

The Development of a Simplified Spot Weld Model for Battelle Structural Stress Calculation

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ABSTRACT

The nodal force based Battelle structural stress method has shown its mesh insensitivity in the stress analysis of spot welds as well as fusion welds. In the conventional structural stress simulation procedure, the structural stress is calculated at the nodes along the nugget periphery. However, implementing a nugget into each spot weld is cumbersome and time consuming not only in preparing mesh for FE analysis but also in preparing a series of structural stress calculation after finishing the FE analysis. Therefore, the efficiency of the current Battelle structural stress practice for spot welds can be improved significantly for structures with a large number of spot welds. The simplified modeling procedure presented here delivers reliable structural stresses at spot welds and these stresses can then be utilized for fatigue life prediction using a master S-N Curve approach that is applicable to wide range of spot welding techniques.

In this paper, a Battelle-structural-stress based simplified procedure for modeling and simulation of spot welds is proposed. The simplified procedure can be summarized as employing shell/plate elements for plates and a beam element for each weld nugget with the plate failure as the major concern. The key contribution of this procedure is that a consistent approach for calculating the Battelle structural stress based on nodal forces and moments is developed for a given nugget with nominal size. The robustness and accuracy of the simplified procedure for spot welds is demonstrated by the fact that a large amount of fatigue data from various loading conditions and specimen geometries can collapse onto a fatigue master S-N curve. Finally, it is found that the fatigue master S-N curve for weld toe failure of fusion welds can be also utilized for sheet failure of spot welds. Furthermore, the simplified procedure demonstrates good mesh insensitivity and can significantly reduce the effort for

modeling/simulation of spot welds without sacrificing the accuracy of the results.

INTRODUCTION

A mesh-insensitive nodal force based Battelle structural stress method has been developed by Battelle researchers and has been proven to be highly effective in correlating fatigue behaviors of welded joints [1, 2, 3, 4, 5, 6]. The Battelle structural stress based weld fatigue master S-N curve has been constructed by incorporating more than 800 fatigue test results which are clearly categorized as weld toe failure. This procedure has been adopted for weld fatigue design by 2007 ASME Sec. VIII Div.2 [7] and API 579-1/ASME FFS-1 2007[8].

The Battelle structural stress method has even been applied successfully to the automotive applications which commonly use thin sheet structures [9, 10, 11, 12] as well as to offshore and heavy industrial applications that typically weld thick plate structures [5, 13]. The details of the method and its validations for automotive applications can be found in [9, 10, 11, 12, 14].

Resistance spot welding process is a widely used technique especially in automotive industry for joining thin sheet metal components. The strength of the spot welds in a car body structure generally controls the structural performance during the service life of the vehicle. Therefore, reliable modeling and evaluation procedures for spot welds are essential for structural integrity and durability analyses.

FE models for spot weld analysis that use the Battelle structural stress method, require weld nugget implementation with nominal nugget size. The structural stresses are calculated using the nodal forces and moments at the nugget edge nodes from the plate elements along the nugget

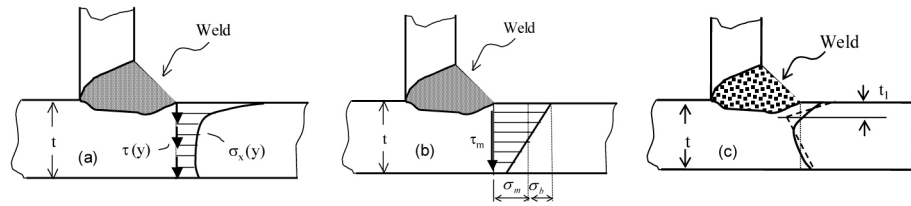


Figure 1. Through-thickness structural stress definition: (a) Local stresses front FE model; (b) Structural stress or far-field stress; (c) Self-equilibrating stress

periphery in the same manner as those calculated at the weld toe along the weld line for fusion welds. The application of Battelle structural stress method on fatigue evaluation of spot welds has been reported [15, 16, 17].

The conventional Battelle structural stress method is a very reliable technique to evaluate laboratory specimens with a few spot welds. However, implementing a nugget for each spot weld is cumbersome and time consuming not only in preparing mesh for FE analysis but also in preparing a series of structural stress calculation after finishing the FE analysis. Therefore, the simplified procedure presented here was developed to enhance the computational performance of the Battelle structural stress method when applied to real structures with numerous spot welds.

The simplified spot weld modeling procedure ignores the nugget, yet retains the accuracy of the Battelle structural stress method. It is applied to shell element models with a beam element connection for each weld nugget. This can significantly reduce modeling efforts and structural stress calculation efforts for spot welds without sacrificing the accuracy of the results. The simplified modeling procedure also shows good mesh insensitivity. It delivers reliable structural stresses at spot welds and facilitates fatigue life predictions using the master S-N curve approach.

The simplified method based design S-N curve used to assess the fatigue resistance of the spot welds incorporates more than 700 spot weld fatigue test data. Moreover, the simplified approach effectively collapses these data on to the weld fatigue master S-N curve for weld toe failures of fusion welds. Therefore, the design S-N curve for spot welds is the identical to the fatigue master S-N curve for weld toe failure of fusion welds.

In this paper, the following areas will be discussed:

- Development of proposed simplified modeling procedure using Battelle structural stress method for spot welds
- Validation of the proposed procedure for spot welds
- Construction of the design master S-N curve using proposed procedure for spot welds
- Discussion of the design master S-N curves for spot welds and for fusion welds.

MESH INSENSITIVE BATTELLE STRUCTURAL STRESS METHOD

The Battelle structural stress method developed by the author and colleagues [1, 2, 3, 4, 5, 6] is based on an equilibrium-equivalent decomposition of an arbitrary through-thickness stress state at the location of interest such as weld toe (Fig. 1a) into the equilibrium-equivalent structural stress part (Fig. 1b) and a self-equilibrating notch stress part (Fig. 1c). 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 a meaningful mesh-insensitivity for analyzing 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 [1, 2, 3, 4, 5, 6].

The Battelle structural stress method describes the through-thickness stress state normal to a hypothetical crack plane in an equilibrium sense in the form of membrane and bending components indicated in Eq. (1). For the fatigue assessment of welds, the corresponding stress range is defined as

$$\Delta\sigma_s = \Delta\sigma_m + \Delta\sigma_b \quad (2)$$

During service, complicated cyclic loads can be applied to the spot welds and a crack can initiate around spot welds. It is important to distinguish the failure modes for applying the proper damage parameter to calculate fatigue lives. Generally, two failure mode types were categorized based on the observations [15]. The crack can grow either into the plate thickness direction of the top or bottom sheet (referred to as “sheet failure”), or into the interfacial direction of plates through weld nugget (referred to as “nugget failure”). The sheet failure is the most stable and preferable failure mode and as such can be a controllable parameter in the context of

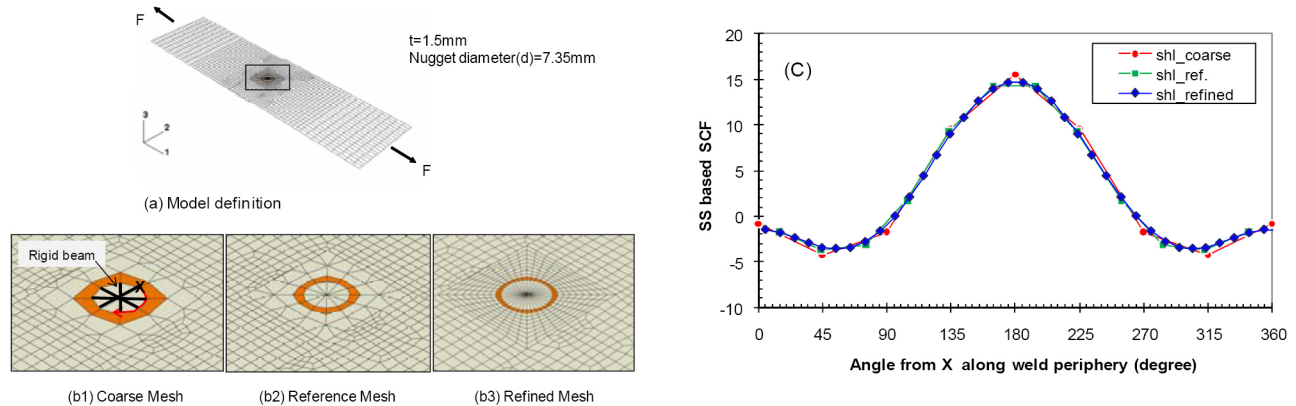


Figure 2. A example of the mesh-insensitivity of the equivalent far-field stress at the weld periphery using a spot welded lap shear specimen under tension loading; (a) Model definition; (b) View of spot welded region with various mesh sizes - (b1) 8 elements along nugget periphery; (b2) 12 elements along nugget periphery; (b3) 36 elements along nugget; (c) Comparison of calculated structural stresses at nugget edge, along the nugget periphery for 3 different mesh sizes.

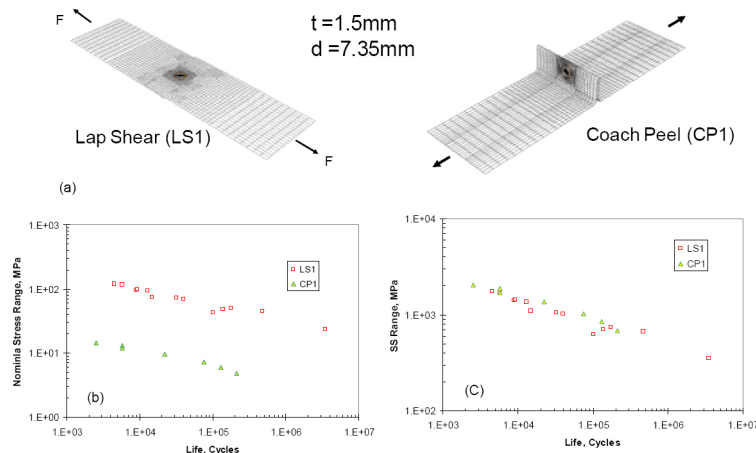


Figure 3. Validation by correlating S-N data from lap shear and coach peel fatigue tests [18]; (a) Lap shear (LS1) and coach peel (CP1) models used for Battelle structural stress calculation; (b) Nominal stress range vs. life; (c) Structural stress range vs. life

the life prediction analysis when proper weld quality is achieved. Whereas, a nugget failure is an unfavorable failure mode and generally is due to poor weld qualities, small nugget size, inadequate spot weld process, etc.

An example calculation of the Battelle structural stress for a spot weld is shown in Fig. 2. Fig. 2a shows the overall FE model of a lap shear specimen and Fig. 2b shows the various mesh sizes at the spot weld indicated by the rectangular insert shown in Fig. 2a. The specimen for a spot welded joint is modeled with shell/plate, beam, and rigid beam connection elements. As shown in Fig. 2b1, the weld nugget in each plate is modeled by triangular shell elements and rigid beams forming a spoke pattern, and the rigid beams are connected from the center node to the peripheral nodal points of the weld nugget in the both plates. Then the center nodes of weld nugget in both plates are connected with a beam element. To

consider sheet failure, the structural stresses are calculated at nugget edge along weld periphery (from 'X' along the arrow direction shown in Fig. 2b1) on the edge of the shaded regions. Structural stresses calculated at nugget edge along nugget periphery are almost identical to each other regardless of element size shown in Fig. 2c.

Fig. 3 shows the effectiveness of the Battelle structural stress method for correlating fatigue data for different types of spot welds. Fig. 3a shows the lap shear (LS1) and coach peel (CP1) fatigue test specimens with thicknesses of 1.5mm and weld nugget diameters of 7.35mm [18]. As expected, S-N data exhibit a large deviation for different specimen types when plotted in terms of nominal stress range (Fig. 3b). However, when the Battelle structural stress method is applied to compute the structural stress range ($\Delta\sigma_s$), these two

apparently different sets of fatigue data are collapsed onto one another (Fig. 3 c).

Fig. 4 indicates the Battelle structural stress component definitions, including normal structural stress (σ_s), transverse shear structural stress (τ_z), and in-plane shear structural stress (τ_s) at the hypothetical crack surface for sheet failure case. The effective structural stress range ($\Delta\sigma_e$) is defined in Eq. (3) in terms of the calculated structural stress components.

$$\Delta\sigma_e = \sqrt{\Delta\sigma_s^2 + 3(\Delta\tau_s^2 + \Delta\tau_z^2)} \quad (3)$$

In the cases that the shear structural stress range is smaller than 1/3 of normal structural stress range, the shear structural stress terms can be ignored, i.e., $\Delta\sigma_e = \Delta\sigma_s$ [7].

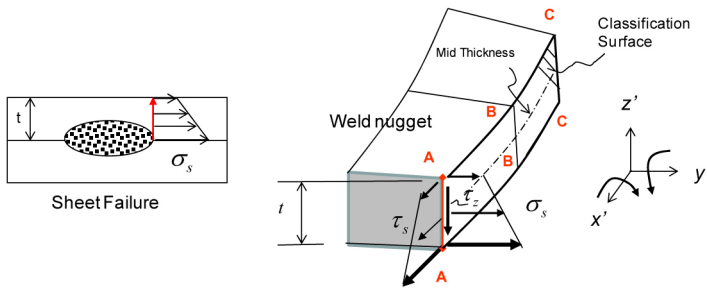


Figure 4. Definitions of Battelle structural stress components for sheet failure

Based on a two stage crack growth model, an equivalent structural stress parameter derived using fracture mechanics principles has been shown to consolidate all plate joint fatigue data relevant to steel structures onto a narrow band, referred to as the master S-N curve. The equivalent structural stress range (ΔS_s) is defined as

$$\Delta S_s = \frac{\Delta\sigma_s}{t^{* \frac{2-m}{2m}} \cdot I(r)^{\frac{1}{m}}} \quad (4)$$

where $t^* = t/t_{ref}$ with $t_{ref} = 1mm$, and $I(r)^{1/m}$ is a dimensionless polynomial function of the bending ratio r (under load-controlled conditions),

$$I(r)^{\frac{1}{m}} = 0.0011r^6 + 0.0767r^5 - 0.0988r^4 + 0.0946r^3 + 0.0221r^2 + 0.014r + 1.2233, \quad (5)$$

$$\text{where } r = \frac{|\Delta\sigma_b|}{|\Delta\sigma_m| + |\Delta\sigma_b|}$$

Note that $m=3.6$ was derived based on a large amount of short crack and long crack growth data in Eqs. (4) and (5).

Similarly, the equivalent in-plane shear stress range (ΔT_s) and the equivalent transverse shear stress range (ΔT_z) can be defined as

$$\Delta T_s (\text{or } \Delta T_z) = \frac{\Delta\tau_s (\text{or } \Delta\tau_z)}{t^{* \frac{2-m}{2m}} \cdot I(r)^{\frac{1}{m}}} \quad (6)$$

where $\Delta\tau_s$ (or $\Delta\tau_z$) replaces $\Delta\sigma_s$ in Eqs. (4) and (5).

Therefore, the equivalent effective structural stress range (ΔS_e) is defined as

$$\Delta S_e = \sqrt{\Delta S_s^2 + 3(\Delta T_s^2 + \Delta T_z^2)} \quad (7)$$

DEVELOPMENT OF SIMPLIFIED STRUCTURAL STRESS PROCEDURE FOR RESISTANCE SPOT WELDS

Mesh refinements around spot welds are required in finite element analysis to obtain reliable structural stress values at each potentially critical crack initiation site around the spot weld. For automotive structures with large numbers of spot welds, one cannot afford to invest too many elements in a single spot weld. A common practice is then to model spot welds with beam elements which connect two sheets of shell elements without mesh refinements. To calculate the structural stress, the forces (F_x , F_y , F_z) and moments (M_x , M_y , M_z) in beam elements are of primary interest as these forces and moments are transferred by each spot weld. Methodologies for estimating structural stress based on the forces and moments were developed by Rupp et al.[19], Maddox[20], Zhang[21-22], Radaj and Sonsino[23]. The simplified structural stress procedure was developed by first evaluating the existing structural stress solutions [19, 20, 21, 22, 23], and then adapted them for implementation into the Battelle structural stress concept.

APPLICATION OF STRUCTURAL STRESS IN THE PLATE

The structural stresses can be calculated at the weld nugget edge, where cracks are likely to originate in the plate by using simple engineering formulae with simplifying assumptions. The schematic in Fig. 5a shows the joint face forces and the structural stresses in the plate connected with weld nugget. The model can be represented by substituting a rigid cylindrical core for the weld nugget. The rigid core provides the proper load transfer locally and remains the original shape during the simulation.

The membrane component of the structural stress at the edge of the weld nugget in the plate can be calculated by the