

PAPER • OPEN ACCESS

## The Design and Theoretical Analysis of Comparison Device of Strain Sensor for Bridge Health Monitoring

To cite this article: Lu Peng *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **252** 052119

View the [article online](#) for updates and enhancements.

# The Design and Theoretical Analysis of Comparison Device of Strain Sensor for Bridge Health Monitoring

Lu Peng<sup>a</sup>, Yixu Wang<sup>b</sup>, Na Miao<sup>c</sup>, Chunxia Zhang<sup>d</sup>, Hongfeng Sun<sup>e</sup>, Bing Zhang<sup>f</sup>

Research Institute of Highway Ministry of Transport, Beijing 100088, China

<sup>a</sup>PengLu@ncmerb.com, <sup>b</sup>wyx@ncmerb.com, <sup>c</sup>305373174@qq.com,  
<sup>d</sup>cx.zhang@rioh.cn, <sup>e</sup>sunhongfeng74@126.com, <sup>f</sup>991654948@qq.com

**Abstract.** The strain monitoring information of bridge health monitoring system plays an important role in the safe operation of the bridge, at present, the monitoring methods are mainly use strain monitoring sensors to obtain the bridge strain information in real time, the strain monitoring sensor can be divided into three categories: electric resistance strain sensor, vibrating wire strain sensor, fiber-optic strain sensor according to the test principle. At this stage, in order to meet the metrological traceability requirements of the strain monitoring sensor with the increasing use of strain monitoring sensors, the research institute of highway ministry of transport designed an equi-intensity cantilever beam device for online calibration service in the laboratory based on finite element analysis and mathematical model validation, combining with the disciplines professional knowledge of transportation engineering, mechanical design, machining and materials engineering and so on, and the equi-intensity cantilever beam device can realize the metrological traceability of different types of strain monitoring sensors for the traffic monitoring.

## 1. Introduction

The Bridge is an important part of the highway, and is the key hub of the traffic engineering, it plays a very important role in the development of the traffic and transportation, and it is also an important infrastructure for national economic and social development. However, in the process of construction and use of the bridge, the bridge own performance will continuous degradation, even damage and deterioration under the influence of the various environmental and human factors[1,2]. Therefore, the quality inspection and health monitoring of the bridge structure has become a hot topic in academic and engineering circles at home and abroad[3]. As the stress and strain testing is an important task during the construction and operation process of the bridge structure, the sensor should be calibrated regularly during the strain monitoring, However, in the static calibration process before installing the sensor[4], there is a lack of a detachable, adjustable composite calibration device which can transform the strain sensor strain values of different types and shapes into basic quantities of metrological traceability such as mechanics and length[5]. This paper takes calibration requirement of the fiber grating strain monitoring sensor for the bridge health monitoring of national center of metrology for equipments of road and bridges as an example, and designed an equi-intensity cantilever beam device for online calibration service in the laboratory based on finite element analysis and mathematical model validation, combining with the disciplines professional knowledge of transportation engineering[6], mechanical



design, machining and materials engineering and so on, which can realize the metrological traceability of different types of strain monitoring sensors for the Traffic monitoring. And the device fills the metrological blank area of the strain monitoring sensor [7].

## **2. The Measuring principle of the equi-intensity cantilever beam**

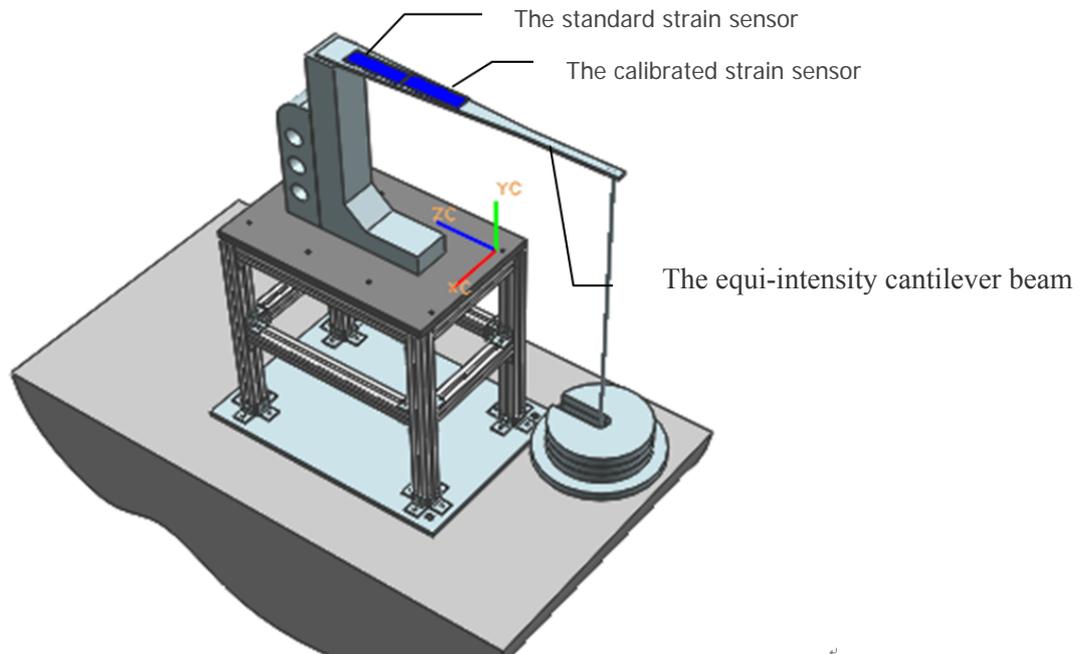
### *2.1. The Theoretical principle*

In order to verify the measurement accuracy of the fiber grating strain monitoring sensor, Further prove the reliability of the metrological traceability of the fiber grating strain sensor for the bridge health monitoring, we use the equi-intensity cantilever beam to test the metrological traceability of the fiber grating strain sensor for the bridge health monitoring, At the same time, other strain sensors are mounted (adhered or welded) on the equi-intensity cantilever beam for comparison, Therefore, the accuracy and reliability of the measured values of the fiber grating strain sensor for bridge health monitoring are further verified[8]. The measurement range of the fiber grating strain sensor is  $-2000\mu\epsilon\sim 2000\mu\epsilon$ , so the designed strain value of the equi-intensity cantilever beam is at least  $2000\mu\epsilon$ . As the measurement error of fiber grating strain sensor for the bridge health monitoring is 3%, according to the accuracy theory, the measurement uncertainty of calibration device of the equi-intensity cantilever beam is at least 1% [9].

As the existing laboratory models and strain sensor calibration systems can't be directly applied to calibration services of on-site environmental sensors, and the sensors can't be calibrated after disassembly, in order to meet the requirement of national center of metrology for equipments of road and bridges online calibrate these sensors, This paper explore the on-site calibration technology of strain sensors applied to bridges, and it is necessary to design a test device for the simulation test of on-site calibration of the strain sensor for the bridge health monitoring, which is one of the technical difficulties of this subject [10].

### *2.2. Design Scheme*

This project will build a test system for simulation test research as is shown in Figure 1, using the standard strain sensor (partial) as a transfer standard to calibrate the other fiber grating strain sensors online. The device adopt an equi-intensity cantilever beam structure which the analog sensor will install on it, the cantilever beam will produce the strain by loading a weight, this structure has a uniform surface strain, which is convenient for selecting the installation position of the sensor, and the weight loading is stable and easy to measure.



**Figure. 1** The calibration device of equi-intensity cantilever beam

Comparing the calibrated strain sensor measured value with standard strain sensor measured value by loading the weight step by step, and we obtain the sensitivity coefficient of the calibrated strain sensor.

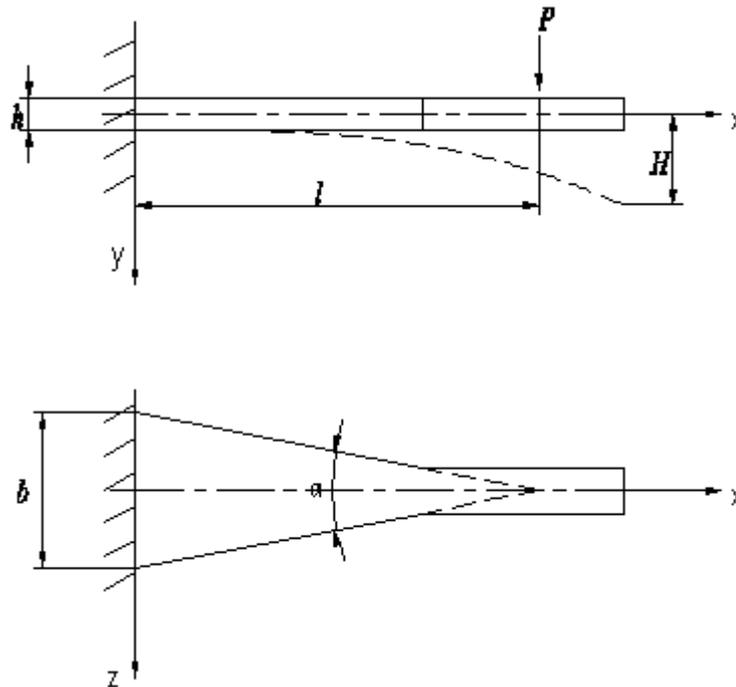
At the same time, the high-precision resistance strain gauge is attached to the cantilever beam to monitor the strain value, and it will aided validate the measured value of the standard fiber grating strain sensor.

The calibration method of the standard strain sensor will refer to JJF (Military)62-2014 《the Calibration Specification for Fiber-optic Strain Sensor》, and the technical indicators and evaluation methods of the calibrated strain sensor will refer to the JJG623-2005 《Verification Regulation of Resistance Strain Gauge Indications》 and GB/T13992-2010 《Metallic bonded Resistance Strain Gauges》.

The device is mainly composed of the equi-intensity cantilever beam, a base and a weight, the weight of each weight is 100N, and different number weights can be selected for the experimentation within the permissible load range. The overall structure is compact and stable, which can meet the requirement of the test experiment of fiber grating strain monitoring sensor for the bridge health monitoring

### 3. The theoretical analysis of the equi-intensity cantilever beam

The equi-intensity cantilever beam which is commonly used in the routine experiment is a cantilever beam of equal thickness and an isosceles triangle surface, which is shown in figure 2.



**Figure. 2** The schematic diagram of the equi-intensity cantilever beam

In figure 2,  $l$  is the length of the cantilever beam,  $b$  is the width of the cantilever beam root, and  $\alpha$  is the relative slope of the two sides of the cantilever beam. Since  $\alpha$  is small, it can be approximated as  $\alpha=b/l$ ,  $P$  is the applied load of the cantilever beam,  $H$  is the deflection of the cantilever beam,  $\theta$  is the rotation angle at the beam end, and  $\rho$  is the radius of curvature. According to the relevant theory of material mechanics, integrating the deflection equation of the beam to determine the integral constant combining with the boundary conditions. Finally, we obtain the expression of the deflection and rotation angle of the neutral axis of the cantilever beam. According to the geometric relationship  $\varepsilon=h/2\rho$ , the following formula can be obtained:

$$\left\{ \begin{array}{l} H = \frac{6l^2}{\alpha E h^3} P = \frac{l^2}{2\rho} = \frac{l}{2} \theta = \frac{l^2}{h} \varepsilon \\ \theta = \frac{12l}{\alpha E h^3} P = \frac{2}{l} H = \frac{l}{\rho} = \frac{2l}{h} \varepsilon \\ \rho = \frac{\alpha E h^3}{12P} = \frac{l^2}{2H} = \frac{l}{\theta} = \frac{h}{2\varepsilon} \\ \varepsilon = \pm \frac{6}{\alpha E h^2} P = \pm \frac{h}{l^2} H = \pm \frac{h}{2\rho} = \pm \frac{h}{2l} \theta \end{array} \right. \quad (1)$$

The normal stress of any cross section of the equi-intensity cantilever beam is equal, therefore, the normal stress on the cantilever beam is independent of the position of the cross section. For cantilever beams with a rectangular cross section, the permissible load is as follows:

$$[P] = \frac{[\sigma] b h^2}{6l} \quad (2)$$

In the formula (2),

$$[\sigma] = \frac{\sigma_s}{n_s} \quad (3)$$

$\sigma_s$  is the yield limit,  $n_s$  is the yield factor of safety, at normal temperature,  $n_s$  is between 1.4 and 1.7.

The working load  $P$  applied to the cantilever beam in actual experiments satisfies the following relation:  $P \leq [P]$ .

The above formula is based on the elastic working range of the cantilever beam, so the deflection  $H$  at the end of the equi-intensity cantilever beam should satisfy the following conditions:

$$H \leq H_{\max} \quad (4)$$

In the formula (4),  $H_{\max}$  is the permissible deflection at the end of the cantilever beam and can be expressed as follows:

$$H_{\max} = \frac{[\sigma]l^2}{Eh} \quad (5)$$

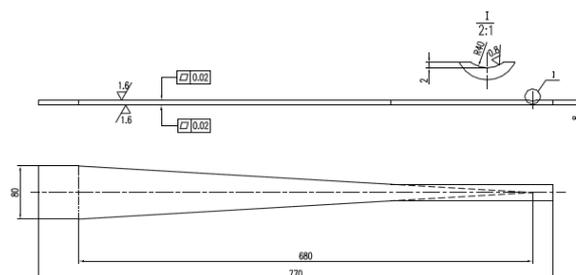
The designed equi-intensity cantilever beam strain value should reach  $2000\mu\epsilon$ , considering the installation size of the fiber grating strain sensor, we initially select the geometric dimensioning of the cantilever beam as follows:  $b=90\text{mm}$ ,  $l=700\text{mm}$ ,  $h=8\text{mm}$ . As the yield strength of ordinary carbon steels (such as Q235) is small, so we initially select the superior alloy steel which is commonly used: 40Cr and 42CrMo (GB/T 3077-1999), the elastic modulus of both is  $2.1 \times 10^5 \text{ MPa}$ . The yield limit of 40Cr is 785MPa, 40Cr can be used for the manufacture parts under heavy loads after quenching, medium temperature or low temperature tempering; the yield limit of 42CrMo is 930MPa, the 42CrMo mainly used for the heavy load parts. Considering the factors such as cost performance and safety factor, we initially select the 42CrMo as the cantilever beam material.

We Substitute the  $\epsilon$ ,  $b$ ,  $l$  and  $h$  into the formula (1), and obtain the actual working load  $p$  is 576N. According to the formula (2) and formula (3), we get the permissible load of Cantilever beam is  $[P] = 750\text{N}$ , and  $p < [P]$ , Therefore, the maximum stress on the cantilever beam don't exceed the elastic limit and the cantilever beam can work normally.

According to the formula (1), the angle  $\alpha$  between the two oblique sides of the cantilever beam is  $\alpha = b/l = 0.09/0.7 = 0.128$ , that is  $\alpha = 7.3^\circ$ .

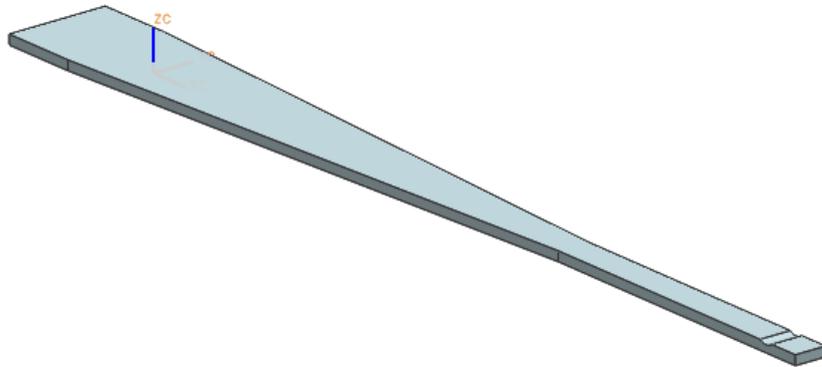
According to the formula (1), we can get the deflection  $H$  of the cantilever beam is that:  $H = 122.5\text{mm}$ , and according to the formula (4), the maximum permissible deflection  $H_{\max}$  of the cantilever beam is 159.5 mm, that is,  $H < H_{\max}$ , so the cantilever beam with load  $P$  applied to the free end is still within the elastic working range, which satisfies the experimental requirements.

In summary, the processing dimension of equi-intensity cantilever beam is shown in figure 3.



**Figure. 3** The processing dimension of the equi-intensity cantilever beam

The three-dimensional structure of the equi-intensity cantilever beam is shown in Figure 4.

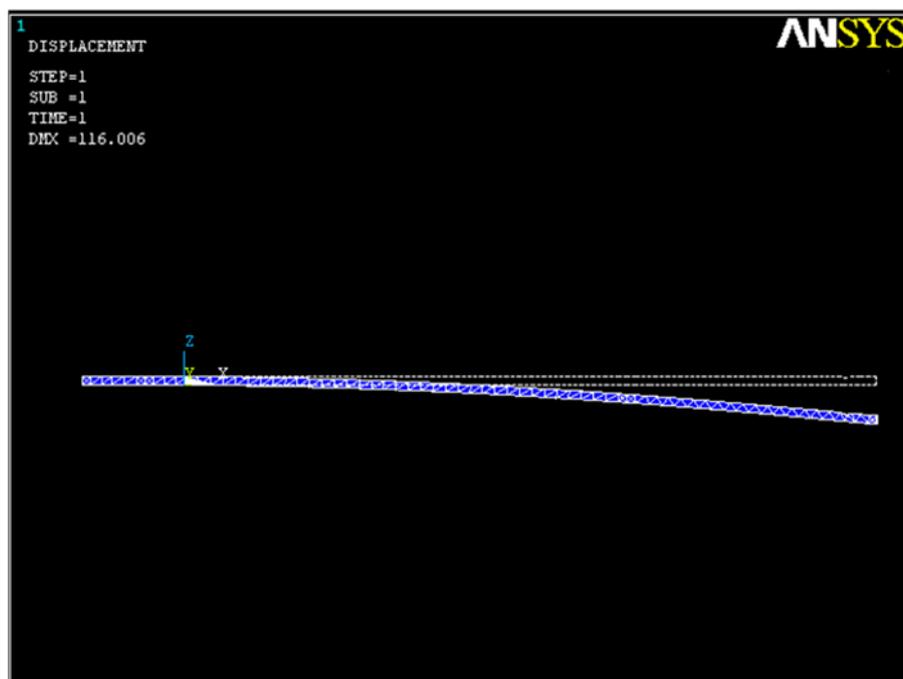


**Figure. 4** The three-dimensional structure of the equi-intensity cantilever beam

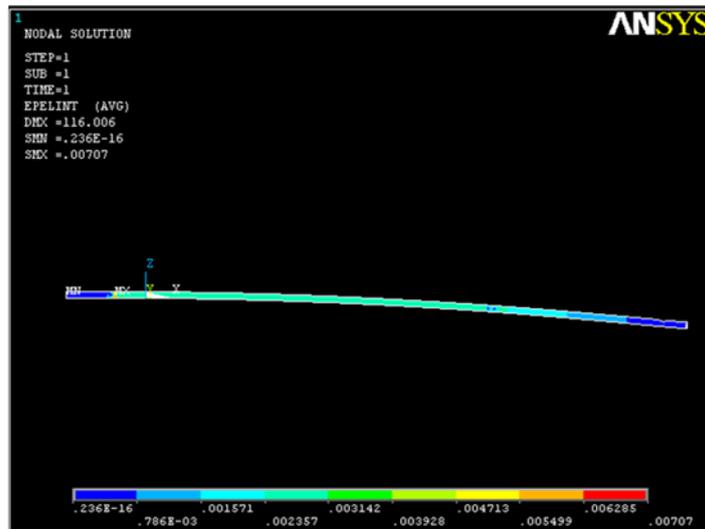
As the density of 42CrMo is  $7.85\text{g/cm}^3$ , we obtain the designed mass of the equi-intensity cantilever beam is 2.2kg.

#### 4. The finite element analysis of the equi-intensity cantilever beam

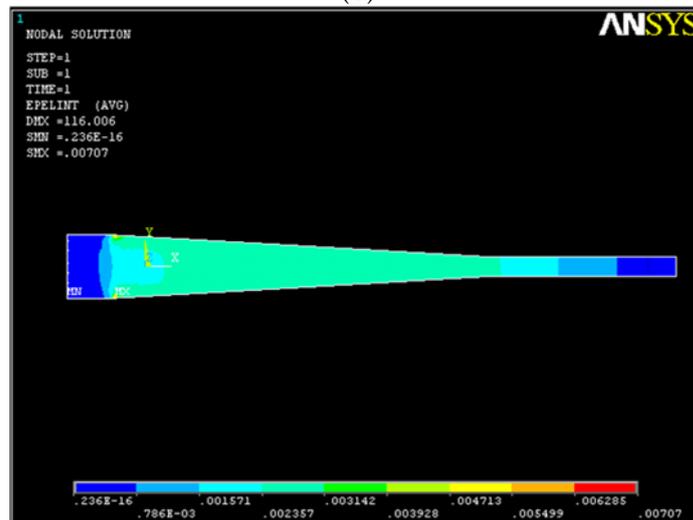
We simulate the cantilever beam with Ansys software, the material of the cantilever beam is 42CrMo, and its modulus of elasticity is  $2.1 \times 10^5$  MPa, and the Poisson's ratio is 0.3, we import the cantilever model of UG6.0 3D Software into Ansys software. When the deflection of the cantilever beam is 116 mm, the deformation diagram of the cantilever beam is as shown in figure 5.



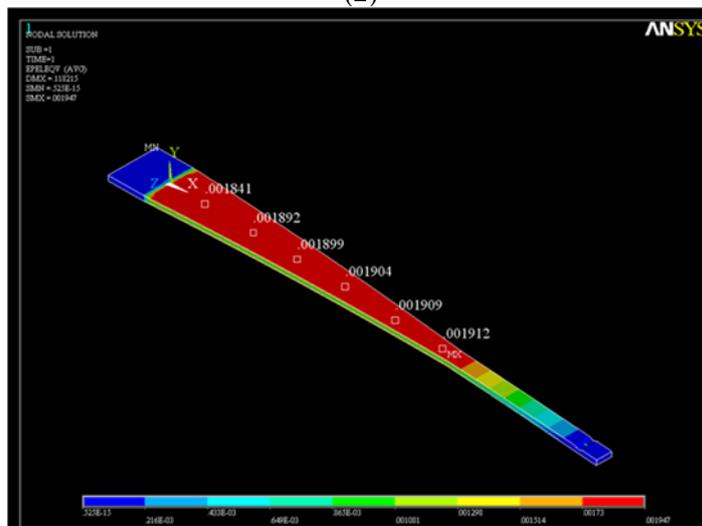
**Figure. 5** The deformation diagram of the cantilever beam



(1)



(2)

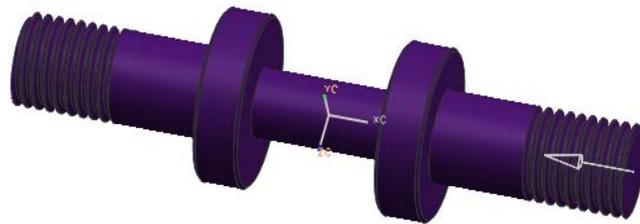


(3)

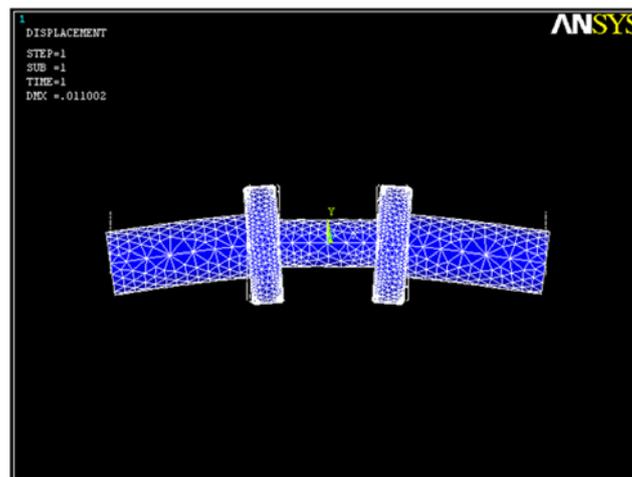
**Figure. 6** The strain diagram of the cantilever beam

According to figure. 6, we obtain that the strain monitoring demand value is within the effective working range of the designed equi-intensity cantilever beam, and the strain is basically equal, so the designed equi-intensity cantilever beam meet the bridge monitoring requirements.

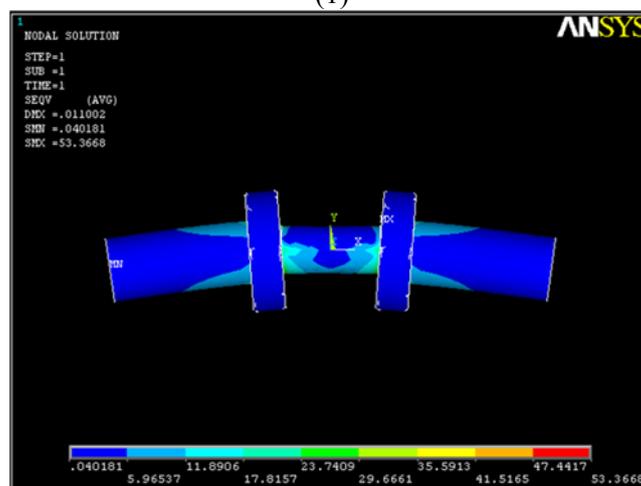
According to the structure of the calibration table, there is a weighing shaft between the cantilever beam and the weight hanger, and its structure diagram is shown in figure 7.



**Figure. 7** The structure diagram of weighing shaft



(1)



(2)

**Figure. 8** The deformation map of bearing shaft

According to the calculation, in order to achieve the designed strain value ( $2000\mu\epsilon$ ) of the equi-intensity cantilever beam, a force value of 527 N should be applied, and in consideration of the design margin, the applied force  $F=600\text{N}$  in simulation. The material of the bearing shaft is 40Cr, the elasticity modulus is  $2.1\times 10^5$  MPa, and the Poisson's ratio is 0.3. The deformation map of bearing shaft is as shown in Figure 8.

According to the figure 8, under the circumstances of loading 300N on one side of the bearing shaft, the deformation of the end of the bearing shaft is 0.011mm, the maximum stress is 53.4MPa, and the allowable stress is less than the permissible stress of the 40Cr, which meet the design requirements. In the figure 6, The bending deformation results in the horizontal displacement at the end of the cantilever beam, according to the bending moment formula  $M=FL$ , the effective distance  $L$  changes, and the variation  $\Delta$  is the difference between the original length of the beam and the deflection curve, and the formula is as follows:

$$\Delta = \frac{1}{2} \left[ \frac{12Pl}{Ebh^3} \right]^2 \cdot \frac{l^3}{3} \quad (6)$$

Then we obtain the  $\Delta=0.025\text{mm}$ ,  $\Delta/l=0.025/100=0.025\%$ , so the influence of the variation  $\Delta$  on the measured strain can be completely ignored.

## 5. Conclusion

According to the above theoretical analysis and finite element analysis conclusions, The designed equi-intensity cantilever beam with 42CrMo alloy steel material can satisfy the metrological traceability requirements of strain monitoring sensor for the bridge health monitoring in the laboratory. The equi-intensity cantilever beam effectively eliminates the influence of the different strain sensors with such as different work principle, different appearance and layout process, different strained condition, different force of measuring head, different hardness of material contact surface on the accuracy of the measurement result in the metrological service. The equi-intensity cantilever beam improves the accuracy of the metrological calibration verification, and fills the blank of the metrological scheme for the strain monitoring of the transportation industry, satisfies the calibration requirements of the strain sensor in the transportation industry.

## Acknowledgments

This work was financially supported by 1. Projects funded by the Special funds for science and technology innovation in Highway Research Institute, Ministry of Transport. (Approval No.: 2018-E0042); 2. Central research institutes of basic research and public service special operations of China (Approval No.: 2018-9031) 3. National Quality Infrastructure of China (Approval No.: 2017YFF0206305) fund.

1. E-mail: wyx@ncmerb.com, Telephone No. : 86-13370157114, 8610-62079890
2. E-mail: cx.zhang@rioh.cn. Telephone No. : 86-18612966714, 8610-62079863

## References

- [1] ZHANG Qi Wei. Conception of Long-span Bridge Health Monitoring and Monitoring System Design [J]. Journal of Tongji University, 2001, 29 (1): 65-69.
- [2] Laursen E, Bitsch N, Andersen J E. Analysis and mitigation of large amplitude cable vibrations at the Great Belt East Bridge [C]//IABSE Symposium Report. International Association for Bridge and Structural Engineering, 2006, 91 (3): 64-71.
- [3] Bao Y, Li H, An Y, et al. Dempster-Shafer evidence theory approach to structural damage detection [J]. Structural Health Monitoring, 2012, 11 (1): 13-26.
- [4] An Y H, Ou J P. Experimental and numerical studies on accurate damage location based on the SDLV method [C]//Proceedings of the 5th World Conference on Structural Control and Monitoring. 2010.

- [5] Cao, X., Y. Sugiyama, and Y. Mitsui. "Application of artificial neural networks to load identification." *Computers & Structures* 69.1 (1998): 63-78.
- [6] Kudva J N, Munir N, Tan P W. Damage detection in smart structures using neural networks and finite-element analyses[J]. *Smart Materials & Structures*, 1992, 1 (2): 108.
- [7] Elkordy M F, Chang K C, Lee G C. Neural Networks Trained by Analytically Simulated Damage States [J]. *Journal of Computing in Civil Engineering*, 1993, 7 (2): 130-145.
- [8] Rytter A, Kirkegaard P H. Vibrational Based Inspection of a Steel Mast[J]. *Proceedings of SPIE - The International Society for Optical Engineering*, 1995.
- [9] Ko J M, Sun Z G, Ni Y Q. Multi-stage identification scheme for detecting damage in cable-stayed Kap Shui Mun Bridge [J]. *Engineering Structures*, 2002, 24 (7): 857-868.
- [10] Kaminski P C. The approximate location of damage through the analysis of natural frequencies with artificial neural networks [J]. *ARCHIVE Proceedings of the Institution of Mechanical Engineers Part E Journal of Process Mechanical Engineering 1989-1996 (vols, 1995, 209 (209): 117-123.*