more easily measured than that of Raman scattering and Brillouin scattering. At present, optical time domain reflectometry (OTDR), coherent optical time domain reflectometry (COTDR), and optical frequency domain reflectometry (OFDR) have been developed based on Rayleigh scattering. In 2015, the Yangtze River Scientific Research Institute introduced the distributed optical fiber demodulation instrument NBX7020 from Neubrex Company in Japan. The NBX7020 involves the adjustable wavelength optical time domain reflectometry technology (TW–COTDR) and pulse-pre-pump Brillouin optical time domain analysis technology (PPP–BOTDA). When tested by TW–COTDR, the highest spatial resolution ever available is 5 cm and the accuracy of strain measurement is 0.5με.

Figure 1 demonstrates the principle of Rayleigh scattering theory of the optical coherence test. The signal light and reference light are coupled into the photodetector through a coupler. Rayleigh scattering optical signals, which are produced during the mixing of signal light and reference light, are transferred into an electric signal and amplified by an amplifier. The frequency difference between the initial and variation measurements is read from the electrical signal. The strain is calculated through the expression below:

\[ \varepsilon = \text{(frequency difference)}/R_{11} + \text{Reference strain} \]  

where coefficient \( R_{11} \) is the ratio of frequency difference between the initial and variation measurement and strain change. The unit is GHz/με.
3. Tunnel anchor scale model of Baotaping Bridge

Baotaping Bridge is in the mouth of Meixi River, about 5 km away from New Fengjie County. As a single-span suspension bridge, it is 1,270 m long, and has a main span of 800 m. The anchor on the right bank is gravity-type, with spread foundation; that on the left bank is tunnel-type. The design bearing capacity for a single main cable is $2 \times 10^5$ kN. The underlying bedrock is gray to dark gray marly limestone and marl with shale of Triassic Badong Formation. The bedrock has a saturated uniaxial compressive strength of 10.92 MPa, and is classified as soft rock. At present, there is little practical experience about tunnel anchor in soft rock. The on-site tunnel anchor scale test was carried out to test the design.

The on-site model was scaled by 1:10, as shown in Figure 2. The center of the left model was 2.45 m away from that of the right model. The jack installed at the anchor back provided load.

Two distributed optical fibers were set in each anchor, as shown in Figure 3. The other monitoring sensors included the displacement gauge at the anchor–rock interface, extensometer, and strain gauge in the surrounding rock.

According to the on-site survey, the model location was selected at the upstream of engineering where bedrock was exposed. Before excavation, some boreholes were drilled near the site, and sonic wave tests were conducted. The test results show that the site was basically identical to the actual site in geological conditions. After the model caves were excavated, the monitoring system was installed, and the anchors were grouted. The finished model photo is presented in Figure 4.

![Figure 2. Schematic size of the 1:10 scale model anchor.](image)

![Figure 3. Arrangement of distributed optical fibers.](image)
4. Test results and analysis
The cyclic loading–unloading test, over-tension test, and rheological test were conducted in a certain order. The over-tension test was arranged in the end. The load began with 1P (1P is the equivalent load of the main cable design load in the scale model) and then increased by each step of 1P until the maximum jack output was reached; it finally decreased gradually. The strain of optical fiber was measured during the over-tension stage, with a spatial resolution of 5 cm.

4.1 Strain distribution of anchor along the axial direction
The distribution of strain on the two side walls of the right anchor is shown in Figure 5, and that on the top and bottom of the anchor is illustrated in Figure 6. The ±0.7 to ±4.7 section represents the full length of the anchor, and the −0.7 to 0.7 section denotes the anchor back where the load is applied.

As shown in Figure 5, the distribution of strain on the side wall presents the following law:
(1) The concrete strain decreases almost linearly from back to front.
(2) The strain difference between the left side wall and the right one is relatively small if the load is less than 7P; as the load increases, the strain in the back of the right side wall is slightly greater than that in the back of the left side wall.

Under large load condition, the strain in the back of the side wall is not symmetric, which is related to the surrounding rock properties. When the load is small, the surrounding rock around the side wall is under elastic condition and various parts of surrounding rock have similar load bearing capacity. When the load is large, the surrounding rock with poor strength will become damage at first and unable to bear all the increased load. Part of the load will be transferred to the side of the anchor body in contact with the damaged part.
The distribution of strain on the anchor top and bottom, from Figure 6, has the following law:

1. Within the ±0.7 to ±1.1 m section, the load is locally eccentric due to unsymmetrical cave section. The strain concentrates in the anchor top (up to 150με) and then decreases sharply to 100με; the strain in the anchor bottom is relatively small and increases from 50με to 75με.

2. Except for the strain concentration area, the strain in the anchor top and bottom decreases in an approximately linear way and presents a low difference with a small effect of load eccentricity.

To analyze the response of the anchor under different loads, the strain of the left side wall of the anchor along the central axis was fitted and normalized. The curves are shown in Figure 7, where $\varepsilon_0$ is the axial strain on the loading surface, L is the axial length of the anchor, and x is the axial distance from the anchor section to the anchor back, and $\varepsilon(x)$ is the strain in the section x away from the anchor back. Figure 7 shows that the strain $\varepsilon(x)$ has a good linear relationship with distance x, and the function can be expressed as follows:

$$\frac{\varepsilon(x)}{\varepsilon_0} = \frac{L - x}{L}$$

(2)

Figure 7. Fitted strain curve of the left wall of the right anchor.

In this model, the anchor section could approximately be regarded as a combination of semi-circle and rectangle, and the section area was roughly estimated by radius R of semi-circle. The normalized section area is written as

$$A(x)/A_0 = \frac{(R - x \cdot \tan \theta)^2}{R^2}$$

(3)

where R is the radius of semi-circle in the anchor back, $\theta$ is the diffusion angle of the anchor (shown in Fig. 2), $A_0$ is the section area of the anchor back, and $R - x \cdot \tan \theta$ denotes the radius of semi-circle x away from the anchor back.

Axial force can be determined based on the strain and elastic modulus of the anchor. Assuming that the average strain of the anchor also behaves linearly as that in Equation (2), the normalized axial force was obtained by the average stress times section area, which was written as follows:

$$N(x)/P = \frac{(L - x)}{L} \cdot \frac{(R - x \cdot \tan \theta)^2}{R^2}$$

(4)
where \( P \) is the load exerted on the anchor back, and \( N(x) \) is the axial force in the section \( x \) away from the anchor back. Equation (4) shows that the axial force is \( x \) cubed.

As a result of the diffusion angle, normal force and tangential force exist on the anchor–rock interface, which cannot be directly obtained based on axial force. Further tests on the contact surface are needed to resolve the axial force in two directions.

4.2 Strain–load curve of anchor

The strain–load curve was drawn using the measured strain values at the rear and middle of both side walls of the anchor body, as shown in Figure 8. The strain–load curve could be divided into two stages. In the initial loading stage, the strain of the side wall increased linearly with load, and the strain rate increased greatly after 7\( P \), denoting that the anchor strain varied nonlinearly as load increased. The displacement–load curve of the ground surface on the side of the anchor is shown in Figure 9. The load of 7\( P \) was the turn point from linear to nonlinear, demonstrating similarity to the strain–load curves. Therefore, the two kinds of curves exhibited good similarity in terms of nonlinearity.

The maximum strain at the turn point of strain–load curves was 61\( \mu \)ε, and the corresponding stress was 12 MPa based on the elastic modulus of 20 GPa. This value was less than the compression strength of C30 concrete. Therefore, the nonlinear behavior of anchor was only related to the elastic–plastic state of surrounding rock rather than the anchor damage, indicating that the surrounding rock was under elastic–plastic state.

Given that the surrounding rock in this case was soft, the nanometer-level displacement could be measured under initial conditions. However, the displacement of hard rock is difficult to measure because it approaches the sensor resolution and is affected by temperature and rod. The nonlinear turn point of the displacement–load curve for hard rock may deviate from the actual situation. The variation in anchor strain with load is far greater than sensor resolution, so the strain is a reliable index to describe the nonlinear behavior of the anchor system.

![Figure 8. Strain–load curves of various points on side wall.](image-url)
Figure 9. Rock mass deformation near anchor.

In summary, the scale test of tunnel anchor in soft rock confirmed that the strain response of the anchor body could be used to evaluate the elastoplastic state of the surrounding rock and bearing capacity of the anchor system. Nevertheless, its applicability in different types of rock mass conditions needs to be further confirmed, because rock mass conditions such as burial depth, rock mass structure, and lithology can affect the failure mode of the anchorage system[15].

5. Conclusions
The TW–COTDR-based optical fiber strain sensing technology was used to measure the anchor strain in the tunnel anchor scale test. The strain response of anchor = under overload was analyzed as follows:

(a) The strain of the anchor side wall decreases in an approximately linear way from back to front, generally with symmetric distribution under low load condition. When the load is greater than the linear critical load, the strain of side wall with poor surrounding rock will increase.

(b) The strain at the top of the anchor back increases and that at the bottom decreases due to the irregular model shape and local load eccentricity. Except for the strain concentration area, the strain in the anchor top and bottom decreases in an approximately linear way and presents a lower difference than the concentrated area.

(c) The load at the turn point from linear to nonlinear of the anchor strain–load curve is similar to that of the displacement–load curve. The nonlinear behavior of anchor is only related to the elastic–plastic state of surrounding rock rather than the damage of the anchor. The strain response can be used to assess the elastic–plastic state and bearing capacity of the anchor system.

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