Consideration for a Proper Stress Definition in Fatigue Analysis of Welded Structures

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ABSTRACT At present, fatigue design of welded structures is primarily based on nominal stress or hot spot stress approach with a series of classified weld S-N curves. However, these methods are known to possess drawbacks, such as difficulty associated with defining proper nominal stress and the finite element size sensitivity etc. Recently, a mesh-size insensitive structural stress definition is proposed by Battelle that gives a stress state at weld toe with relatively large mesh size. The structural stress definition is based on the elementary structural mechanics theory and provides an effective measure of a stress state in front of weld toe. As an experimental validation of the structural stress method in obtaining the fatigue strength of weldments, a series of experiment is carried out for various sizes of weldments. Based on the result from this study, it is expected to develop a more precise fatigue strength evaluation technique and to save time period required in the fatigue design of ship and offshore structures.

1. Introduction

Common practice for a fatigue design of welded structures is primarily based on a nominal stress or hot spot stress approach with a series of classified weld S-N curves. Although well accepted by major industries, the nominal stress based fatigue design approach is cumbersome in terms of securing a series of S-N curves corresponding to each class of joint types and loading modes. Moreover, it is very difficult, if not impossible, to determine the nominal stress at each structural components, particularly in complex ship structures. The hot spot stress based fatigue design is based on the stress at the weld toes obtained by linear or quadratic extrapolation of stresses over 2 or 3 points in front of the weld toe. However, this method is known to be sensitive to finite element size. On the other hand, a mesh-size insensitive structural stress definition (structural stress method) is recently proposed that gives a stress state at weld toe with a relatively large mesh size. The structural stress definition is based on the elementary structural mechanics theory and provides an effective measure of a stress state in front of the weld toe. In this study, a series of experiment is carried out for various sizes of weldments as an experimental validation of the structural stress method in obtaining the fatigue strength of welded structures. A total of twelve specimen edge details are fabricated in duplicates as shown in Fig.1. The stress distribution at both edge sides are measured using strain gauges placed in a specified distance from the edge. Both hot spot stress and structural stresses are calculated using the stress measurements, and the measurement values are compared to those of calculated values using finite element analyses. Then, a fully reversed fatigue tests were carried out in order to find the fatigue life of each specimen. The propagation of the crack was recorded at every 5000 cycles for each specimen, while the stiffness defined as the ratio of load divided by displacement was recorded as well. Finally, typical fracture surface of failed specimen are observed. Based on the result from this study, it is expected to develop a more precise fatigue strength evaluation technique and to save time period required in the fatigue design of ship and offshore structures.

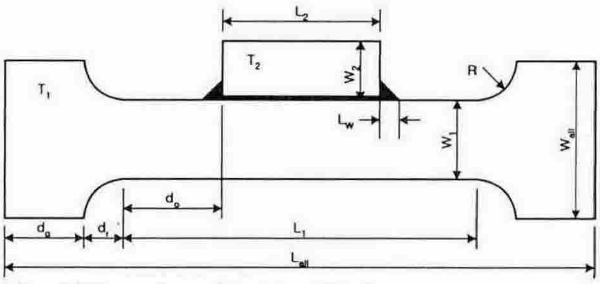

Fig. 1 Dimension of test specimen

2. Comparison of structural stress (SS) and hot spot stress (HSS) from the measurements

As discussed by Dong et al. [1], the membrane and bending components in the structural stress definition can be estimated by using a series of strain gauges on both top and bottom surfaces, as shown in Fig. 2 for a fillet weld. Then, the structural stress at the weld toe (A-A) can be estimated by using extrapolations with respect to bending stresses at B-B and C-C as:

$$\begin{aligned} \sigma_b &= \sigma_b^B + \frac{L}{l}(\sigma_b^C - \sigma_b^B) \\ \sigma_s &= \sigma_{Top}^B + \frac{L}{l}(\sigma_b^C - \sigma_b^B) \end{aligned} \quad (1)$$

In conjunction with fatigue testing of edge details, detailed strain gauge measurements are collected before starting fatigue test. The strain gauge readings were collected at two loading levels: 20% and 50% of nominal yield strength of the base metal. The strain gauge measurements obtained from the strain gauge pairs located both at the top and bottom edges of the specimens were used to calculate the structural stress by means of Eq. (1).

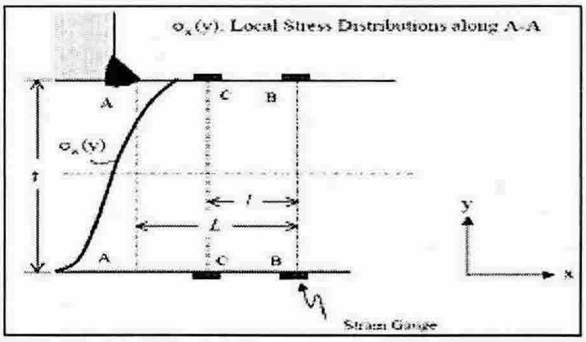

Fig. 2 Illustration of structural stress measurement

Hot spot stress is the most common to evaluate the fatigue strength in ship structures because it includes the stress concentration due to the geometric shape. While there are three different stress extrapolation techniques as commonly recommended procedures for the calculation of hot spot stresses in welded structures, the linear extrapolation of stress over reference points at 0.5 and 1.5 of plate thickness away from the hot spot is used in this study based on Eq. (2):

$$\sigma_{HS} = 1.5\sigma_1 - 0.5\sigma_2 \qquad (2)$$

where σ_1 and σ_2 are measured stresses at 5mm and 15mm respectively. These hot spot stresses are used for comparison purpose with structural stress in this study. Average stress values measured at distances of 5mm and 15mm from both sides of weld toe are used to obtain hot spot stress.

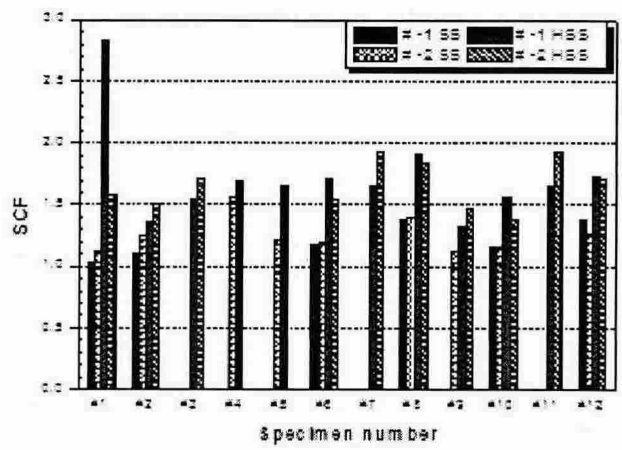

Fig. 3 Stress concentration of each specimen using structural stress (SS) and hot spot stress (HSS)

Fig. 3 illustrates the structural stress results based on the strain gauge measurements for each given strain gauge pairs located both at the top and bottom edges of the specimens by means of Eq. (1) and the hot spot stress obtained using Eq. (2) for the entire specimen. Here three pairs of strain gauges are used to measure the top and bottom stress distribution in the vicinity of weld toe. It is observed that hot spot stress values are typically higher than structural stress values, and in general, higher stress concentration values are obtained as the length of gusset plates increases. Note that the structural stress values using any combination of measurements 2, 3 and 4 show good agreement. It is found that the edge details design reflects different stress concentrations with respect to various gusset lengths in an effective manner.

3. S-N data correlation

This section presents the S-N data obtained from the fatigue test. Fig. 4 illustrates the fatigue life of each specimen with respect to nominal stress vs. fatigue life.

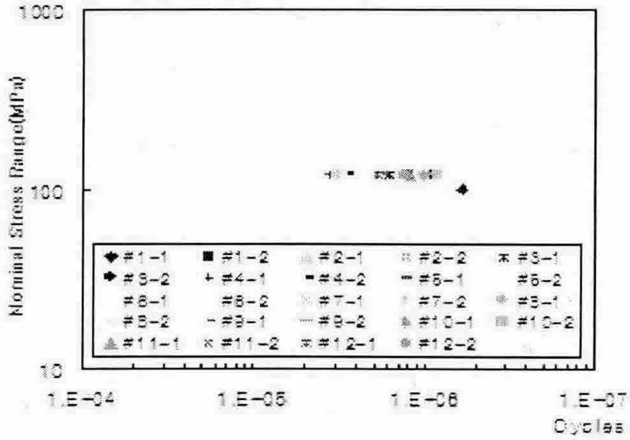

Fig. 4 S-N curve using nominal stress vs. life

Fig.5 shows the fatigue life of tested specimens with respect to hot spot stress vs. fatigue life. No significant consolidation is observed.

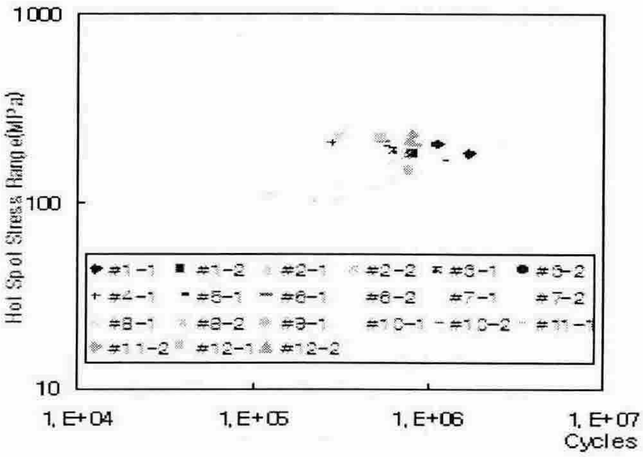

Fig. 5 S-N curve using hot spot stress vs. life

An equivalent structural stress can be defined by normalizing the structural stress range with two variables expressed in terms of the thickness (t) and the loading mode(r) as follows [1]:

$$\Delta S = \frac{\Delta\sigma}{t^{\frac{2-m}{2m}} I(r)^{\frac{1}{m}}} \qquad (3)$$

where $r=\sigma_b/\sigma_s$ and $m=3.6$. As the effect of the thickness term and the bending ratio are considered using Eq. (3), S-N curve shows an improved correlation, and all data essentially gathered into a single narrow band, as shown in Fig.6.

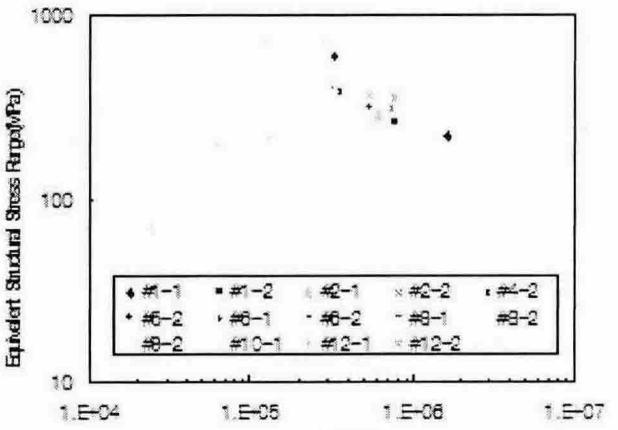

Fig. 6 S-N curve using equivalent structural stress with thickness correction vs. life

A massive amount of welds S-N data (over 2000 fatigue tests) from both literature and well-documented lab reports have been analyzed in the Battelle structural stress JIP [3]. With the equivalent structural stress range parameter as a basis, all data points obtained from this study is inserted into the comprehensive JIP database for all small details to verify if the data belong to the same master S-N curve, as shown in Fig. 7.

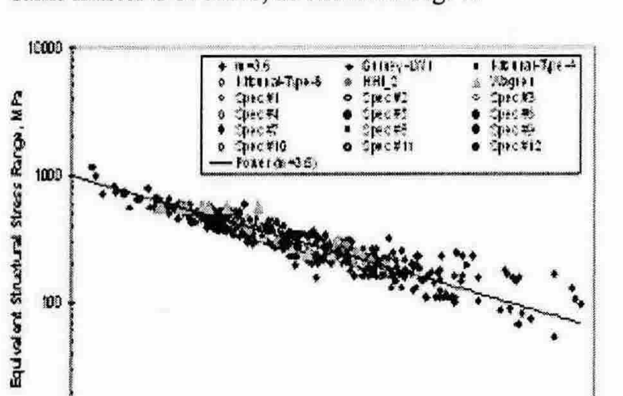

Fig. 7 Correlation of all edge details with other small details using the equivalent structural stress range parameter

The agreement is evident, clearly demonstrating the transferability of the S-N data once expressed in the form of the equivalent structural stress parameter. The presence of the master S-N curve resulting from the present structural stress method implies not only the improved life predictability (the data from one set of tests can be used to predict others), but also data transferability (from simple joints to structures).

4. SUMMARY

In this study an experimental structural stress measurement technique is investigated. The measurement techniques are based on a series of strain gauge pairs placed on both sides of a specimen thickness in the vicinity of weld toes to resolve both membrane and bending stress components. Based on the results obtained from this study following conclusions are drawn.

1) Consistent structural stress values can be obtained experimentally using stress measurements in proper distance. Stress values obtained using linear regression are used to calculate structural stresses to minimize the fluctuation from experiments.

2) Stress concentration increases when plate width and/or gusset length increases. However, stress concentration decreases as plate thickness increases, and the wider the base plate, the final life gets shorter.

3) Both hot spot stress and structural stress can be successfully obtained from the experiment. Structural stress values calculated result in lower stress value than those of hot spot stress.

4) Hot spot stress vs. life shows good consolidation between similar types of edge detail specimens. However, hot spot stress vs. life cannot show further consolidation with those of different types/thickness of specimens.

5) Structural stress with thickness correction vs. life shows good consolidation between edge detail test results and other edge details. Equivalent structural stress vs. life for edge details exhibit consolidated band.

References

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