

Fatigue Evaluation of Notched Plate Specimens by the Battelle Structural Stress Method

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ABSTRACT

In this paper, the applicability of the finite element-based, mesh insensitive Battelle structural stress method is demonstrated for fatigue life predictions of notched specimens (non-welded) with different specimen types, and notch shapes. Well-documented notch fatigue data were analyzed using the Battelle structural stress fatigue evaluation procedure, including notched plate fatigue data for steel and aluminum alloys.

The effectiveness of the Battelle structural stress procedure has been demonstrated in a series of earlier publications for welded structures with different joint types, plate thicknesses, and loading modes. Here, a similar Battelle structural stress procedure suitable for finite element modeling and service life simulations is proposed for structures with notches. Unlike weld fatigue data, the crack propagation portion of the fatigue life associated with a notch does not always dominant the total number of cycles to failure. It depends on the stress state at the notch tip. Also, mean stress effects can be seen clearly in S-N curves for notched fatigue data.

Based on the characteristics of the notch stress, a structural stress calculation procedure for notched plates is proposed. A characteristic ligament size is introduced for the equivalent structural stress range calculation. It is found that fatigue test data for notched specimens can be effectively collapsed onto a single master S-N curve regardless of notch geometry, notch stress concentration factor, and mean stress. The proposed procedure can be utilized for fatigue life predictions of notched plates.

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INTRODUCTION

Notched components (non-welded) are widely used in various industries especially automotive and aerospace industries. Fatigue life evaluation of a component becomes complicated by the presence of geometrical discontinuities such as notches and geometrical changes which cause stress concentrations.

Fatigue characteristics of notches and welds can be schematically compared as indicated below.

In a non-welded smooth plate specimen, a major portion of the total fatigue life is spent initiating a crack and a smaller proportion of the total life is spent propagating the crack through the structure. However, in welded components, the majority of the total fatigue life is spent propagating the crack because crack like anomalies in welds often become crack initiation sites and reduce the fatigue life of welded joints. The consequences of this difference in fatigue behavior are shown in Fig. 1. For a notched specimen, the fatigue behavior is located between those of smooth specimens and welded specimens, and varies depending on notch shape and location.

Notch-induced fatigue behavior has been investigated in terms of fatigue crack initiation and propagation by considering material behavior at a notch tip [e.g. 1,2,3,4]. One of the traditional solutions is based on geometric elastic stress concentration factor, K_t [1-2]. The solutions using K_t have demonstrated their effectiveness in estimating initiation based fatigue lives.

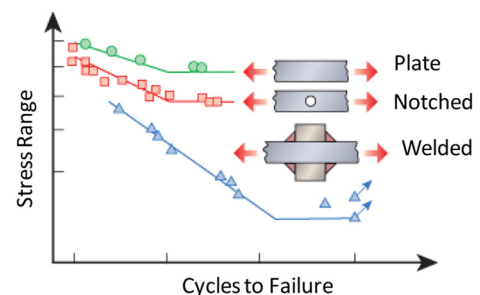


Figure 1. Effect of plate, notched, and welded components on fatigue life

In this paper, the Battelle structural stress method is applied to evaluate fatigue behavior of non-welded notched plates. A mesh-insensitive Battelle structural stress method has been developed and has been proven to be highly effective in correlating fatigue behavior of welded joints by Battelle researchers [5,6,7,8,9,10]. This procedure has been adopted by design codes for weld fatigue, e.g., ASME Sec. VIII Div.2 and API 579/ASME FFS-1 in 2007 [11-12]. The details of the method and its validation for applications including automotive, heavy equipment, offshore/marine structures, etc. can be found in [8, 9, 13, 14, 15, 16, 17, 18].

Examinations of notched plate fatigue experiment data in the literature [19,20,21] clearly show that the fatigue behavior depends on the elastic stress concentration at notch, K_t and the mean stress.

A two-stage crack growth law has been developed to model fatigue behavior (see the details in [22]). It includes a characteristic ligament size, l_c to capture the notch stress concentration effect. In the model, a “structural stress” acting along the characteristic ligament is calculated using a series of equations that satisfy force/moment equilibrium and continuity conditions. The structural stress effectively consolidates fatigue test data for notched specimens within a small scatter band regardless of notch stress concentration factor, K_t .

The mean stress effect can be incorporated into the two-stage model by introducing a ΔK^* parameter from fracture mechanics [23-24]. When the ΔK^* parameter is applied an equivalent structural stress fatigue parameter that expresses the effect of mean stresses as a function of load ratio, R , which is defined as the ratio of minimum applied load to the maximum applied load.

When the proposed structural stress calculation procedure is applied to notched plate specimens, fatigue test data can be effectively consolidated onto a single S-N curve regardless of notch stress concentration factor, K_t , load ratio, R , and specimen type.

BATTELLE STRUCTURAL STRESS METHOD PROCEDURE

The Battelle structural stress method has been documented extensively [5,6,7,8,9,10]. It is based on an equilibrium-equivalent decomposition of an arbitrary through-thickness stress state at the location of interest such as geometric notch (weld toe in Fig. 2a) into the equilibrium-equivalent structural stress part (Fig. 2b) and a self-equilibrating notch stress part (Fig. 2c). The structural stress part is characterized as

$$\sigma_s = \sigma_m + \sigma_b \quad (1)$$

which represents a simple stress state in the form of membrane and bending components that satisfies the equilibrium conditions with external loading at the location of interest. To achieve mesh-insensitivity for welded joints

within the context of displacement based FE methods, the equilibrium agreements can be most effectively implemented by using balanced nodal forces and moments in shell, plate, and 3D solid FE models for any arbitrary weld geometry. The detail formulation, calculation procedures, as well as calculation examples are given in previous publications [5,6,7,8,9,10].

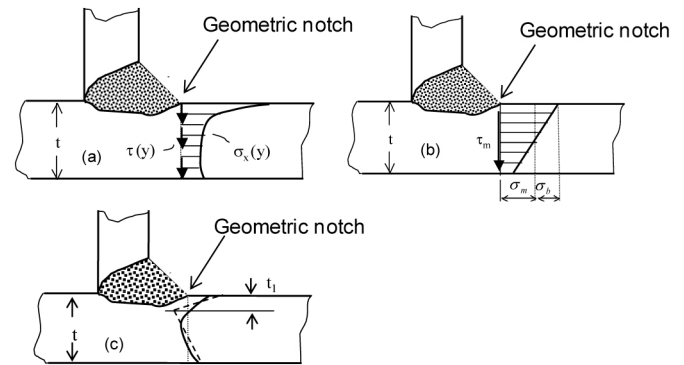


Figure 2. Through-thickness structural stress definition: (a) Local stresses from FE model; (b) Structural stress or far-field stress; (c) Self-equilibrating stress

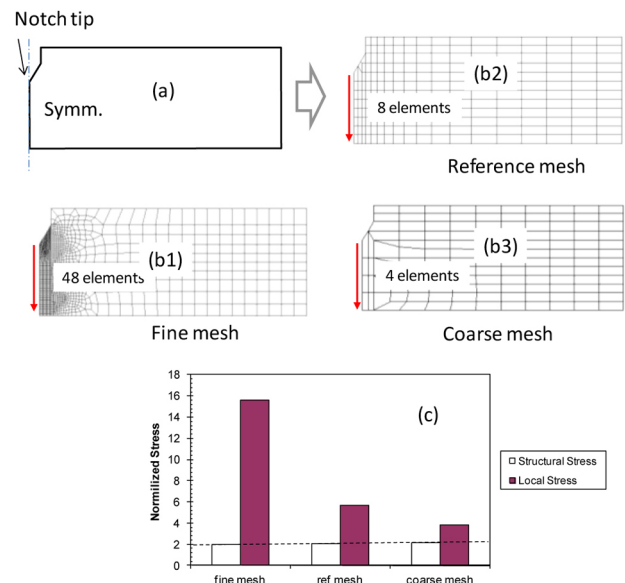


Figure 3. Mesh-insensitivity demonstration for calculating structural stress at notch tip: (a) Model definition; Simple sharp notch under tension loading; (b) Representative FE models with: fine mesh (b1), reference mesh (b2), and coarse mesh (b3); the arrows show the ligament extending from the notch tip. The numbers of element along the ligament for fine, reference, and coarse mesh are 48, 8, and 4, respectively, and (c) Comparison of calculated stresses at the notch tip between structural stress method and output of FE models

Fig. 3 shows a calculation example using a sharp notched plate under tension loading. Due to geometry symmetry, only one half models need to be analyzed. (Fig. 3a). Three different mesh densities were employed for the structural stress calculations along the ligament (indicated with an arrow); Figs. 3b1 to 3b3 show a refined mesh (48 elements along ligament), a reference mesh (8 elements along ligament), and a coarse mesh (4 elements along ligament). Fig. 3c shows that the structural stresses calculated at the notch tip are identical among the three FE models that have drastically different element sizes. However, the local stress values at the notch tip location, i.e., the direct output from the FE analysis, exhibit considerable dependency of element sizes.

OBSERVATION OF FATIGUE TEST DATA

Experimental fatigue test data generated by Battelle researchers in the 1950s [19,20,21] were evaluated. These data provided two relatively complete series of data comprising a significant range of stress concentration factors, K_t , and mean stresses, σ_{mean} . The mean stresses were converted to R ratios.

Double notched specimens (DNS) made of SAE 4130 steel notched plate ($\sigma_y = 680$ MPa and $\sigma_{ult} = 810$ MPa) under cyclic tension loading were selected to observe the characteristics of notch fatigue behavior.

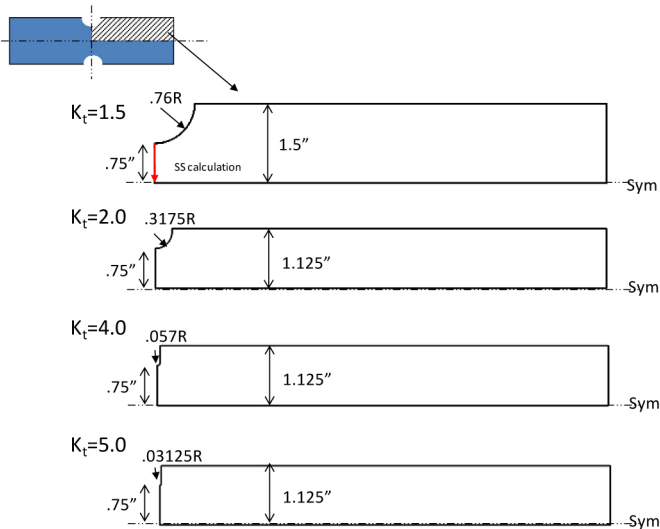


Figure 4. Dimensions of double notched specimens (DNS) with various K_t ($K_t=1.5, 2, 4$, and 5) of SAE 4130 steel notched plate

The specimen geometry information can be seen in Fig. 4. Four different notch shapes, with different notch stress concentration factors, $K_t = 1.5, 2, 4$, and 5 were used in this investigation. Due to loading and geometry symmetry, only one-quarter models were necessary for the FE analyses. The plate thickness, t and the ligament size, l are 0.075 inch

(1.905 mm) and 0.75 inch (19.05 mm) due to symmetry condition, respectively.

Fig. 5 shows the fatigue test results for SAE 4130 steel notched plates based on nominal stress range [19,20,21]. Here the nominal stress is defined as far-field loading over net the area at notch tip along the ligament. It is well known that the mean stress affects the fatigue behavior of non-welded materials. Four different mean levels were tested with $\sigma_{mean} = 0, 10, 20$, and 30 Ksi, i.e., $0, 68.95, 137.90$, and 206.85 MPa. From the fatigue results, the effect of the notch stress concentration and the mean stress effect can be observed as anticipated. When K_t becomes higher, the mean stress effect becomes clear - for the same K_t , increasing the mean stress shortens the fatigue life.

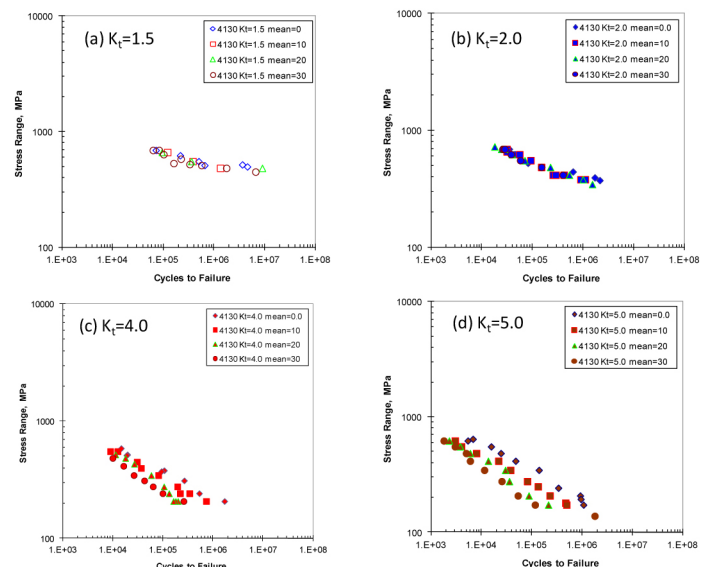


Figure 5. Fatigue test results of SAE 4130 steel double notched plate specimens with various K_t and different mean stress levels ($\sigma_{mean} = 0, 10, 20$, and 30 Ksi) [19,20,21]; (a) $K_t=1.5$, (b) $K_t=2$, (c) $K_t=4$, (d) $K_t=5$

Fig. 6 shows the fatigue test results for the same mean stress level ($\sigma_{mean} = 0$, i.e., $R = -1$) and various K_t values for SAE 4130 steel notched plates [19,20,21].

In the figure, it is apparent that the data consolidate into two groups, namely a high K_t (4 and 5) group and a low K_t (1.5 and 2) group with the following characteristics: the high K_t data have shorter lives than the low K_t data, the high K_t data have a steeper slope than the low K_t data, and as a group the high K_t data consolidate more closely than the low K_t data.

From Lazzarin et al. [25]'s fatigue test results, it is observed that when the notch tip radius is very small, the propagation phase becomes much more important. When K_t becomes low, the crack initiation life dominates the total failure life. However, as the notch tip becomes sharper, the