

Probabilistic Analysis of Stress Concentration Factor of an Orthotropic Steel Bridge with FBG-Based Structural Health Monitoring System

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ABSTRACT

Stress concentration factor (SCF) calculation is a significant task for the fatigue design and assessment of orthotropic steel bridges. It is essential to develop a reliable field sensing and analysis method for effectively grasping the stress level of critical fatigue-prone welded joints in orthotropic steel bridge deck. In this study, an optical fiber Bragg grating-based (FBG-based) hot spot stress approach is proposed and applied to derive the SCF of welded joints in an orthotropic steel bridge crossing the Beijing-Hangzhou Grand Canal located in Hangzhou, China. The framework of the proposed method is introduced containing the design and deployment of specific FBG sensors and evaluation of hot spot stress analysis method. The raw wavelength data obtained from the FBG sensors are firstly transferred to the strain and stress data, and the hot spot stresses are calculated on the basis of the extrapolation method in accordance with the joint type. Then, the SCF can be easily determined as the quotient of hot spot stress and nominal stress in the concerned joint. Furthermore, the probability density function (PDF) of the SCF is estimated by use of a normal distribution in consideration of the stochastic characteristic of stress distribution.

1. INTRODUCTION

In recent years, many attentions have been paid to the stress state analysis of welded components worldwide (Radaj 1996, Fricke 2002). The nominal stress method is the most widely used approach in standards of various countries because of its simplicity (AASHTO 2012). However, due to the inherent discontinuity of configuration and external complexity of loading, in practice, the stress concentration effect caused by section change is ignored, and the nominal stress is hard to be defined in some cases (Chan et al. 2005, Ye et al. 2012, Tveiten et al. 2013).

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With the development of finite element analysis (FEA) technique in the calculation of structural stress of the welded components, many researchers have proposed various hot spot stress (HSS) methods considering the local stress concentration caused by the configuration sudden change (Kyuba and Dong 2005, Aygul et al. 2012). However, the HSS values directly obtained from the weld toe through FEA are affected by the mesh size at the discontinuous region and tend to be inversely proportional to the mesh size at the welded toe. In order to avoid the effects of configuration and notch weld quality, the HSS value is connected to the local stress value of reference points in vicinity of the weld toe. Accordingly, the extrapolation methods are proposed based on one, two or multiple reference points (IIW 2006).

However, the experimental and field-data based fatigue analysis from an instrumented bridge is still deemed as a more convincing approach than numerical simulation analysis (Schumacher and Nussbaumer 2006). To secure structural and operational safety throughout the bridge life-cycles and issue early warnings on any deterioration or damage of bridges prior to costly repair or even catastrophic collapse, the significance of implementing long-term structural health monitoring (SHM) systems for bridges has been increasingly recognized worldwide. In this study, an FBG-based long-term SHM system instrumented on an orthotropic steel bridge crossing the Beijing-Hangzhou Grand Canal located in Hangzhou, China is introduced, and the SCF of key welded joint is calculated based on the real-time field monitoring data. Furthermore, the probability density function (PDF) of the SCF is estimated using a normal distribution.

2. FBG-BASED SHM SYSTEM

Steel bridges are usually composed of lots of longitudinal and transverse plate-type structural members with welded joints at their intersections, thus it is difficult to determine the stress distribution for the welded joints of steel bridges in comparison with the structures mainly composed by relative simple bars or beams. When a bridge is instrumented with an on-line SHM system, this problem can be easily solved since the monitoring strain data can be directly obtained through deployed sensors in the vicinity of the welded details. In general, experimental stress analysis is accomplished based on strain measurements using electric resistance strain gauges. In comparison with the traditional mechanical and electrical sensors, the optical fiber sensors possess some unique advantages such as small size, light weight, immunity to electromagnetic interference (EMI) and corrosion, and embedding capability, and therefore they have been employed in monitoring of engineering structures worldwide.

In this study, an FBG-based SHM system was instrumented on a steel bridge crossing the Beijing-Hangzhou Grand Canal located in Hangzhou, China. This system is mainly comprised of the FBG sensors, transmission fiber and demodulation, as shown in Fig. 1. Many strain and temperature FBG sensors were installed on the specific critical joints of half section and 1/4 or 3/4 section. The selection of joints in each section is primarily based on the literatures, such as the reported fatigue-prone joints containing rib-to-deck and rib-to-diaphragm with cutout, 8 joints in each section are concerned and installed with FBG strain and temperature sensors. Temperature compensation sensors are installed on corresponding location for a more accuracy results. The installation locations of the FBG sensors are illustrated in Fig. 2 and Fig. 3.

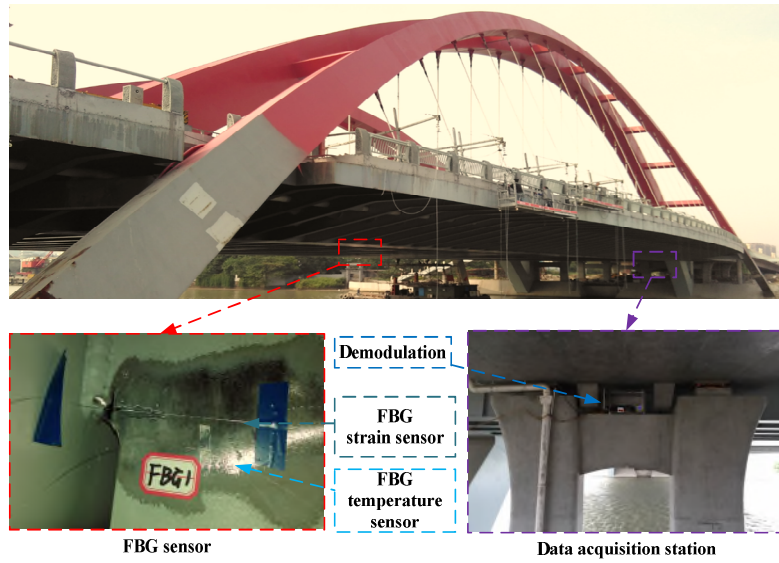


Fig. 1 Deployment of FBG-based SHM system

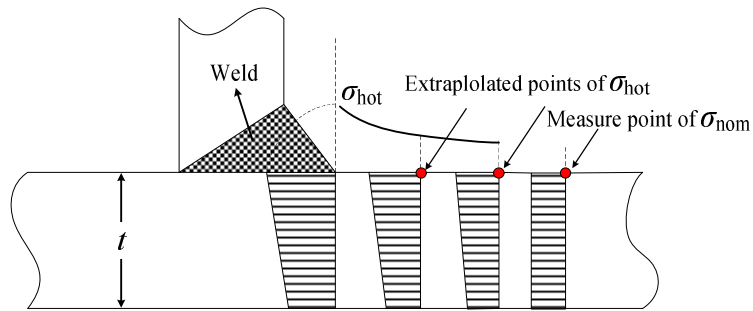


Fig. 2 Locations of measurement points

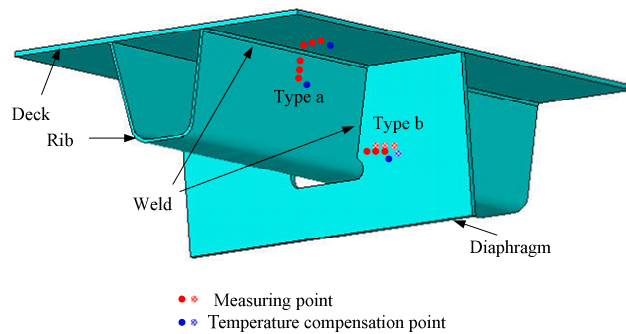


Fig. 3 Details of measurement points

3. PROBABILISTIC ANALYSIS OF SCF

3.1 Calculation method

The SCF can be calculated by dividing the hot spot stress, σ_{hot} , by the nominal stress, σ_{nom} , according to

$$SCF = \frac{\sigma_{hot}}{\sigma_{nom}} \quad (1)$$

The hot spot stress, resulting from the local stress concentrations due to geometric irregularities and discontinuities at welded connections, is difficult to determine due to the extremely complicated stress distribution in the vicinity of the weld toe. It is commonly obtained by numerical finite element methods or experimental measurements. According to International Institute of Welding (IIW) reports, the weld joints is classified into three types, a, b, and c according to the location of hot spot and the weld pattern. The hot spot stress can be obtained when the measuring point at distance $0.4t$ and $1.0t$ from weld toe on the plate surface for type a and c, as expressed as

$$\sigma_{\text{hot}} = 1.67\sigma_{0.4t} - 0.67\sigma_{1.0t} \quad (2)$$

The hot spot stress of type b is regardless of plate thickness t , measuring point should be located at 5mm and 15mm from the weld toe, as determined by

$$\sigma_{\text{hot}} = 1.5\sigma_{5\text{mm}} - 0.5\sigma_{15\text{mm}} \quad (3)$$

3.2 Analysis results

The raw wavelength data obtained from the FBG sensors are firstly transferred to the daily strain and stress data, as shown in Fig. 4 and Fig. 5. The hot spot stress is obtained on the basis of particular method of extrapolation according the joint type. The SCF can be easily determined as the quotient of hot spot stress and nominal stress in each concerned joint. In this preliminary study, 8 joints are selected to perform the stress analysis, hot spot stress of types a and b are calculated by the above-mentioned formulation respectively. It can be found that the SCFs of the same hot spot type are relative stable. However, the experimental determination of SCF is a complicated process considering various factors and uncertainties and thus the SCF has a nature of randomness subjected to the stochastic behavior of complex operational conditions, especially in actual bridge monitoring. In this study, the SCF is presumed to be a random variable with an assumed probability distribution, the fitting of the PDF of SCF is performed to obtain quantitative descriptions of the stochastic characteristics, as shown in Fig. 6 and Fig. 7. In accordance with the fitting results, the SCFs of both type obey a normal distribution with the mean value of 1.23 for type a and 1.76 for type b.

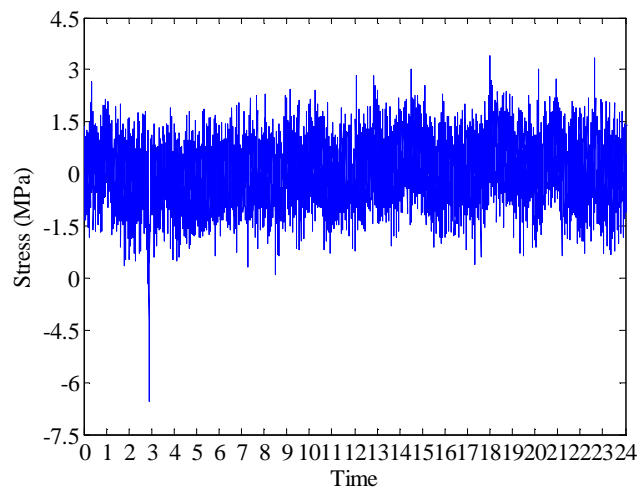


Fig. 4 Measured daily stress time history (type a)

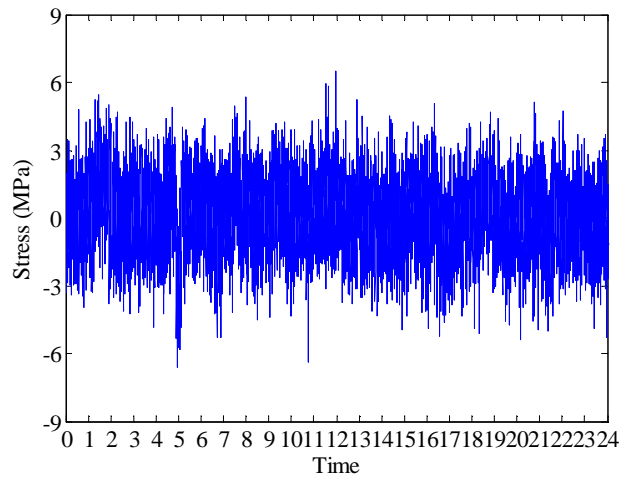


Fig. 5 Measured daily stress time history (type b)

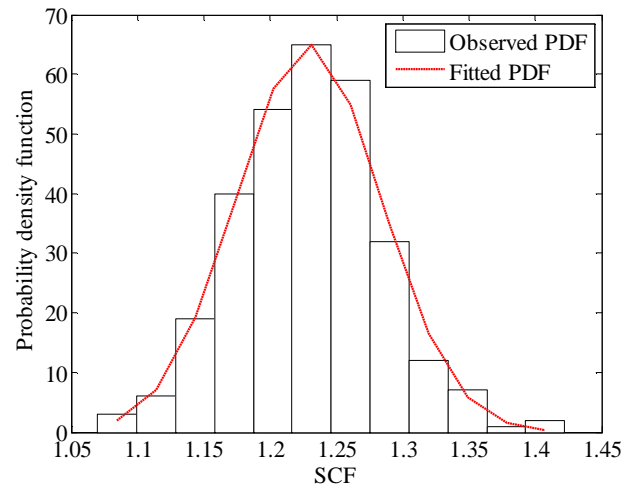


Fig. 6 PDF of SCF (type a)

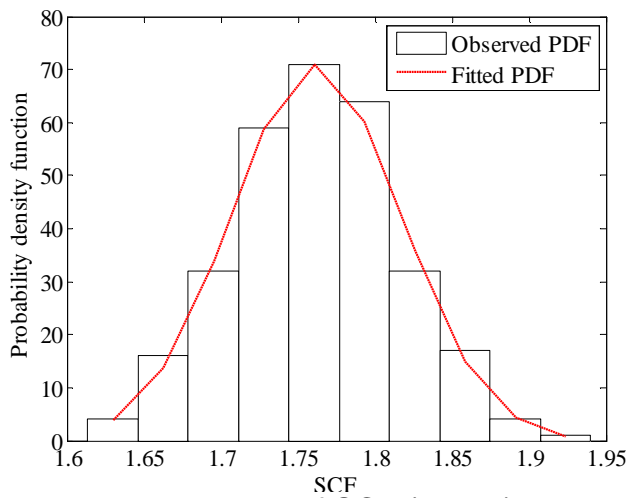


Fig. 7 PDF of SCF (type b)

4. CONCLUSIONS

In this study, an FBG-based hot spot stress approach is proposed and applied to SCF calculation of welded joints in an orthotropic steel bridge crossing the Beijing-Hangzhou Grand Canal located in Hangzhou, China. The framework of the proposed method is introduced concerning the fabrication and employment of specific FBG sensors and selection of hot spot stress approach. The results reveal that the SCF can be easily determined by the proposed method. Meanwhile, the PDF of the SCF is obtained using normal distributions in consideration of the stochastic characteristic of stress distribution of concerned location.

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