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Fatigue life analysis of welded joints in the frequency plane in a structure designed for the defense industry

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Abstract: Welded joints are used in many industrial products and evaluations against static and dynamic stresses are important in terms of structure and life safety. It is very difficult to predict and model the vibration fatigue life of welded joints in the frequency plane under dynamic stresses. In this study, fatigue life estimation was made in the welded joint on a structure under vibration stresses in the frequency plane. Vibration characteristics for modes up to 1000 Hz were determined by modal analysis of the structure. In the MIL-STD 810G standard, power spectral density (PSD) is offered for composite wheeled vehicles, which are products of the defense industry. Random vibration analyses were performed by defining PSD data as analysis input. With the effective notch stress approach, geometry and material S-N definitions were made and evaluations were carried out according to the Dirlik method. As a result of this study, the fatigue life of welded joints was determined as 4.582e+11 seconds. Approaches for structural reliability in a welded joint structure designed for the defense industry are proposed.

Keywords: Welded joints, defense industry, finite element method, spectral analysis, fatigue life estimation

1. Introduction

Fatigue life begins with the investigations of August Wöhler and different design approaches due to the occurrence of fatigue damage in a railway vehicle in the 1800s [1, 2]. These examinations are important in terms of maintaining the functional needs of the machines, ensuring structural safety and life safety. For this reason, fatigue life approaches have been developed for about 200 years.

When estimating fatigue life under dynamic stress, it is evaluated by two different methods as stress and strain. S-N (Stress-Life) graphs are created as a result of experimental studies when examining with strain variables and E-N (Strain-Life) graphs are examined with strain variables and calculations are made according to these graphs [3]. It is calculated according to the cumulative damage rule called Palmgren-Miner rule according to S-N curves depending on time or frequency in a structure exposed to variable stresses [4]. Fatigue calculations can be made in different sectors with finite element analysis [5]. In addition, it is possible to perform simulation verifications with experimental studies and perform different optimization studies [6]. Theoretically, random vibration fatigue life can be realized in the time or frequency plane. In order to perform calculations in the frequency domain, time-dependent data is converted to the frequency domain with FFT transformations, and PSD data is obtained with the signal strength called the Parseval Theorem [7]. Random vibration analyses can be performed according to the results of frequency response analysis by using PSD data in finite element method (FEM) analysis. Such spectral analyses are preferred because time-dependent data are costly in terms of time with FEM analyses [8].

In the evaluation of spectral fatigue analysis, there are several frequency plane evaluation methods such as Dirlik, Benasciutti and Tovo, Lalanne, narrow band, Steinberg, and Wirsching [9-13]. In the experimental comparison of these methods in the literature, it is seen that Dirlik and Benasciutti-Tovo methods yield more accurate results and especially the Dirlik method has the highest accuracy rate [3, 14, 15].

MIL-STD-810G standard can be used for the development of vehicles designed for many defense industries [16, 17]. In FEM analysis, there are PSD data for random vibration analysis according to different vehicle types

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and air, road, and railroad types. Evaluations are made according to the PSD data in the standard so that the vehicles of the defense industry can safely fulfill their functional purposes.

While welded joints are evaluated according to the FEM analysis results, the approaches of the International Welding Institute (IIW) recommendations that have been validated in many literature studies are used. According to IIW, nominal stress, hot spot stress, effective notch stress and linear elastic fracture mechanics approaches are recommended as regional approaches [18, 19]. The choice of these approaches can vary depending on the complexity of the structure, the weld tip or root examination, accuracy, and time effort, as shown in Figure 1. While performing fatigue life calculations, there are different fatigue class (FAT) tables for these three approaches according to IIW recommendations. The FAT value is defined as the stress range value in 2x10^6 cycles. By making selections for the welded joint designed from these tables, the S-N curve is defined and fatigue life estimates are made [20]. While evaluating the spectral analyses of the welded joint region, stress values can be determined using IIW approaches [21, 22]. In addition, for structures with small thicknesses such as the automotive sector, evaluations can be made with methods such as BS7608 and Volvo method [23].

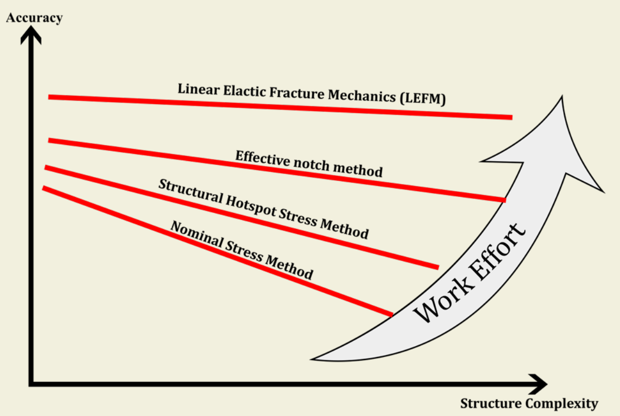


Figure 1. FEM analysis evaluation approaches of welded joints [24]

In this study, the welded joint area in a structure designed for the defense industry was examined. For random vibration analysis of this structure, dynamic analyses were performed using PSD data in MIL-STD-810G standard. In the literature studies, the Dirlik method, which is the most accurate evaluation method in the frequency plane, was used. For the welded joint area, the effective notch approach was used and the FAT225 class was determined and the S-N curve was defined, and calculations were made according to the Miner rule for the cumulative damage sum. Designs have been developed to ensure that the calculations are above the test period for the standard. As a result of the study, 4.582e+11 seconds were found in the examined weld zone according to the final design.

2. Materials and Method

2.1. Assessed Welded Joint Zone

Studies have been carried out for the welded joint of a vehicle designed on the defense industry on the chassis joint element. Ansys software was used for FEM analysis of the structure and nCode Designlife software was used for fatigue calculations. The investigated chassis connection structure was defined as ultra-high strength S960QL steel. For the selection of the welding filler wire, a filler wire close to the mechanical properties of S960QL steel was selected. In the structure examined in Table 1, the mechanical properties of the steel used for linear material definitions in FEM analysis are given.

Table 1. S960QL Mechanical Properties

Parameter	Value
Yield Strength [MPa]	1027
Ultimate Strength [MPa]	1066
Young Modulus [GPa]	203.4
Elongation [%]	16
Poisson Ratio	0.33

The model, which was analyzed, was created in the Ansys software as a result of the analysis, and simplifications were made in the modeling. With the sub-model, mass moments of inertia, boundary and loading conditions are defined according to the analysis result. Thus, random vibration analyses are solved faster. The model simplification region realized in Figure 2 is shown.

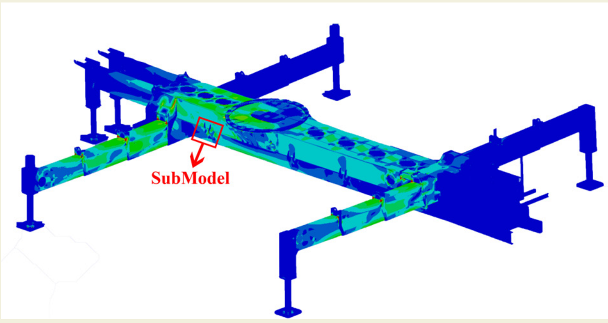


Figure 2. Simplification of the analysis model by applying the submodel

2.2. Effective Notch Stress Approach

Welding modeling of FEM analyses performed with the effective notch stress approach, a 1 mm radius is created on the weld tip with a solid geometry, as shown in Figure 3. It gives more accurate results than the nominal stress and hot spot stress approach, and more time and effort is spent in terms of welding geometry modeling in analysis. Material S-N curve definitions are defined according to IIW recommendations. A single S-N curve was used as in the IIW recommendations at different stress ranges defined according to the effective notch stress approach. There is only one FAT225 class when performing fatigue calculations in the time or frequency domain. This class indicates that it will fail after Nf=2.10^6 cycles in the Δσ=225 MPa stress range. The slope of the S-N curve is taken as m=3, and fatigue life calculations are made with the Basquin equation specified in Equation (1) at different stress range values [25, 26].

$$N_f = \left(\frac{FAT}{\Delta\sigma}\right)^m .2.10^6 \tag{1}$$

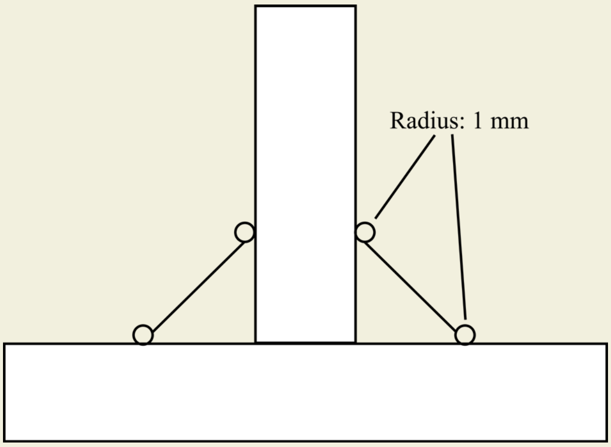


Figure 3. Efficient notch stress approach weld modeling [24]

2.3. 2.3 Performed Spectral Analysis and Dirlik Method

While the structures are forced under external loads, there are actually dynamic effects. Analytical calculations or analyses are assumed to be static because of their time and ease. In fact, structures are under dynamic stress at low or high frequency. For dynamic situations in the general law of motion, dynamic calculations of structures with mass M, stiffness K and damping matrix C specified in Equation (2) are performed under external stresses in time dependent u(t) deformation [27]. In static analysis, the mass inertia of the structure is performed without including the damping of the structure. Therefore, dynamic analyses are recommended for the reliable evaluation of structures. Analyses were carried out with linear material descriptions according to the Euler-Bernoulli deformation approach according to Hooke's law. Stress evaluations were examined according to von-Misses stresses.

$$M.\ddot{u}(t) + C.\dot{u}(t) + K.u(t) = F(t) \tag{2}$$

In the FEM random vibration analysis, the stresses generated by the loadings and responses are analyzed statistically in the frequency plane. The power spectral density (PSD) in the frequency domain is obtained by performing the FFT of the signals received in the time domain with the power stability of the signal in Parseval's theorem. The g^2/Hz PSD data obtained by the FFT of the acceleration sensor is defined as the loading input in FEM analysis. In the study, PSD values obtained as a result of tests carried out in laboratory environments for the road transport configuration of composite wheeled defense industry vehicles in MIL-STD-810G standard were used. The tests were carried out for 120 minutes. Root mean square (RMS) values are 2.24 in the vertical direction, 1.48 in lateral direction and 1.90 in longitudinal direction. It is recommended that the test data of the standard be used in damage calculations for composite wheeled defense industry vehicles. Figure 4 shows the PSD data defined in random vibration analysis.

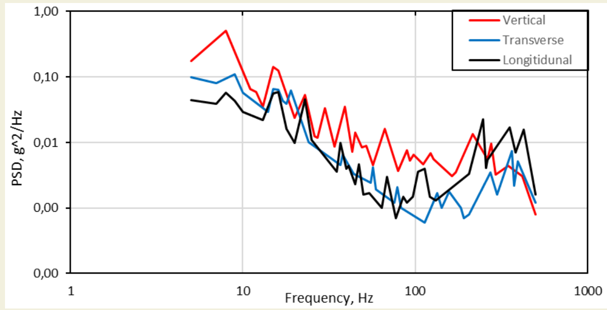


Figure 4. Input PSD data used in analysis

In Dirlik method, spectral analyses are evaluated using cycle counting method. The cumulative damage sum is calculated by the Miner rule specified in Equation (3), the number of cycles in the voltage amplitude (ni) and the number of damaged cycles (Ni) in the S-N graph [28]. In vibration fatigue analysis, the vibration amplitude specified in Equation (4) should be expressed as a probabilistic density function (PDF) fsa(Sa) and by integrating the damage sum (Ddirlik). If the total of the damage is one, the structure is considered to be damaged. The empirical solution for the probability density function of the stress amplitude with the commonly used rain flow was proposed by Dirlik [10, 29, 30]. In this study, Dirlik method was used for random vibration analysis of PSD data in a structure designed for the defense industry industrial. M1, M2, M3, M4 are the spectral moments of the PSD data on the zero frequency axis. D1, D2, D3, R are functions of spectral moments and are specified in Equation (4)-(13) [30].

$$D = \sum_{i=1}^{n_f} \frac{n_i}{N_i} \tag{3}$$

$$D_{dirlik} = \frac{E[P]T}{b} \int_0^\infty S_a^m f_{Sa}(S_a) dS_a \tag{4}$$

$$f_{Sa}(S_a) = \frac{\frac{D_1}{Q}.e^{-\frac{Z}{Q}.S_a} + \frac{D_2.Z}{R^2}.e^{-\frac{Z^2}{2R^2}.S_a{}^2} + D_3.Z.e^{-\frac{Z^2}{2}.S_a{}^2}}{2.\sqrt{M_0}} \tag{5}$$

$$D_1 = \frac{2.(x_m - \gamma^2)}{b} \tag{6}$$

$$D_2 = \frac{1 - \gamma - D_1 - D_1{}^2}{b} \tag{7}$$

$$D_3 = 1 - D_1 - D_2 \tag{8}$$

$$R = \frac{\gamma - (x_m - D_1{}^2)}{1 - \gamma - D_1 + D_1{}^2)} \tag{9}$$

$$Q = \frac{1.25.(\gamma - D_3 - D_2.R)}{D_1} \quad (10)$$

$$Z = \frac{1}{2.\sqrt{M_0}} \quad (11)$$

$$\gamma = \frac{1}{\sqrt{M_0.M_4}} \quad (12)$$

$$x_m = \frac{M_1}{M_0}.\sqrt{\frac{M_2}{M_4}} \quad (13)$$

2.4. Proposed Method

While performing local evaluations in FEM analyses of welded joints, the effective notch stress approach has a higher accuracy than other local evaluation approaches. When examining welded joints in the frequency plane, if the structure is complex, it is recommended to create a submodel and enter the reaction forces and moments as a loading input in the analysis where only the submodel is present. Thus, the effective notch stress approach in complex models can be efficient for the solution time. For the effective notch stress approach, it is suggested that the mass and mass moments of inertia of the other structures should be defined in the sub-model in order to get more accurate results for the frequency response function of the structure after the S-N curve of the FAT225 class and the solid model are completed. According to the PSD data in the MIL-STD-810G standard for defense industry vehicles, the application of the Dirlik method, which is also confirmed in the literature studies, gives more accurate results. Figure 5 shows this proposed approach, since it is more convenient in terms of solution time, effort and accuracy for fatigue calculation in the frequency plane of welded joints in FEM analysis.

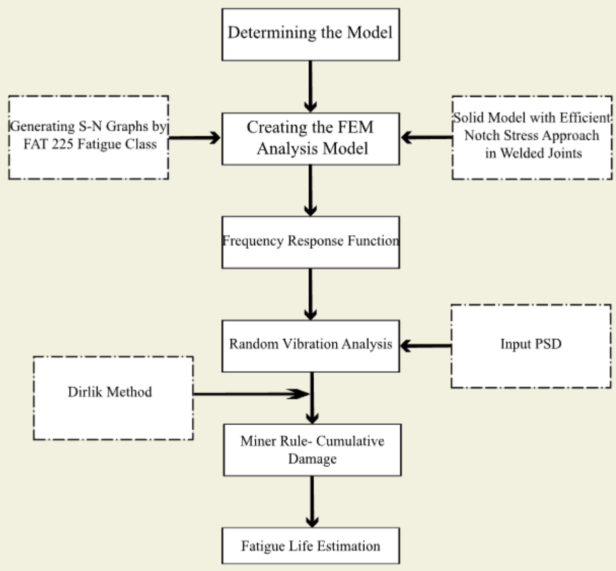


Figure 5. Proposed approach for fatigue life calculation in the frequency plane in welded joints

3. Findings

Modal analyses were carried out to determine the vibration characteristics of welded joints in the frequency plane. How the welded joints on the structure respond to different vibration modes is investigated. Modal analysis results provided important information such as resonance frequencies, mode shapes and modal masses in the structure. Through these analyses, a comprehensive understanding of the vibration characteristics and resonance behavior of welded joints has been obtained. In addition, the energy distribution and vibration patterns on the structure were determined according to different modes. Modal analysis results provided important information that can be used in the evaluation of the structural performance of welded joints and design optimization before random vibration analyses. The results of the modal analysis performed as a result of design improvements and model simplifications are shown in Figure 6. It has been determined that the 1st mode is 49.31 Hz, the 2nd mode is 151.85 Hz, the 3rd mode is 263.88 Hz and the 4th mode is 512.69 Hz. Since the maximum frequency in PSD input data is 500 Hz, it is seen that the frequency values of the first 4 modes are sufficient. The mass participation factors were found to be 36.18% in the 1st mode vertical direction, 49.45% in the 2nd mode longitudinal direction, 47.07% in the 3rd mode longitudinal axis rotation direction and 0.17% in the 4th mode longitudinal direction.

Modal analysis results provided baseline data for random vibration analyses using nCode DesignLife software. These analyses were performed to evaluate how welded joints respond to dynamic loading. Random vibration analyses were used to predict the stress and deformation levels that may occur in the welded joints of the structure. Thanks to these analyses, the behavior of welded joints against random vibration loadings was determined and stress information was obtained in terms of structural reliability. In addition, fatigue life estimates of welded joints are made according to different random vibration scenarios and important inputs for structural design improvements are presented. Figure 7 shows the block flowcharts implemented in the nCode Designlife software in the final design. Here, the PSD data indicated in Figure 4 are defined as the input of random vibration analysis. Blocks were created to obtain the results of frequency response analysis and probabilistic density functions from the highest stressed node of the welded joint.

The results of the random vibration analysis performed were used to evaluate the structural performance and durability of the welded joints, using the blocks shown in Figure 7. According to the analysis results, the joint with the highest stress value and the lowest fatigue life was determined. This node is defined as the critical node. This knot indicates that the welded joint is a sensitive region to dynamic stresses and is subject to high stress

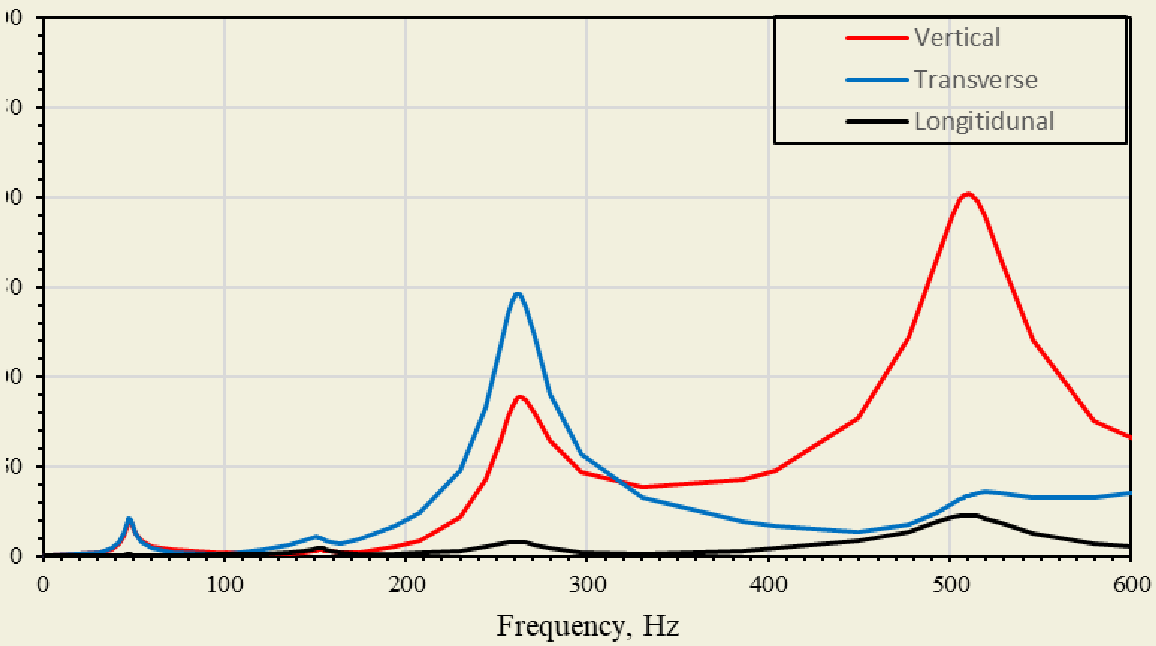


Figure 6. Results of modal analysis

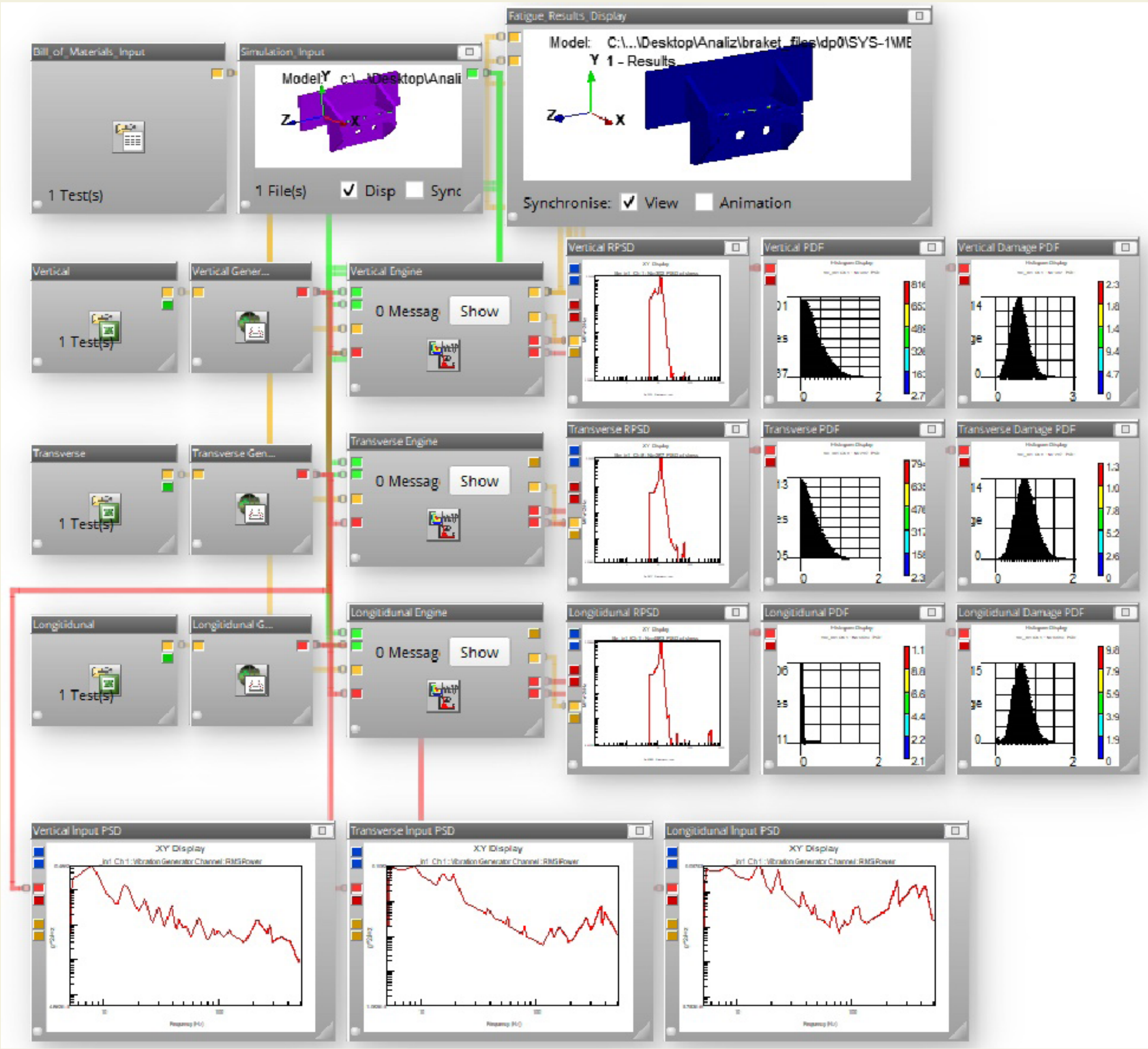
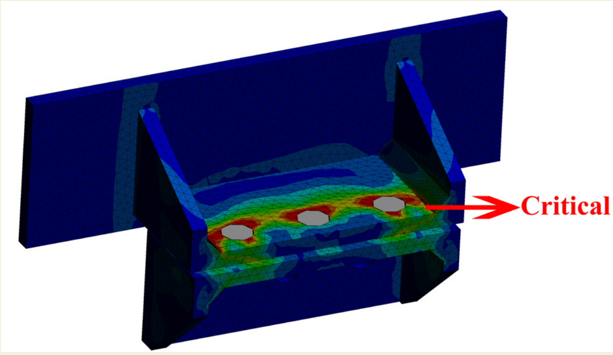
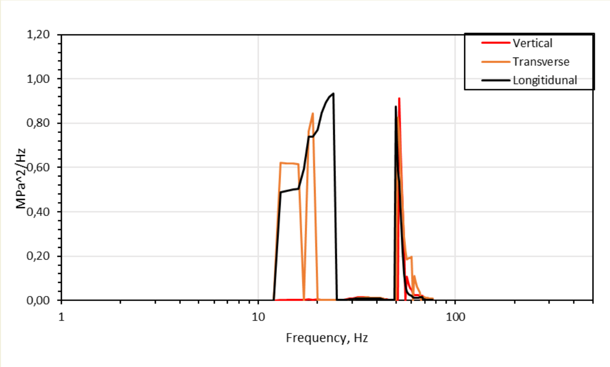


Figure 7. Model-based block diagram generated for random vibration analysis



(a)



(b)

Figure 8. (a) Critical node according to random vibration analysis result (b) Critical nodal response PSD data

concentrations. These findings provide important information for design improvements, such as reinforcing welded joints and making geometric or material changes. According to the improved final design, the critical joint point (a) in the most critical welded joint region and the response PSD results obtained as a result of random vibration analysis from this critical point are shown in Figure 8.

Response PSD values obtained at the critical node were used. Probabilistic density function (PDF) values were obtained by taking the moments of the response PSD data according to the frequency according to the Dirlik method. In addition, cycles and damage values were determined by using the S-N curve determined according to the FAT 225 value with a probability of 97.7% according to the effective notch stress approach since the welded joint area was examined. Figure 9 shows the cycle and damage results according to vertical, lateral, longitudinal directions. The results were evaluated according to the direction with the lowest life. According to the results of random vibration analysis, it has been determined according to the PDF results that it has the lowest lifetime in the vertical direction.

The fatigue life of the welded joint was determined according to the 120-minute test period specified in the MIL-STD 810G standard by taking the cumulative totals according to the Miner rule in the PDF results. By using all the stress range values in the PDF results determined according to the Dirlik method, the fatigue life of the critical joint point was determined to be 4.582e+11 seconds in the vertical direction. It was found 9.297e+10 according to Lalanne theory and 2.05e+10 according to Narrowband theory. In the studies in the literature, it is seen that the Dirlik method gives similar results to the tests in spectral FEM analyses [3, 14, 31]. Since it is appropriate to use the results of the Dirlik method used in different studies in the literature, the Dirlik method was used in this study as well [32, 33]. It is seen that the effective notch stress approach gives more accurate results with FAT 225 fatigue class in welded joints and 1 mm radius to the weld tip [19, 34, 35]. With this application, it is proposed to use the effective notch stress approach and the Dirlik method together in welded joints in random vibration analysis.

4. Result

This study includes research in which welded joints are evaluated on a structure under vibration stresses in the frequency plane. Vibration characteristics were determined according to different modes using the modal analysis of the structure. Test studies using data generated in the MIL-STD 810G standard used the fast Fourier transform (FFT) method to transform the data obtained in the time domain into power spectral density (PSD) data.

In this study, the stresses occurring in the welding joints were determined by using the PSD data prepared for composite wheeled vehicles together with the FEM analysis. Cycle values based on probabilistic density functions were determined depending on the stress range using the Dirlik method. In addition, using the effective notch stress approach, S-N definitions were made with geometry and material information, and evaluations were carried out with the Dirlik method.

As a result of this study, it has been determined that the fatigue life of welded joints is 4.582e+11 seconds. The proposed approaches for structural reliability in a structure with welded joints used in the defense industry make an important contribution. This study provides a reliable method for fatigue life estimation in welded joints. In critical applications such as the defense industry, this approach is viable and is an important step towards building reliability.

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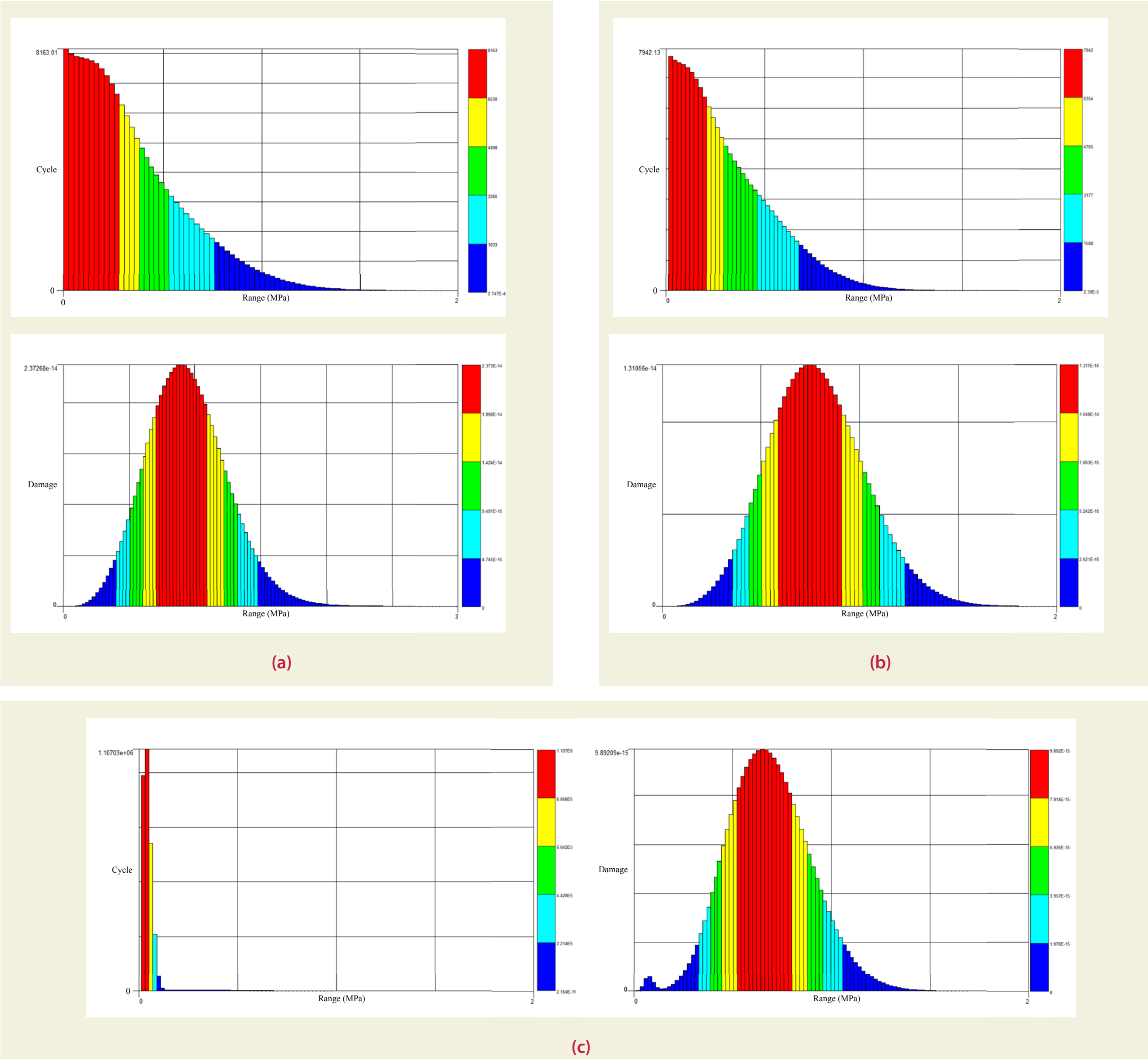

Figure 9. PDF results of cycle and damage of critical node according to Dirlik method (a) Vertical direction (b) Lateral direction (c) Longitudinal direction

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