Longitudinal force measurement in continuous welded rail with bi-directional FBG strain sensors

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Abstract

In this work, a new method has been proposed to accurately determine longitudinal force measurement in continuous welded rail (CWR) with bi-directional fiber Bragg grating (B-FBGs) strain sensors (vertically and longitudinally installed according to the axis of rail). The response of B-FBGs has been theoretically analyzed by binding on CWR under different restrained conditions, where the coefficient of strain sensitivity of FBG is calibrated by its temperature sensitivity. Then the proposed sensor structure has been installed at two elaborately selected points on the subgrade on a Chinese high-speed railway in field. The experiment lasts for about 23 h. During the experiment, the rail temperature varied by about 7.8°C and the differentials of relative value of wavelength change of B-FBGs of two points were 1.7850 × 10⁻⁵ and 1.4969 × 10⁻⁵. The maximum difference between the experimental and theoretical results is 13.8 kN. The experimental results agree with the theoretical analysis very well. To guarantee the measurement accuracy of over 95%, the ratio of strain sensitivity coefficients of two FBG sensors of B-FBGs structure at one test point shall be within 0.78 ~ 1.22.

Keywords: continuous welded rail, fiber Bragg grating, longitudinal force, temperature and strain, cross-sensitivity, bi-direction

(Some figures may appear in colour only in the online journal)

1. Introduction

Since the late 1920s, when Germany began to lay long welded rail, the total length of continuous welded rail (CWR) has already exceeded 500 000 km. With the acceleration of global railway modernization, the total kilometrage of CWR keeps growing at a great speed. The strengthening of track structure reduces the probability of defects in CWR (such as rail breakage, track buckling and other problems on strength and stability). However, if CWR lays on the zones with large temperature difference, small radii or large span bridges, the longitudinal force will increase significantly because of the increased rail temperature change scope and intensified track-bridge interaction. Furthermore, the stress-free temperature of CWR changing unevenly and nonlinearly, further increases the longitudinal force after a long operation time. And then, the increased force may lead to rail buckling deformation, track buckling and rail breakage [1, 2]. Derailment accidents occur every year due to buckling or rail breakage, which causes great damage to life and property of passengers [3–5]. So monitoring the longitudinal force in CWR is essential.
for the scientific assessment, management and maintenance of CWR and for ensuring the riding safety of railway vehicles.

Current methods for measuring rail longitudinal force widely recognized can be clustered into energy method [6–11], stress method [12–14] and strain method by measuring principles. Among them, strain method is regarded as a main focus of research on rail longitudinal force monitoring for its simple equipment configuration and long-term monitoring capability. The most popular sensors fall into two categories, i.e. resistance strain gauge based on principle of metal resistance change and FBG sensor based on optical principle. Resistance strain gauge may cause zero drift and enlarge measuring error under the long-term effect of temperature, humidity and sunlight, so it is less frequently used in long-term monitoring. In contrast, FBG sensor is increasingly favored in railway application for its ability of anti-electromagnetic interference, high precision, long service life and other advantages [15–21]. Previous studies mainly focus on the application of FBG sensor in measuring the dynamic change of related physical quantities during the passage of a vehicle, but the application of FBG sensor in monitoring longitudinal force in CWR is less studied. Yan et al, Wei et al, Lee et al, Lee et al verified the feasibility of establishing axle counting system with FBG sensor through theoretical, indoor and field tests [22–24]. Tam et al, Yuen et al, Lai et al performed real-time monitoring on track and vehicle based on the relationship between rail deformation and rail load when a vehicle travels on certain section of the rail [25–27]. The two studies depend on the monitoring of instant strain, and differ from long-term monitoring greatly. Chung-Yue Wang and Weilai Li tested the longitudinal force of the rail within breathing area of CWR with FBG sensor based on 3D beam model and strain calibration method respectively [28, 29]. Xin DAI provided the installation and sealing design for FBG sensor for monitoring rail temperature force, relative displacement of multilayered structures and closure status of turnout, and had it tested on site [30]. The above analyses have realized long-time monitoring, but the test principle have not considered the effect of the difference between thermal expansion coefficients of FBG sensor and rail, and the restrained conditions of the rail on the output of the sensor. That is why test results and tested physical quantities have not been identified.

Therefore, the principle of measuring longitudinal force of CWR with FBG sensor was deduced in the paper by incorporating the impact of the difference between thermal expansion coefficients of FBG sensor and rail, and the restrained conditions of rail based on the principle of bi-directional strain method. And the principle was verified on site by choosing several test points in a Chinese high-speed railway line. The study provides theoretical and testing support for the upgrading and promotion of testing methods for longitudinal force of CWR with FBG sensor, and can guarantee the state monitoring effectively for the operation safety of high-speed railway.

2. Principle of bi-directional strain method

The longitudinal deformation of rail in the fixed area of CWR has been limited, so certain force may be produced at the rail temperature change of $\Delta t$ (positive for temperature rise, negative for temperature drop) against stress-free temperature. This is the so-called temperature force of CWR, which can be expressed by:

$$F_t = -EF\beta\Delta t,$$

where $F_t$, $E$, $F$ and $\beta$ denote temperature force, the Young’s modulus, cross-sectional area and thermal expansion coefficient of rail respectively. The Young’s modulus, cross-sectional area and thermal expansion coefficient of a CHN60 rail are taken as $2.1 \times 10^1$ Pa, $77.45 \times 10^{-4}$ m$^2$ and $1.18 \times 10^{-5}$/°C respectively. In equation (1), the negative sign indicates that the tensile force is positive and the compressive force is negative. Since the rail longitudinal deformation is limited, but the rail is free in vertical direction. A vertical strain may be produced in the rail due to the stress-strain relationship, expressed by $(\mu + 1)\beta\Delta t$, passion’s ratio of the rail, taken as 0.3.

For the CWR on bridge, the rail longitudinal force may consist of temperature force and additional force induced by track–bridge interaction. Given that the longitudinal strain induced by additional force is $\varepsilon_f$, the additional force will be $EF\varepsilon_f$, and the corresponding rail vertical strain will be $-\mu\varepsilon_f$. In the fixed area of CWR on bridge, the rail longitudinal strain $\varepsilon_x = \varepsilon_n$, vertical strain $\varepsilon_y = (\mu + 1)\beta\Delta t - \mu\varepsilon_f$ and the rail longitudinal force is the sum of temperature force and additional force

$$F_l = EF\varepsilon_f - EF\beta\Delta t = EF(\varepsilon_f - \beta\Delta t)$$

$$= EF(\varepsilon_x - \varepsilon_y)/(\mu + 1).$$

As can be seen from equation (2) that, the longitudinal force in CWR can be determined by measuring the strain in at least two directions. So equation (2) reflects the basic principle of measuring longitudinal force in CWR with bi-directional strain method.

Therefore, in testing the longitudinal force in CWR with FBG sensors, two sensors installed perpendicularly to each other will be used to measure the longitudinal and vertical strains of the rail. The layout of sensors is shown in figure 1, which is also applicable to field test.
3. Test principle of FBG sensor method for longitudinal force in CWR

The essence of the principle of FBG sensor is that the change of physical quantities (temperature, strain, etc.) will lead to change in central wavelength of sensors which can be measured by demodulator, and then deduce the change of physical quantities based on the definitely corresponds between the two.

3.1. $\Delta \lambda/\lambda$ of FBG sensor in free state

When an FBG sensor is in free state, given the temperature change of $\Delta T$, axial strain change of $\Delta \varepsilon$ induced by external force, the relative value of change in central wavelength of the sensor will be:

$$\Delta \lambda/\lambda = K_c \Delta \varepsilon + K_T \Delta T,$$

where $\lambda$ represents the central wavelength of FBG sensor, $\Delta \lambda$ denotes the change in central wavelength, $K_c$ and $K_T$ refer to strain sensitivity coefficient and temperature sensitivity coefficient respectively. The influence of FBG thermo-optic coefficient $\zeta$ (refractive index changes with temperature) and thermal expansion coefficient of fiber (thermal expansion coefficient $= \alpha$) on grating period is taken into account for temperature sensitivity coefficient, $K_T = \zeta + \alpha$ [31].

When the sensor is attached to an object in free state, the temperature of test specimen changes slowly ($\Delta T$), and the thermal expansion coefficient of the test specimen is $\alpha_c$. Since the temperature of test specimen changes slowly, it may be deemed as that the temperatures of sensor and test specimen are consistent all the time. In this case, the relative change in central wavelength of the sensor will be:

$$\Delta \lambda/\lambda = K_c (\alpha_c - \alpha) \Delta T + (\zeta + \alpha) \Delta T.$$  

(4)

The physical meaning of equation (4) is that, when the thermal expansion coefficients of the test specimen and FBG sensor are different, the free expansion state of the sensor is somewhat limited, manifested by strain $(\alpha_c - \alpha) \Delta T$. The principle is further elaborated in figure 2.

Figure 2(a) depicts the initial state of FBG sensor attached to the test specimen. Figure 2(b) shows that specimen is subject to a slow temperature change of $\Delta T$, and the temperature of FBG sensor changes $\Delta T$ accordingly. Taking the free expansion of FBG sensor and test specimen into account, the corresponding strains will be $\alpha \Delta T$ and $\alpha_c \Delta T$ respectively. Despite the difference in thermal expansion coefficients between the two, the strains must be kept consistent, so the strain represented by the shaded area in figure 2(c) occurs. And consequently, the two strains become the same in the final state as shown in figure 2(d). Subtracting temperature-induced strain $\alpha \Delta T$ from total strain $\alpha_c \Delta T$, and substituting the result into equation (3) yields (4).

3.2. $\Delta \lambda/\lambda$ of FBG sensor under restrained condition

The principle in equation (4) is based on the assumption that the test specimen is in free state which may be deemed as the same as the rail in vertical direction. As the rail in CWR is restricted longitudinally, no longitudinal strain occurs as the rail temperature changes, and then the relative change of central wavelength of the sensor will be:

$$\Delta \lambda/\lambda = K_c (\alpha_c - \alpha) \Delta T + \zeta \Delta T,$$

where, $-\alpha \Delta T$ represents the strain of sensor which is restrained relatively by specimen in tested direction. The principle is as shown in figure 3.

Figure 3(a) depicts the initial state of FBG sensor attached to the test specimen. Figure 3(b) shows when the temperature of test specimen changes gradually $(\Delta T)$, as the test specimen is fully restrained in the test direction of FBG sensor, there is no strain in this direction. Supposing that the sensor could move freely, its strain would be $\alpha \Delta T$. Figure 3(c) indicates that the strain of the sensor at the attached position shall be consistent with that of the test specimen, so strain changes $-\alpha \Delta T$ as compared with that in figure 3(b). Figure 3(d) shows the final state, as the strain of the test specimen becomes zero, the sensor strain is restrained, represented by the effect on sensor strain under the action of external force, i.e. $K_c (\alpha_c - \alpha) \Delta T$ in equation (4). However, the temperature changes $\Delta T$ of FBG sensor may still influence the change of refractive index, resulting in the change in
central wavelength. So the factor $\Delta T$ is also included in equation (4) to a certain extent.

3.3. Test principle of rail longitudinal force

Based on above measure method and principle, when the test scheme as shown in figure 1 is adopted for FBG sensor, and track–bridge interaction is taken into account, the relative changes in wavelength of sensors installed in longitudinal and vertical directions can be expressed by:

**Longitudinal:** $\Delta \lambda_1 / \lambda_1 = K_e (\varepsilon_f - \alpha \Delta t) + \zeta \Delta t.$  \hspace{1cm} (6)

**Vertical:** $\Delta \lambda_2 / \lambda_2 = K_e \left[ -\mu \varepsilon_f + \mu \beta \Delta t + (\beta - \alpha) \Delta t \right] + (\zeta + \alpha) \Delta t.$ \hspace{1cm} (7)

Subtracting equation (7) from (6) yields:

$$\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2 = K_e (\varepsilon_f - \beta \Delta t) - \alpha \Delta t.$$

Combination of equations (2) and (8) gets the rail longitudinal force:

$$F_z = EF (\varepsilon_f - \beta \Delta t)$$
$$= EF \left( \frac{\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2 + \alpha \Delta t}{K_e (\mu + 1)} \right)$$
$$= \frac{EF (\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2)}{K_e (\mu + 1)}$$
$$+ EF \alpha \Delta t / [K_e (\mu + 1)].$$  \hspace{1cm} (9)

where, $F_z$ is precise measurement of rail longitudinal force without considering measuring error. As the thermal expansion coefficient of FBG sensor is about $10^{-7}/^\circ C$, $\alpha \Delta t$ in equation (9) may be ignored in actual calculation, and then the actual test principle can be altered to:

$$F_{e, z} = \frac{EF (\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2)}{K_e (\mu + 1)} = F_z - F_{e, x}.\hspace{1cm} (10)$$

As can be seen from equation (10), measuring error $F_{e, x}$ is inevitable when measuring rail longitudinal force with FBG, which is mainly caused by the restrained longitudinal deformation of rail.

Equation (10) also shows that, strain sensitivity coefficient $K_e$ of FBG sensor affects test result most. Equation (9) is the conclusion drawn on the assumption that the parameters of two sensors at one test point are consistent. FBG sensor functions based on the theory of light propagation, so several sensors connected in series by one optical fiber can operate simultaneously. But these sensors must differ in central wavelength to facilitate the identification by demodulator. For sensors differing in central wavelength, their strain sensitivity coefficients may also differ even if they are made of the same material. As the coefficients may also be easily affected by errors in manufacturing, calibration or other aspect. Therefore, the influence of difference in strain sensitivity coefficient on the test result must be analyzed in principle. Supposing the strain sensitivity coefficient of vertical sensor ($K_{e, z}$) is $n$ times of that of longitudinal sensor ($K_{e, x}$), i.e. $K_{e, z} = n K_{e, x}$, so:

$$\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2 = n K_e \left[ (\mu + 1) (\varepsilon_f - \beta \Delta t) \right]$$
$$+ (1 - n) K_e (\varepsilon_f - \beta \Delta t) - \alpha \Delta t.\hspace{1cm} (11)$$

Substituting equation (11) in (10) gets:

$$F_z = \frac{EF (\Delta \lambda_1 / \lambda_1 - \Delta \lambda_2 / \lambda_2)}{K_e (\mu + 1)} = \frac{n EF (\varepsilon_f - \beta \Delta t)}{K_e (\mu + 1)}$$
$$+ \frac{EF (1 - n) (\varepsilon_f - \beta \Delta t)}{K_e (\mu + 1)} - \frac{EF \alpha \Delta t}{K_e (\mu + 1)}.\hspace{1cm} (12)$$

By comparing equations (12) and (10), one gets:

$$\Delta F_z = (n - 1) \mu EF (\varepsilon_f - \beta \Delta t) / (\mu + 1).\hspace{1cm} (13)$$

It can be seen from equation (13) that the measuring error induced by difference in strain sensitivity coefficient between two sensors relates not only to actual longitudinal force, but also to the ratio of two strain sensitivity coefficients. Given that the measuring error not exceeding 5% of the actual rail longitudinal force is allowable, one gets:

$$| \Delta F_z / EF (\varepsilon_f - \beta \Delta t) | \leq 5\%.\hspace{1cm} (14)$$

For CHN60 rail, $n$ is within 0.78 $\sim$ 1.22 as obtained from equation (14). That is to say, when the ratio of strain sensitivity coefficients of two sensors (longitudinally and vertically installed) is within 0.78 $\sim$ 1.22, the longitudinal force can be obtained with equation (10). When the two sensors are of the same material, the ratio of strain sensitivity coefficients will be equal to that of central wavelengths for the two sensors [32]. So, to minimize measuring error on site, the wavelengths of two sensors at one test point shall be as close as possible to each other.

4. On-site test

4.1. Layout of test points on site

The test method for longitudinal force in CWR based on above test principle with FBG sensor has been justified by a field test at a station in Chengdu-Mianyang-Leshan high-speed railway in China. In the test, two test points were selected on the bridge subgrade, instead of on bridge. As for test points on subgrade, theoretical rail longitudinal force can be obtained easily and that will help a lot in the comparison between measured value and theoretical value. However, for the test points on bridge, the longitudinal force may also be affected by track–bridge interaction, and no actual theoretical value can be obtained. Figure 4 is the layout of field test points, where test point 1 is over 70 m away from the abutment of the nearest bridge (32 m simply supported beam
bridge), so it can be deemed as that the two test points are located in the fixed area of CWR track, meeting the basic requirements of the test principle.

As the theoretical temperature force of the rail on subgrade has to be obtained from equation (1), the change in rail temperature shall be measured at test point 1.

4.2. FBG sensor and test instruments

As stated in subsection 2.3, the difference in central wavelengths of the two FBG sensors arranged at one test point shall be as small as possible, so as to ensure the consistency of their strain sensitivity coefficients. Therefore, the central wavelengths of sensors at test point 1 were taken as 1554 nm and 1555 nm with ratio between the two of 0.999; and those at test point 2 were taken as 1550 nm and 1551 nm with ratio of 0.999. Rail temperature sensor is an independent instrument with unlimited central wavelength. Nevertheless, its central wavelength shall be different from the above four, taken as 1548 nm.

The drift of central wavelengths of FBG sensors were measured by single-channel FBG interrogator (SM130 from MOI Inc, USA, max. sampling rate of 100 Hz, accuracy of 1 pm). As the change scope of rail temperature and rail longitudinal force change slowly and constantly, the sampling rate was set to 0.5 Hz in the test.

4.3. Calibration of sensitivity coefficient of the sensor

The accuracy of strain sensitivity coefficient directly relates to the accuracy of test results. Strain sensitivity coefficient is generally calibrated through obtaining strain by loading method. This calibration method is quite complex and requires high-precision dynamometers. However, the calibration process for temperature sensitivity coefficient is much easier and needs no additional force applying on device. So in this paper, a new method of calibrating strain sensitivity coefficient through calibrating temperature sensitivity coefficient was proposed based on equations (3) and (4). This method includes three steps. Firstly, the temperature sensitivity coefficient \( K_T = \zeta + \alpha \) is calibrated by investigating the relationship between \( \Delta T \) and \( \Delta \lambda/\lambda \) using the fiber in the free state. Secondly, attach the sensor to an object (such as a copper tube as used in the test) in free state with different material from the sensor and given thermal expansion coefficient. Thirdly, the nominal temperature sensitivity coefficient \( K = K_c(\alpha_r - \alpha) + K_T \) is calibrated in the same manner as the first step, and then \( K_c \) is obtained by \( K \) and \( K_T \) as:

\[
K_c = \frac{K - K_T}{(\alpha_r - \alpha)}.
\] (15)

In general conditions, the order of magnitude of thermal expansion coefficient of FBG sensor is \( 10^{-3}/°C \), that of ordinary metal is \( 10^{-5}/°C \), so \( \alpha \) of the sensor may be neglected in actual calculation. Specific data validation will be provided during data processing.

The temperature sensitivity coefficients of the sensors (central wavelengths of 1554 and 1551 nm) in free state were calibrated with results as shown in figures 5 and 6.

As can be seen from figures 5 and 6, the temperature sensitivity coefficients of the two sensors are \( 7.69 \times 10^{-6}/°C \) and \( 7.71 \times 10^{-6}/°C \) respectively. This is mainly because that the temperature sensitivity coefficient of bare grating is determined by thermal expansion coefficient and thermo-optic coefficient. As the two sensors are basically of the same material, the two temperature sensitivity coefficients will also be similar, agreeing with the actual condition.

Figures 7 and 8 show the results of calibration of temperature sensitivity coefficient when FBG sensors of different central wavelengths are attached to copper tube (thermal expansion coefficient \( 1.95 \times 10^{-5}/°C \)).

The strain sensitivity coefficients at test points 1 and 2 are 0.144 and 0.122 respectively, obtained from above calibration results and equation (15). The results can be applied directly in processing the data picked up from test points 1 and 2.
4.4. Testing process and results

To ensure the consistence of the strains of sensor and rail, the rail surface shall be ground before the installation of sensor to remove rust. Then the sensors were fastened on rail web with aviation glue and protected with sealing installation from being affected by external environment during operation. During the installation, the longitudinal sensor was attached along the neutral axis of the rail, vertical sensor was kept vertical to the neutral axis at the central position, so as to avoid the influence of other loads on test results. The field installation process is as shown in figure 9.

The measurement work began from 9:30am on the first day and finished at 8:30am on the second day, lasting for about 23 h to ensure the integrity of the data.

Figure 10 shows the test results of rail temperature; figures 11 and 12 show the test results at test point 1 and 2. For better understanding, the x-axes in figures 10–12 represent time (s), the y-axis in figure 10 represents change in rail temperature as compared with initial value, the y-axes in figures 11 and 12 represent the difference between the relative change in wavelengths of longitudinal and vertical sensors at test points 1 and 2, i.e., $\Delta\lambda_1/\lambda_1 - \Delta\lambda_2/\lambda_2$.

The varying of initial data in figures 10–12 is text noise which is attributed to the resolution of single-channel FBG interrogator. As the test is a quasi-static process, S-G filter which can make the shape and width of signal unchanged when reducing the noise is used to smooth the signal.

5. Results and analysis

5.1. Without weighting thermal expansion coefficient of sensor

The thermal expansion coefficient of the sensor is much smaller than that of the rail, taken as 0 in the analysis. The change tendency of longitudinal force in CWR can be obtained from figure 10 and equation (1), as shown in figure 13. In figure 13, there also have two other lines representing longitudinal force got from figures 10, 11 and equation (10). As the CWR is locked before the beginning of the test, all measurement values are the results relative to initial test state.

Figure 13 shows that, the test results at test points 1 and 2 agree well with theoretical results with minor difference. The maximum differences at test points 1 and 2 of 8.6 kN and 13.8 kN respectively. This difference may come from two aspects: (i) objective aspect, including measuring errors of rail temperature and the change of wavelength, uneven distribution of rail temperature and different sensitivity of the two sensors at one test point, and (ii) subject aspect, including insufficient consideration on thermal expansion coefficient of the sensor and data processing error in analyzing the data. However, in view of the test rule and size of measuring, FBG sensor can obtain accurate longitudinal force of CWR, and justify the principle of measuring longitudinal force of CWR with FBG and calibrating strain sensitivity coefficient through calibration of strain sensitivity coefficient of FBG as proposed in the paper.

To further justify the test principle, the test results will be corrected with the thermal expansion coefficient of the sensor.
Figure 9. Installation of sensors on site.

Figure 10. Change in rail temperature.

Figure 11. Results at test point 1.

Figure 12. Results at test point 2.

Figure 13. Comparison of test results.
5.2. Weighting thermal expansion coefficient of sensor

As FBG sensor has smaller thermal expansion coefficient than rail, measuring the thermal expansion coefficient of the sensor directly may be quite demanding for measuring instruments. Restricted by test conditions in the lab, it may be difficult to obtain accurate value of the coefficient. As mentioned in section 4.1, the test theory and calibration method have been justified, so we regard the thermal expansion coefficient of the sensor as an unknown factor in this section and try to obtain it with mathematical programming method based on the comparison of measurement values and theoretical values. The programming objectives and restrictions are as follow:

\[
F_E = K_{z1} \alpha_T - K_T = K - K_l
\]

where, \(F_{z1}\) is the theoretical value of rail longitudinal force obtained by equation (1).

The results for the programming objectives under different values of thermal expansion coefficient of FBG sensor are shown in figure 14. In the figure, there is a value at test points 1 and 2 respectively that can lead to the minimum programming function, of which the corresponding thermal expansion coefficients are \(0.781 \times 10^{-7}/°C\) and \(0.848 \times 10^{-7}/°C\) respectively. The two values differ from the thermal expansion coefficient in normal conditions, as the error induced by thermal expansion coefficient cannot be separated from the error induced by other factors during programming calculation. So equation (16) reflects the result obtained by combining errors induced by other reasons and thermal expansion coefficient. Since the errors at two test points originate from the same sources, the programming results at the two points differ slightly. The above analysis has also been justified.

It can be seen from figure 14 that, regardless the size of thermal expansion coefficient, the results at test point 1 is closer to the theoretical value of longitudinal force as compared with the results at test point 2. This lies in that the rail temperature is distributed unevenly in longitudinal direction, and the test point for rail temperature is closer to test point 1.

The thermal expansion coefficient obtained with programming method can be used to calibrate the measurement value. Figure 15 depicts the comparison of the corrected value and theoretical value.

After calibration, the maximum differences between the values measured at test points 1 and 2 and the theoretical values are 7.5 kN and 10.9 kN respectively. It has reduced by 1.1 kN and 2.9 kN as compared with the differences before correction. By comparing figures 15 and 13, it can be found that, correcting the measurement values with the thermal expansion coefficient of FBG sensor can mitigate the difference between measurement value and theoretical value to certain extent. However, this mitigation amount has little impact on practical application. Therefore, thermal expansion coefficient of FBG sensor can be neglected in practice, and the longitudinal force of CWR may be obtained with the data collected at test points.

6. Conclusion

The principle of testing the longitudinal force of CWR with FBG was put forward and explored on the basis of bi-directional strain method, which has also been verified on site with the conclusions as follow:

1. In the application of FBG sensor in measuring the longitudinal force of CWR, the impact of different restricted conditions of rail in vertical and longitudinal
directions on test results shall be considered. Moreover, the ratio of strain sensitivity coefficients of the two FBG sensors at one test point shall be within 0.78 ∼ 1.2 to limit the relative error of test results within 5%.

(2) The test principle of FBG sensor under different restricted conditions at the test direction of the test specimen was analyzed. The test principle for longitudinal force of CWR was deduced and justified on site.

(3) Based on the test principle of FBG sensor under the free state of test specimen, the method of determining strain sensitivity coefficient by calibrating the temperature sensitivity coefficient twice was proposed and verified on site.

(4) By taking the thermal expansion coefficient of FBG sensor into account, the test result of rail longitudinal force can be corrected, so as to mitigate the difference between measurement value and theoretical value. However, the correction can make little difference. So, it is recommended to calculate the longitudinal force in CWR directly with data collected at test points by disregarding the thermal expansion coefficient of FBG sensor.

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