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HOT SPOT STRESS APPROACH FOR FATIGUE LIFE ASSESSMENT IN WELDED BRIDGE CONNECTIONS USING MONITORING DATA AND FEM ANALYSIS

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Abstract

This paper presents a study of using long-term monitoring data and the hot spot stress approach for fatigue life assessment of a suspension steel bridge installed with a long-term structural health monitoring (SHM) system. First, a global finite element model (FEM) of the bridge and a local FEM for typical welded connections are developed using the general-purpose commercial software ABAQUS. Hot spot stresses and stress concentration factors (SCFs) at failure-critical locations are calculated by means of the surface extrapolation technique with FEM analysis. Then the hot spot stress approach is applied to evaluate the fatigue life of welded details by using the strain measurement data from the long-term monitoring system. The fatigue assessment results obtained by the hot spot stress approach are also compared with those obtained by the nominal stress approach.

INTRODUCTION

SHM has become an increasingly accepted technology for diagnosing and prognosing bridge condition and safety (Pines and Aktan, 2002; Ko and Ni, 2005). The continuously measured strain data from a long-term monitoring system can be used to assess the status of fatigue which is among the most critical forms of damage potentially occurring in steel bridges. However, due to the limitations of implementation technology and specific field conditions, the sensors for strain measurement usually are not installed at the most critical locations where fatigue cracks are expected to occur, and therefore only nominal strain/stress is obtained. The nominal stress approach has been widely used for fatigue evaluation because most design specifications (BSI, 1980; AASHTO, 1990) for steel structures contain a standard procedure for fatigue analysis based on this approach. However, the nominal stress approach cannot consider the most critical stress of the fatigue damage location. An alternative method for fatigue analysis of complicated welded steel details is the hot spot stress approach, which can provide more reliable and accurate fatigue life evaluation than the nominal stress approach.

The hot spot stress approach which takes the dimensions and stress concentrating effects of the critical detail into consideration has been well accepted and recommended by several national and international codes and standards (CEN, 1992; IIW, 1996). Analysis and assessment of the hot spot stress with respect to fatigue has already a rather long history. Pioneering investigations were made in the 1960's by several researchers, including Peterson, Manson and Haibach, to relate the fatigue strength to a local stress or strain measured at a certain point close to the weld toe (Radaj *et al.*, 2006). The development, in 1970's, of the well-known hot spot stress approach with the definition of reference points for stress evaluation and extrapolation at certain distances away from the weld was reviewed by van Wingerde *et al.* (1995), which was particularly successful for the fatigue strength assessment of tubular joints. First attempts to apply the approach to welded joints at plates were seen in the early 1980's. Remarkable investigations were performed in Japan to analyze stress concentration due to the local structural geometry of ship hull details, which were summarized by Matoba *et al*. (1983). Radaj (1990) summarized these and other investigations and defined the hot spot stress as the surface stress which can be calculated at the weld toe in accordance with structural theories used in engineering. He demonstrated that the hot spot stress can be analyzed either by surface extrapolation or by linearization through the thickness. In the early 1990's, Petershagen *et al*. (1991) derived a generalized hot spot stress approach for plate structures and applied it to complex welded structures. Detailed recommendations concerning hot spot stress determination using the surface extrapolation technique for fatigue analysis of welded components were made by Niemi *et al*. (2003).

However, little research has been conducted on the application of the hot spot stress approach to fatigue damage evaluation and life prediction of large-scale welded steel structures, especially for cable-supported steel bridge fatigue evaluation (Chan *et al.*, 2005). In this paper, a study of using long-term monitoring data and the hot spot stress approach for fatigue life evaluation of a suspension steel bridge installed with a long-term SHM system is addressed. Both the global FEM of the bridge and the local FEM for typical welded connections are first developed using the general-purpose commercial software ABAQUS. Hot spot stresses and SCFs at failure-critical locations are calculated by means of the surface extrapolation technique with FEM analysis. The hot spot stress approach is then applied to evaluate the fatigue life of welded details by using strain measurement data from the long-term monitoring system. The fatigue assessment results obtained by the hot spot stress approach are also compared with those obtained by the nominal stress approach.

SHM SYSTEM AND MEASUREMENT DATA

The Tsing Ma Bridge (TMB), with a main span of 1377 m and total span of 2.2 km, is the longest suspension bridge in the world carrying both highway and railway traffic. It forms a key part of the most essential transportation network linking the Hong Kong International Airport to the urban areas. After completing the bridge construction, a sophisticated long-term SHM system has been devised by the Highways Department of the Hong Kong SAR Government to monitor and evaluate the structural health and performance of the TMB and other two cable-stayed bridges (Wong, 2004). As part of this monitoring system, 110 strain gauges were installed to measure strains at bridge-deck sections as shown in Figure 1. Most strain gauges are attached to the fatigue-critical portions which were identified during the design of the monitoring system.

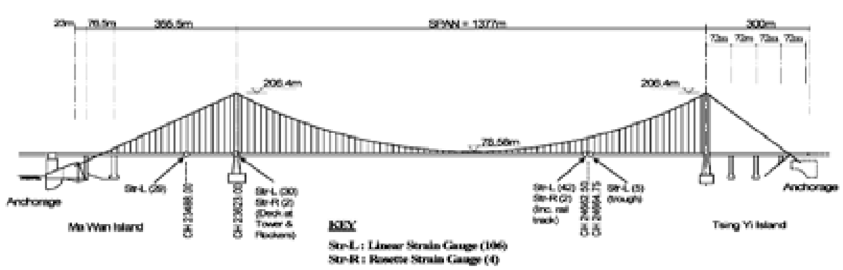


Figure 1 Layout of strain gauges on TMB

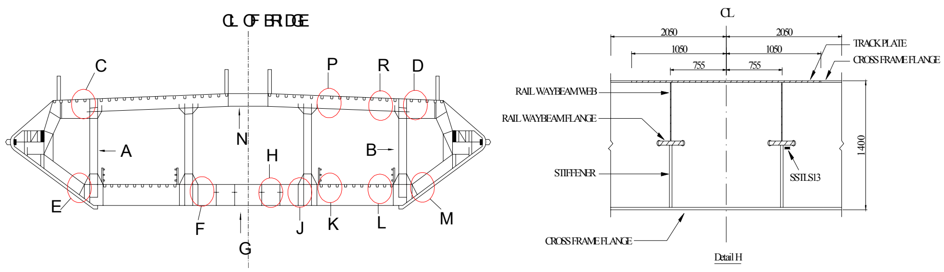


Figure 2 Location of strain gauge SSTLS13 on deck section CH24662.50

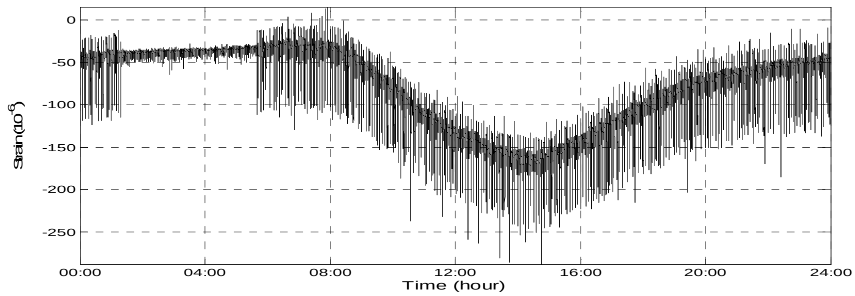


Figure 3 Measured strain time history on September 24, 1999

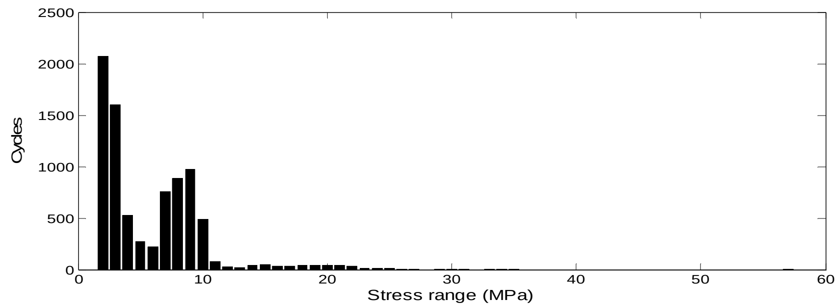


Figure 4 Stress spectrum on September 24, 1999

Strain gauge SSTLS13 is installed under the bottom flange of the railway beam which is made up of two inverted T-beams welded to top flange plate, as shown in detail on H of Figure 2. The strain data are recorded continuously at the sample frequency of 51.2 Hz. The measurement data in the year of 1999 obtained from this strain gauge are selected for fatigue life assessment. Typical daily strain time history data measured by strain gauge SSTLS13 are shown in Figure 3.

FATIGUE LIFE ASSESSMENT BASED ON BS5400

Once a day a strain time history data recorded by strain gauge SSTLS13 are available, the stress time history at the same location can be obtained by simply multiplying the measured strain by the Young's modulus of steel since the strain is elastic. After finding peaks and valleys in the stress time history, the rainflow counting algorithm is applied to obtain a daily stress spectrum. The daily stress spectrum on September 24, 1999 is illustrated in Figure 4.

BS5400 Part 10 (BSI, 1980) is a commonly adopted standard for bridge design, which specifies methods for fatigue assessment. TMB was designed according to this standard. Therefore, the fatigue life evaluation will also be carried out based on BS5400 Part 10. According to the Palmgren-Miner rule, the cumulative fatigue damage in a structural component can be expressed by the Miner's summation as

$$\sum_{i=1}^{n} \frac{n_i}{N_i} = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_n}{N_n} \tag{1}$$

where n_i is the specified number of cycles for the ith stress range and N_i is the corresponding number of cycles of failure for the same stress range. In the present study, n_i is obtained by rainflow counting of the strain measurement data, while N_i is determined using the *S*-*N* relationship which is expressed as

$$N \times S^m = K_0 \times \Delta^d \tag{2}$$

where N is the predicted number of cycles of failure for a stress range S; K_0, Δ, m and d are constant parameters. When the class of the detail and the failure probability are determined, all the parameters can be obtained from the specification (BSI, 1980), and thus an *S*-*N* curve is obtained from Eq. (2).

The fatigue life F, in the number of years, is evaluated by the formula

$$F = \frac{1}{365 \times \sum_{i=1}^{n} \frac{\lambda_i n_i}{N_i}} \tag{3}$$

where λ_i is the reducing factor defined as

$$\lambda_i = \begin{cases} (S/S_0)^2 & \text{if } S < S_0 \\ 1 & \text{if } S \geq S_0 \end{cases} \tag{4}$$

where S_0 is the constant amplitude non-propagating stress range (BSI, 1980).

According to the specification (BSI, 1980), the welded joint near strain gauge SSTLS13 is categorized as group F_2, and therefore the parameters K_0, Δ, m and S_0 are determined as: K_0 = 1.23×10^{12}, Δ = 0.592, m = 3.0, S_0 = 35 MPa. The probability factor is assumed as d = 2 which corresponds to the failure probability of 2.3% and the standard *S*-*N* design curve (BSI, 1980). With these parameters and the daily stress spectrum, the fatigue life can be estimated using Eq. (3) and the measurement strain data (Ni *et al.*, 2006).

HOT SPOT STRESS APPROACH FOR FATIGUE LIFE ASEESSMENT

Global FEM Analysis of TMB

A global 3D FEM of TMB is established by using the general-purpose commercial software ABAQUS as shown in Figure 5. The beam and shell elements in the ABAQUS element library are selected to model the structural components in the bridge. More than 7,375 nodes and 17,677 elements are contained in the global FEM.

Owing to the variation of traffic flow, vehicle types, and the vehicles' lateral positions, etc., it is very complicated to apply the exact traffic loading on the bridge. In this study, the main objective of global FEM analysis is to provide effective justification of the boundary condition determination of the local FEM of TMB, which will be described later in this paper. A relative simple highway and railway traffic loading condition is applied on the deck and rail of TMB, with the load amplitudes for the deck and rail being 10KPa and 10KN/m, respectively, as shown in Figure 6. The displacement and stress response of the whole bridge can be obtained directly. Figure 7 shows the node arrangement in the frameworks on the left and right sides of CH24662.50 section. The maximum node displacements are 0.02864 m at nodes 14663 and 14664 on the left side of CH24662.50 section and 0.02908 m at nodes 14683 and 14684 on the right side of CH24662.50 section. The difference of the maximum node displacement between the two sides is only 0.00091 m. As a result, it can be assumed that there is no relative displacement existing between the left and right sides of CH24662.50 section.

Local FEM Analysis of Typical Welded Joint

After verification analysis of the response determined from the global FEM of TMB, a 3D FEM of typical welded connections extracted from CH24662.50 section where strain gauge SSTLS13 is attached under the bottom flange of the railway beam of TMB is developed, as shown in Figure 8. There are more than 183,040 nodes and 136,218 elements in this local FEM. Figure 9 shows the dimension of the typical welded joint of the local FEM, the weld is simply modeled as triangle and the weld thickness and weld angle are 6 mm and 45^0, respectively. A relatively fine grid is used for the weld seam where the stress concentration zone with a high stress gradient exists, and a coarse grid is used for the zone where stresses are relatively uniform. For the purpose of finding a compromise between the refinement of the meshing and the size in degrees of freedom of the model, 8-node reduced integration continuum element is used to model the plate and weld. The Young's modulus is 205 GPa and the Poisson's ratio is 0.3. The left and right sides of the model are fixed and 1 MPa axial force is imposed on the partial surface of the upper horizontal plate.

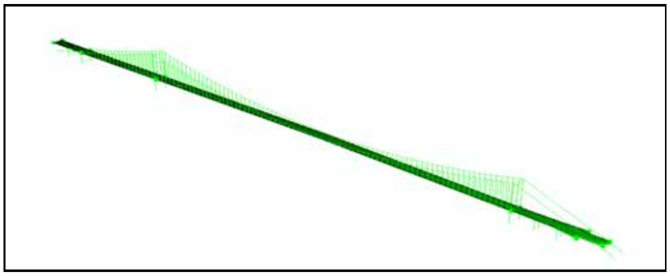


Figure 5 3D FEM of TMB

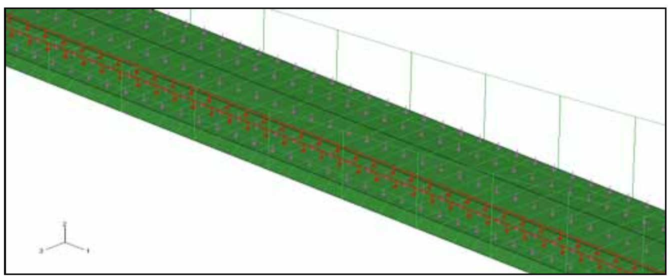


Figure 6 Load applied on the deck and rail of TMB

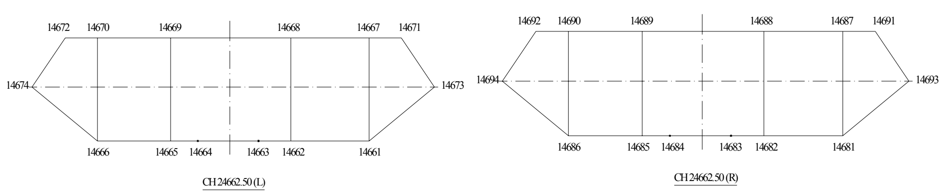


Figure 7 Node arrangement in the frameworks of CH24662.50 section

Hot Spot Stress Determination

In fatigue evaluation of a complex bridge structure, stress ranges at fatigue-prone structural details should be determined as accurately as possible, because the real stress at the weld toe near the strain gauge, which is called hot spot stress, may be much higher than the stress at the location of the strain gauge that is named nominal stress. Hot spot stress, σ_{hs}, can be calculated by multiplying the nominal stress, σ_{nom}, by a SCF, according to Eq. (5), is the value of the structural stress at the hot spot usually located at a weld toe where the crack is expected to occur.

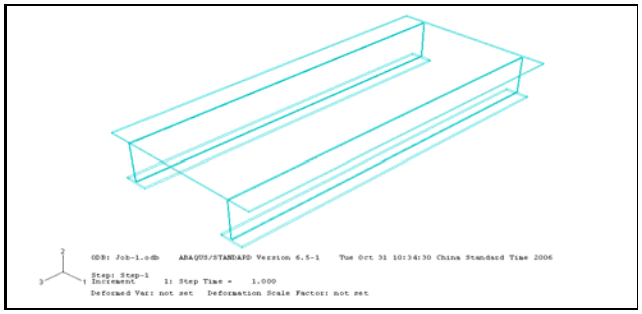
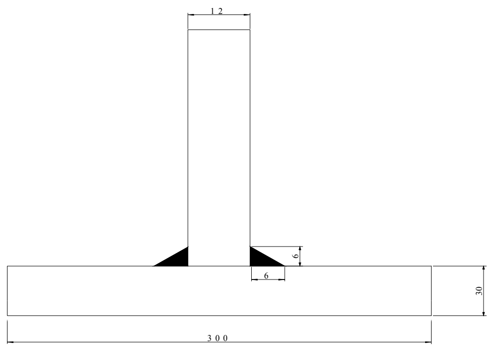


Figure 8 3D local FEM of TMB



(Unit: mm)
Figure 9 Dimension of typical welded joint of TMB

$$\sigma_{hs} = SCF \times \sigma_{nom} \tag{5}$$

The actual value for hot spot stress cannot be determined easily and accurately. It can be estimated through an extrapolation of the stresses at adjacent points where the stresses can be determined easily. Numerous research efforts have addressed hot spot stress evaluation. Many proposals given are based on the surface extrapolation technique and fewer on other techniques.

The traditional way of the surface extrapolation is the linear or quadratic extrapolation over two or three reference points using the stresses along the free surface of a structure, as shown in Figure 10. Extrapolation points are located in front of a weld toe at distances that are defined according to the plate thickness, T. Among the various extrapolation procedures proposed in the public literature, a typical one is based on a linear extrapolation from stress values at both $0.4T$ and $1.0T$ distances from the weld toe (Niemi *et al.*, 2003). The hot spot stress is suggested to be calculated by the formula

$$\sigma_{hs} = 1.67\sigma_{0.4T} - 0.67\sigma_{1.0T} \tag{6}$$

where $\sigma_{0.4T}$ and $\sigma_{1.0T}$ are the stress values at both $0.4T$ and $1.0T$ distances away from the weld toe. During the finite element analysis, the meshes should be generated finely around the region with these two points included. The SCF for the welded joint can be determined using Eqs. (5) and (6) which is 1.393 in this study.

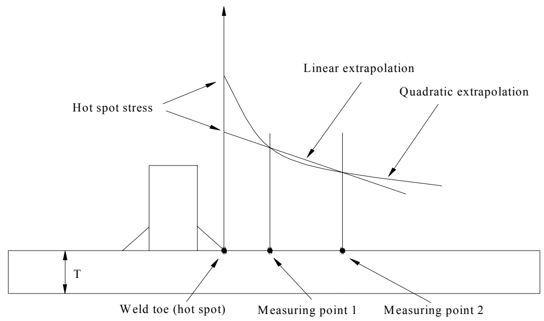


Figure 10 Surface extrapolation technique for stress determination

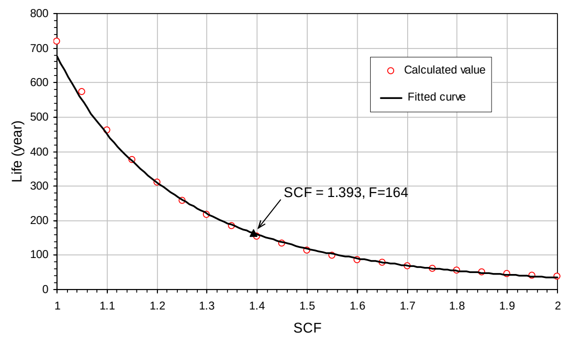


Figure 11 Influence of SCF on fatigue life

Hot Spot Stress Approach for Fatigue Life Assessment

In the SHM system of TMB, a distance between the location of the strain gauge and the welded joint exists. Thus, SCF should be taken into consideration for fatigue life evaluation. Figure 11 shows the calculated results of the fatigue life of the detail near strain gauge SSTLS13 when taking into account SCF from 1.0 to 2.0 with an interval of 0.05. It can be observed that the fatigue life is fitted well as a power function and is very sensitive to the value of SCF, and the introduction of SCF leads to a significant reduction of the calculated fatigue life. For the detail in concern, the value of SCF is 1.393 and the predicted fatigue life is 164 years which is much less than 718 years when SCF is equal to 1.0. It shows that the fatigue life is reduced by 77% if taking the stress concentration phenomenon into consideration. Therefore, it is more reasonable and reliable to use the hot spot stress for fatigue life assessment than the nominal stress when there exists a distance between the location of the strain gauge and the welded joint.

CONCLUSIONS

A study of using long-term monitoring data and the hot spot stress approach for fatigue life assessment of a suspension steel bridge installed with a long-term SHM system has been addressed. Hot spot stresses and SCFs at failure-critical locations are calculated by means of the surface extrapolation technique with FEM analysis. The hot spot stress approach is then applied to evaluate the fatigue life of welded details by using strain measurement data from the long-term monitoring system. The fatigue life predicted using the hot spot stress approach is much less than that obtained using the nominal stress approach. This is due to the fact that the hot spot stress approach takes into consideration the critical fatigue locations where the fatigue cracks are most likely to occur. The hot spot stress approach is more accurate and reliable than the nominal stress approach for fatigue life prediction of complex welded joints using monitoring data, when there exists a distance between the location of the strain gauge and the welded joint.

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