

Fatigue Life Assessment of Welded Structures with the Linear Traction Stress Analysis Approach

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ABSTRACT

Structural stress methods are now widely used in fatigue life assessment of welded structures and structures with stress concentrations. The structural stress concept is based on the assumption of a global stress distribution at critical locations such as weld toes or weld throats, and there are several variants of structural stress approaches available. In this paper, the linear traction stress approach, a nodal force based structural stress approach, is reviewed first. The linear traction stress approach offers a robust procedure for extracting linear traction stress components by post-processing the finite element analysis results at any given hypothetical crack location of interest. Pertinent concepts such as mesh-insensitivity, master S-N curve, fatigue crack initiation and growth mechanisms are also discussed. Then, fatigue life assessment of automotive exhaust systems is conducted and the data correlation with a recently developed equilibrium data analysis method is provided and compared. Finally, the needs for further development of more physically sound analysis approaches are indicated.

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INTRODUCTION

Durability and reliability performance is one of the most important concerns of ground vehicle systems as well as other engineering systems [1]. Great effort has been made to develop the ability to accurately and quickly predict the durability and reliability of the systems in the early development stage [2]. Like other subsystems in an automobile, the exhaust system experiences cyclic loadings due to road vibrations, leading to fatigue failure over time. Years of experience has shown that the prevailing failure modes in exhaust systems are cracked welds at joints between pipes and muffler/resonator/converter (360° welds), cracked hanger-to-pipe welds (line welds), and broken hanger rods [3]. Welded joints are usually the weakest point of an exhaust system and cracked welds include cracking of weld material and of base metals of hanger rods or pipes near the welds [3]. A reliable and validated analytical method to predict fatigue life is urgently needed to predict how and where a welded

part will perform in regards to failure life, while the iterative testing is expensive and time consuming.

In fatigue analysis, the traditional nominal stress concept is still widely used [4]. Nominal stress is the stress calculated in the sectional area under consideration, disregarding the local stress raising of the structural detail, i.e. the stress increase due to the structural joint configuration as well as that of weld toe. The application of this concept requires the definition of the nominal stress as well its permissible value with reference to a corresponding classified structural detail. However, in case of more complex structural details, to which neither a nominal stress nor a design category can be assigned, the nominal concept is not applicable, and hot spot structural stress and many other structural stress methods have been developed for this purpose [4]. The hot spot stress is determined by the linear or nonlinear extrapolation of measured surface stresses to the critical locations such as weld toe. The hot spot stress and many other structural stress

concepts have some limitations, especially for complex welded structures [4].

An alternative node force based linear traction stress procedure has been developed by Dong et al [5, 6]. It has demonstrated its promise in a consistent characterization of stress concentration effects at weld toe while achieving a good mesh-size and element-type insensitivity for continuous welds. Subsequently, for fatigue life assessment, a master S-N curve approach based on fatigue crack growth has been developed and it has been demonstrated that many fatigue test data can collapse onto a single curve [7,8,9]. It should be noted that the similar nodal force approach has been proposed by Fermer et al.[10]. The traction stress approach has been included in a fitness-for-service standard produced jointly by the American Petroleum Institute and ASME titled API579-1/ASME FFS-1 Fitness-For-Service [11], and adopted by ASME Boiler and Pressure Vessel Codes as an alternative means for predicting fatigue life [12].

The linear traction stress method has been used at Tenneco Automotive to predict fatigue life under given load conditions and to predict a load limit for a design under certain fatigue life requirement [13], and some preliminary research work has been reported in a previous SAE conference [14]. In this paper a more detailed analysis is conducted with emphasis on the application scope of the linear traction stress method and related data correlation.

LINEAR TRACTION STRESS AND MASTER S-N CURVE

The linear traction stress approach is based on a linearization of the stress distribution across the plate thickness and along the anticipated crack path [5,6,7,8,9,10]. Using such a stress procedure, the traction stress should be calculated at a location of interest (such as at weld toe) and normal to fatigue crack plane. The distribution of a stress component through thickness can be decomposed into membrane (average value) stress σ_m , bending stress (a linearly varying term) σ_b , and nonlinear self-equilibrating remainder, and the sum of the first two terms $\sigma_s = \sigma_m + \sigma_b$, can be used, based on fracture mechanics, to derive the equivalent traction stress ΔS_s , which will serve as a fatigue damage parameter. This decomposition applies to both normal stress and shear stress components. The basic equations used to calculate the traction based stresses are listed below.

$$\sigma_s = \sigma_m + \sigma_b = \frac{f_y}{t} + \frac{6m_x}{t^2} \quad (1)$$

$$\Delta S_s = \frac{\Delta \sigma_s}{t^{2m} I(r)^{\frac{1}{m}}} \quad (2)$$

$$I(r) = \int_{a/t \rightarrow 0}^{a/t=1} \frac{d(a/t)}{(M_{kn})^n [g_m(a/t) - r(g_m(a/t) - g_b(a/t))]^m} \quad (3)$$

$$r = \frac{|\sigma_m|}{|\sigma_m + \sigma_b|} \quad (4)$$

Where f_y , and m_x , are, respectively, the nodal force and moment at a node along a specific weld line; t is the wall thickness of a plate; r is the ratio of bending stress over the sum of bending and membrane stresses; m is the fatigue crack growth exponent (for steel, $m=3.6$), and n is a small crack growth related parameter (for steel, $n=2.0$); $I(r)$ is a dimensionless parameter derived from fracture mechanics consideration; M_{kn} is the short crack growth factor, and g is a specially defined function [5,6,7,8,9]. Stress has to be converted to stress range before assessing fatigue life.

From Eq.(1), Eq.(2), Eq.(3), Eq.(4) it is clear that the traction stress is extracted directly from nodal forces and moments, which are governed by global force and moment equilibriums, and accurate in terms of displacement-based finite element method. Therefore, the membrane and bending stress components to be used are averaged values at the stress evaluation plane such that a more refined finite element mesh would not change either the membrane or the bending values of the stress components significantly. The mesh insensitivity of traction stress to local mesh refinements has been demonstrated [5,6,7,8,9], as long as the overall geometry is properly modeled and a curve representing a weld line is adequately continuous along weld direction at the weld toe [15]. A weld can be classified as a closed weld or as an open weld. A closed weld starts and ends at the same location while an open weld starts and ends at different locations, and they are treated differently. Open welds can present a difficult analysis because the stress affecting the weld extends beyond and around the weld end. In addition, open welds require the use of a virtual node correction at the end of the weld to account for geometric inconsistencies that causes high stress gradients at the weld end [15].

As a simple fatigue damage parameter, the traction-based equivalent stress range has been found to be consistent in correlating fatigue life of welded structures with various geometries, thickness, and loading conditions by collapsing all data onto a master S-N curve, shown in Fig.1, which is proven to be very useful in fatigue design. The master S-N curve is built upon more than 900 individual test points representing many different test configurations and notch classes of steels [7]. The minus and plus shown in Fig.1 represent the left shift and right shift from the mean curve, respectively, and STD stands for standard deviation.

Multiaxial stress is always present in a component under complex loading or with complex geometrical configuration or both. Thus, the multiaxial effect on fatigue life should be properly considered. There are three stress components

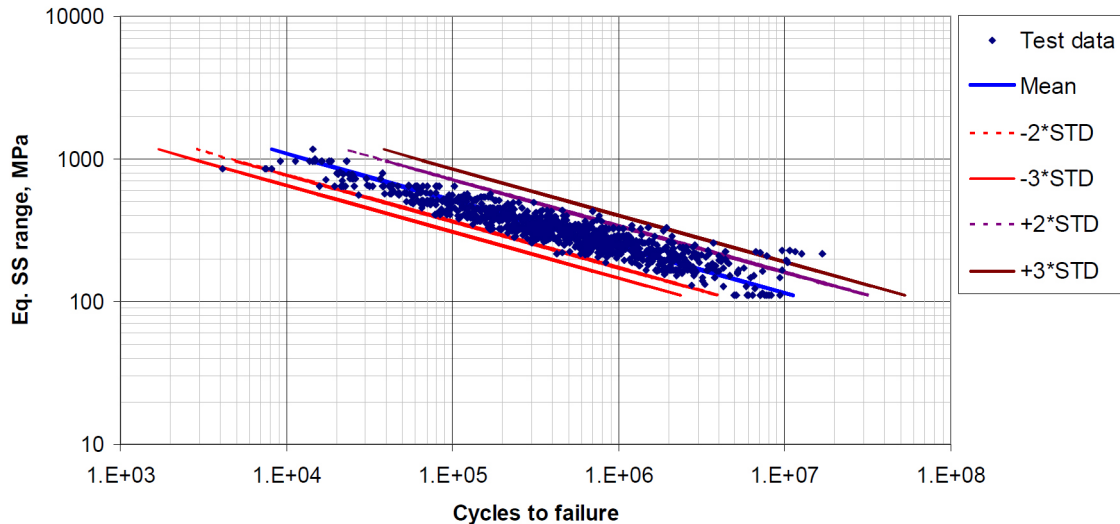


Fig.1. Master S-N curve and the database used to build the S-N curve.

(normal, transverse, and in-plane shear stresses) acting on a hypothetical crack plane of a structure. In fracture mechanics context, these three stress components fully describe the crack driving forces in terms of Mode I, Mode-II, and Mode-III, respectively. In plate structures, transverse shear is typically negligible for most applications. For in-phase loading, the traction based effective structural stress range can be generally expressed as $\Delta\sigma_e = f(\Delta\sigma_s, \Delta\tau_s)$. Commonly used effective structural stress range definitions for in-phase loading are listed below [16]

$$\Delta\sigma_e = \sqrt{\Delta\sigma_s^2 + \beta\Delta\tau_s^2} \quad (5)$$

Where $\Delta\sigma_s$ is the normal stress range, $\Delta\tau_s$ is the shear stress range, and $\Delta\sigma_e$ is equivalent stress range. Values of $\beta = 3$ and $\beta = 4$ are analogous to the von Mises and Tresca stresses, respectively, and are often used. For a pair of normal and shear stress ranges, the difference between the von Mises and Tresca stress definitions is small. Therefore, both von Mises and Tresca-based stress range definitions are seen to be effective with the von Mises form in slightly better correlation with existing data [16]. The out-of-phase loading effect on fatigue life of ductile materials and related multi-axial cycle counting are much more complex and have been addressed by using a recently developed path-length dependent multi-axial cycle counting method and related fatigue life assessment methods [17,18,19]. The loading path-length in the stress space, which is expressed in Eq.(6), is defined as the new damage parameter for out-of-phase loading within a cycle.

$$\Delta\sigma_e = \int \sqrt{d\sigma_s^2 + \beta d\tau_s^2} \quad (6)$$

Eq.(6) can be reduced to Eq.(5) if in-phase loading is applied.

The master S-N curves can be obtained by direct statistical regression from available data with two parameters C and h with $N = C(\Delta S)^{-h}$ or $\Delta S = D(N)^{-1/h}$, where $h = m$ and $D = C^{1/h}$. h represents the inverse slope of the mean S-N curve of the data in log-log scale and D the intercept of the S-N curve on the stress range axis of the same curve. The standard deviation of test data can be expressed as

$$\sigma = \sqrt{\frac{\sum (\log_{10} N - \log_{10} \bar{N})^2}{n-2}} \quad \text{under the assumption of lognormal distribution with constant } \sigma \text{ over the whole interested cycle range. } n \text{ is the number of test data points. } -2\sigma, \text{ which corresponds to a 97.6\% probability of survival or 2.4\% of failure, are often used in the engineering designs [20].}$$

APPLICATION OF THE LINEAR TRACTION STRESS APPROACH TO WELDED STRUCTURES OF AUTOMOTIVE EXHAUST SYSTEMS

A total of five joint types tested at the development validation stage were analyzed and subsequently correlated to the master S-N curve shown in Fig.1: 3-ply (bushing) welds, flange-to-pipe welds, pipe-to-pipe welds, hanger rod-to-pipe welds, and hanger rod-to-rod welds [13]. Three categories of hanger rod-to-pipe joints were correlated: joints with only one rod (main rod only), joints with two rods welded together and to the pipe (main rod + support rod), joints with two or more hanger rods welded together at some points and welded to a muffler headhead (main rod+support rod on muffler headhead).

Only complete data (fail) are considered in this data analysis while the censored data (no fail) are excluded. Failure can be defined as the load drop to a certain value, e.g.

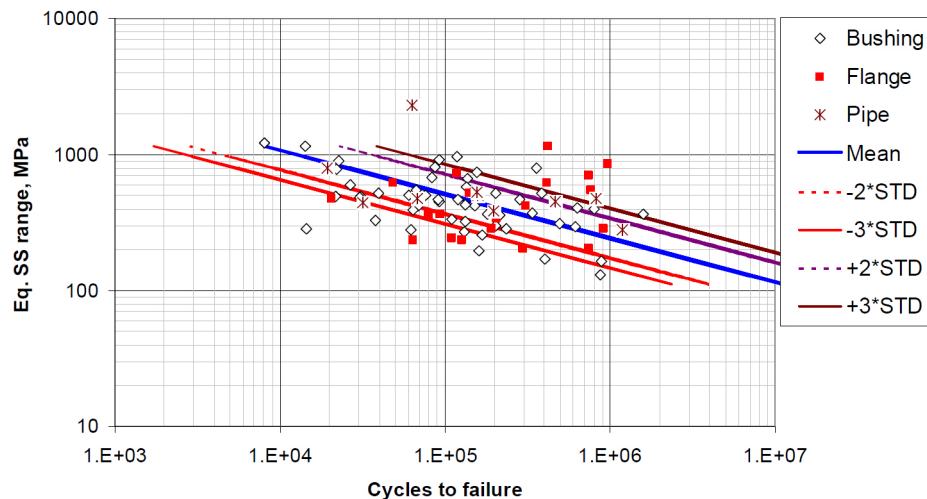


Fig. 2. Master S-N curve and the Tenneco 360° closed welds.

30% of the initial value or breakage of coated marks. Finite element models of the same parts were built to match the loading and constraint conditions of the physical tests, and then tested to simulate the physical testing. A static analysis was run on each finite element model to determine the stresses present within the structure. These stresses were then transformed into the equivalent structural stress range. In simulation, only failure occurring into the pipe was considered while some test points may have experienced failure into the rod, for more details see [13]. These weld data are categorized into three groups according to how the linear traction stress assumption is followed. These are 360° Weld, rod-to-pipe, and rod-to-rod.

360° WELD

360° welds include bushing, flange-to-pipe, and pipe-to-pipe. In physical testing, almost all of the cases, the cracks initiate and propagate into the pipe wall along the continuous weld line. From an analysis standpoint, continuous welds with closed weld ends present a straightforward situation and the transverse and in-plane shear stresses are generally negligible as compared to normal stress. However, the Tresca form of effective stress range is still used in the modeling for consistency purpose. Following the procedures shown above, the equivalent structural stress range was plotted against the fatigue life resulting from the physical tests. The test results were reported in [13, 14] and are also plotted in Fig. 2. From the figure, one can see that all 360° welded joints are uniformly mixed on the master S-N curve and located around the mean master S-N curve indicating a good data correlation. However, it is readily observable that the Tenneco data shows more scatter than the master S-N curve predicts. This is likely due to the variability associated with building and testing components at the development validation level. This will be discussed in a later section. Overall, all continuously 360° welded structures in an exhaust system may be treated in the

same manner and the mean behavior can be described by the mean curve of the master S-N curve.

ROD-TO-PIPE

In contrast to 360° closed welds, almost all of the rod-to-pipe cases, the cracks initiate and propagate at weld ends instead of along the continuous weld line because of stress concentrations present from the weld bead geometry. Therefore, the modeling of a weld end is of paramount importance. However, the simplification required to efficiently mesh open welds typically results in a computationally inadequate number of elements used to model the lateral direction of the weld. In this case, one element was used in the lateral weld direction. Further discussion will attempt to rectify the need for efficient modeling of open welds and with the requirements imposed by the use of the linear traction stress method, as the traction stress approach for an open weld is calculated differently than that for a closed weld [15]. Virtual node correction approach [15] was used to capture the nodal force contribution from all the neighboring elements to a node at weld ends. Once again, the multiaxial formula of the Tresca form was used in calculating the equivalent stress because of anticipated high degree of stress multiaxiality. The final data with various weld configurations are plotted in Fig. 3. It is clear that, overall, the test data roughly fit the master S-N mean curve, however, the scatter band is even bigger than that of 360° welds. Some data points are located far above the master S-N mean curve or lower. The most important observation is that, with only nine data points, the expected mean of main rod +support rod on muffler headbead are systematically lower than that of the master SN curve. Therefore, the master S-N curve does not provide accurate prediction for the rod-to-pipe welds, especially for the scatter band width, and caution should be exercised when the master S-N curve is used.