FATIGUE LIFE ANALYSIS OF FILLET WELDED STRUCTURES OF SEMI TRAILER CHASSIS FRAME USING THE HOT SPOT STRESS APPROACH

DAT TUAN VU
University of Transport and Communications, No 3 Cau Giay Street, Hanoi, Vietnam
Corresponding author's email: datvt@utc.edu.vn; Tel: 0977 55 1375

Abstract: *In this paper, the hot spot stress approach recommended by the International Institute of Welding (IIW) has been applied to estimate fatigue life of fillet welded structures for the chassis frame of semi trailer, which was locally manufactured in Vietnam. The combined method of the finite element analysis (FEA) and the multi-body dynamic simulation (MBDS) is proposed for structural analysis. The FE model of chassis frame is established with the effects of the geometry and stiffness of welded joints are considered by using shell element. The nodal stress-time histories of structure are determined using FE dynamic analysis with dynamic loads acting on chassis frame that were obtained from the results of the MBDS. In order to analyse the fatigue strength in crack initiation period, the structural hot spot stress is calculated by the linear extrapolation of stress at the reference points. The fatigue life of the critical locations of fillet welded joint is determined with the selected fatigue curve corresponding to the associated fatigue class (FAT) according to IIW recommendations.*

Keywords: *Fatigue life, fillet weld, hot spot stress approach, chassis frame of semi trailer, finite element analysis, multi-body dynamic simulation, IIW recommendations.*

Received: 04/03/2021 Accepted: 13/03/2021 Published online: 31/05/2021

I. INTRODUCTION

Welding is most commonly used in many industries as an efficient and economical method for permanent joining of machine parts and structures. In automotive industry, there are many main load-bearing structures such as chassis frame are manufactured with steel plates and the assembly are performed by seam welding. However, stress concentration and residual stress due to geometrical deformation induce micro-crack that often alters the properties of parent metal and reduce fatigue strength of welded joint. Therefore, fatigue failure of the welded structures remains the most common type of failure. When assessment of the durability of welded structure, priority should be given to fatigue evaluation of welded joints [1].

Fatigue design and analysis is generally based on structural stress data and classified S-N curves with corresponding fatigue classes. There are four main methods for fatigue stress determination of welded structures: nominal stress, hot spot stress, effective notch stress and fatigue crack propagation [2,3]. Of which, the hot spot stress approach is typically used where the nominal stress is hard to estimate due to complicated geometry and loading effects [3-5]. This approach is increasingly used to determine the structural stress for fatigue life analysis of welded joint with the application of the FEA, which is considered an effective method for structural analysis. Numerous FE models have been developed to analyze the stress state of welded structures with solid element or shell element [6-10]. In these models, the shell elements with meshing rules have been proposed for fatigue analysis of welded structures. Because it allows determination of the hot-spot stress location and assessment of weld toe fatigue in crack initiation period [6]. In addition, this type of modeling also has the advantage in model size and time calculations.

The aim of this study is to estimate fatigue life of fillet welded structures of the semi trailer's chassis frame, which was locally manufactured in Vietnam. The combined method of the FEA and MBDS is proposed for structural analysis [11,12]. The FE model of chassis frame is established using shell element with the effects of the geometry and stiffness of fillet welded structures are considered. The MBD model of the full vehicle is built with the body of chassis frame as rigid body can be converted from the modal neutral file of FE model. The dynamic loads acting on chassis frame are obtained from the results of the MDS under random excitation of road roughness. These dynamic loads are used as inputs in the structural dynamic analysis to determine the nodal stress-time histories of chassis frame structure. Based on hot spot stress approach according to IIW recommendations in crack initiation period [3], the nodal stress values of the specified reference points are used to calculate the structural hot spot stress-time histories by extrapolation to the weld toe. The fatigue life of fillet welded structures is determined using fatigue curve of the associated fatigue class (FAT), which is chosen depending on the welded structure.

II. METHODOLOGY

2.1. Structural hot spot stress approach

The hot spot stress (also called structural stress or geometrical stress) has been used for the fatigue analysis of welded tubular joints, then extended to fatigue analysis of plated welded structures [9]. The "hot spot" is simply the critical location where the initiation of the fatigue crack is likely to appear. The hot spot stress is generally considered to be the stress in the base metal at the weld toe, considering the effect of stress concentration and residual stress due to the geometrical deformation of welded joint. It is used to analyse fatigue strength at weld toes. Traditional approach to calculate hot spot stress is based on linear or quadratic extrapolation of stress from two or three reference points at certain distances from the weld toe of welded joint as illustrated in Figure 1[3].

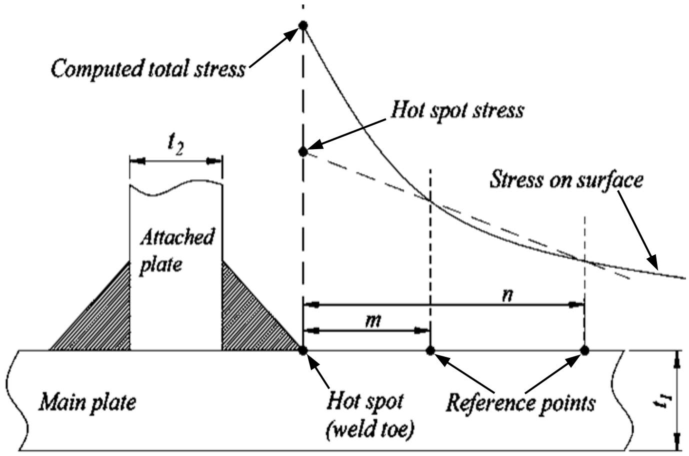

Figure 1. *Sample surface extrapolation of the reference points to the weld toe in order to approximate the structural hot spot stress.*

When applying the FE method, the number and distances of reference points (m and n) from the weld toe and extrapolative equation are selected depending on main plate thickness (t_1) and meshing rules (element size). In this paper, the structural hot spot stress (σ_{HS}) are calculated based on linear extrapolation from Equation (1) [3] with $m = 0.5t_1$ and $n = 1.5t_1$:

$$\sigma_{HS} = 1.5\sigma_m - 0.5\sigma_n = 1.5\sigma_{0.5t_1} - 0.5\sigma_{1.5t_1} . \qquad (1)$$

2.2. Finite element model of the semi trailer's chassis frame

The chassis frame of 40 feet semi trailer is made of JIS-G3106 SM490A steel plate, which is suitable for welded structure. The basic specifications of the vehicle are described in Table 1.

Table 1. *The basic specifications of the semi trailer*

Specifications	Value (*unit*)	Specifications	Value (*unit*)
Model	Terminal container semi trailer	Size: *L*×*W*×*H*	12260×2500×1500 (*mm*)
Tare weight	5,260 (*kg*)	Axle number	3
Payload	34,740 (*kg*)	Tire	11.00R20 × 12 units
Total weight	40,000 (*kg*)	Traction pin	2.0 inche - Weld bolt type

The ANSYS software including advanced features was used to establish the FE model of the chassis frame. When establishing the FE model, the shell elements with varied real constants of thickness are used to model the components of chassis frame, with the shell elements are arranged in the mid-plane of the structural components. In order to simplify when building the model, only consider the fillet welded joints that are used to connect the components with two main I beams such as front bolster, middle bolster, rear bolster, crossmembers, suspension hangers, landing gears, etc. and the parts in the mounting bracket of traction pin. Here, the fillet welded structures are modelled using the inclined shell elements having appropriate stiffness with the geometrical dimensions as shown in Figure 2. In this model, the mechanical properties such as elastic modulus and poisson's ratio of the material in weld zone and heat affected zone are equivalent to those of parent metal.

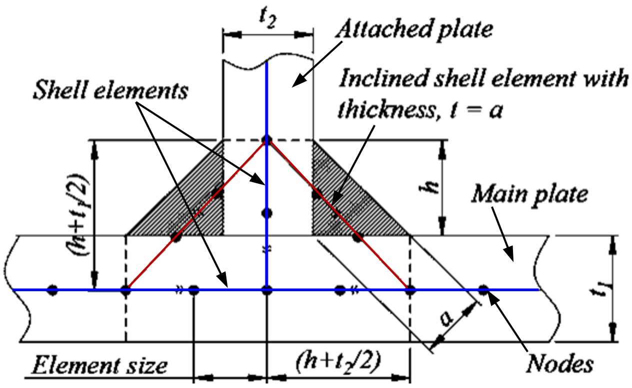

Figure 2. *The modeling of fillet welded joint using inclined shell elements*

The real constant of inclined shell element thickness (t) is chosen to be equivalent to the throat thickness (a) and calculated according to welded height (h):

$$t = a = \frac{h}{\sqrt{2}}. \quad (2)$$

When meshing model, based on the geometrical dimensions of fillet welded joints on the chassis frame, the element size is selected so that the distance from the node at the welded toe to the reference nodes ensures an approximate calculation of the hot spot stress according to Equation (1). The FE model of the chassis frame consists of 1,317,951 nodes and 1,335,263 elements as shown in Figure 3. In this FE model, 10 interface nodes (*INs*) are created and connected to the chassis frame by rigid regions: 1 *IN* is located at the traction pin and connected to the support surfaces of traction pin; 1 *IN* is located at the center of mass of 40 feet container in the case of full load and connected to the upper support surfaces of two main I beams; 8 *INs* as connecting points between the suspensions components of semi trailer and the suspension hangers. These *INs* are connected to the support surfaces of suspension hangers. These *INs* are used as connecting points between the body of chassis frame and other bodies in the MBD model of vehicle.

In ANSYS software, the ANSYS-ADAMS interface feature is used to create a modal neutral file (*.*mnf*). This file contains the structural properties of the chassis frame such as mass, center of mass, moment of inertia, etc.

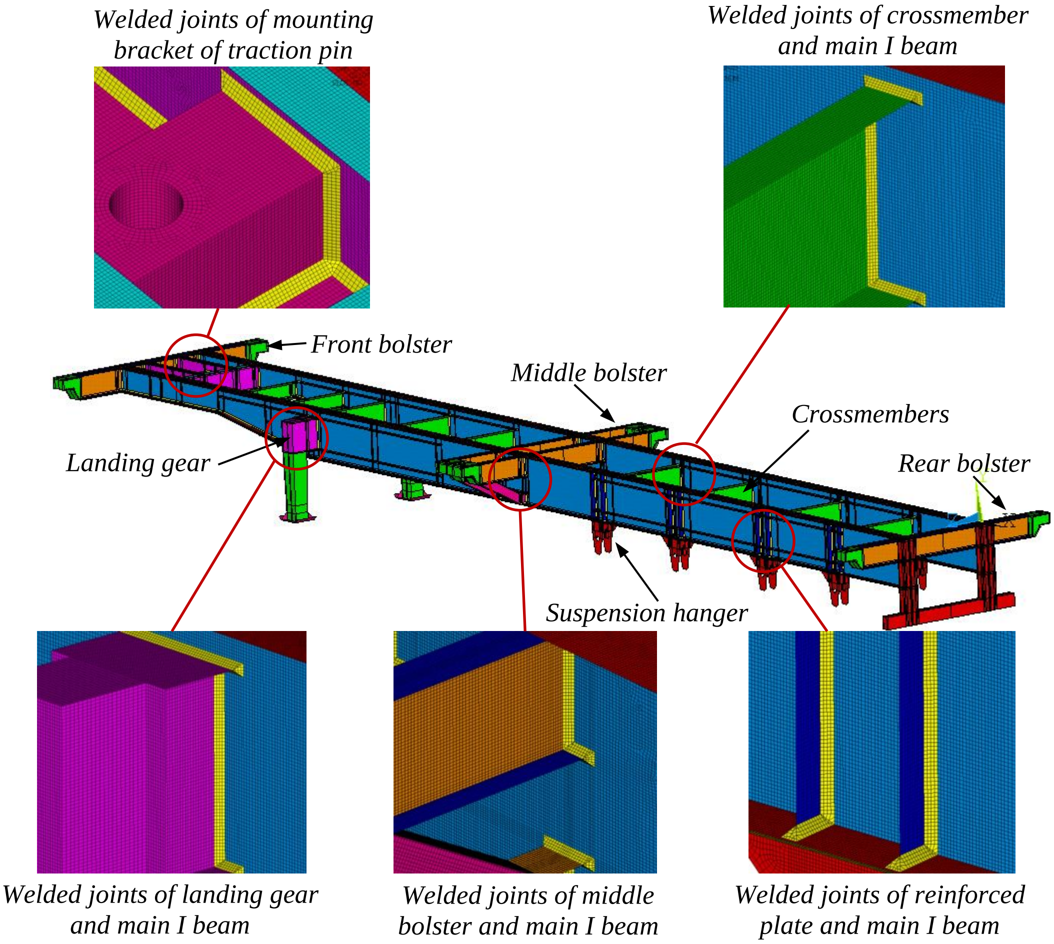

Figure 3. *The FE model of chassis frame with some typical fillet welded joints*

2.3. Multi-body dynamic model of the full vehicle

A tractor-semi trailer truck is selected for building MBD model with the dependent suspension system-leaf spring type for tractor's front axle and the equalizing beam suspension system-leaf spring type for tractor's tandem rear axle and semi trailer's tridem axle. In ADAMS software, the modal neutral file (*.*mnf*) is imported in order to create the body of chassis frame and the different constraint types of joints are used to connect the other rigid bodies with the chassis frame body. The MBD model of 5-axle full vehicle with 18 degrees of freedom is built as shown in Figure 4.

When building the MBD model, it is assumed that the vehicle moves straight with constant speed. The road roughness is considered to be the source of the random oscillation excitation at the wheels and the excitative profiles of the left and right wheel on any one axle are the same. Based on GB/T 7031-2005 [13] and the Inverse Fast Fourier Transform method [14], the numerical simulation of road roughness were perform with the bad road surface level of *D* grade, vehicle speed of 60 *km/h* (≈16.67 *m/s*) and time steps of 0.01 second. The road roughness random excitation (q) in time-domain is show in Figure 5.

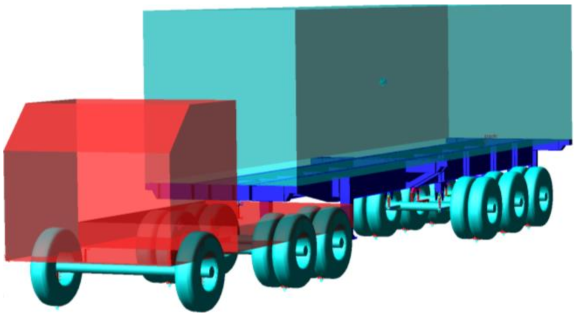

Figure 4*. The MBD model of full vehicle in ADAMS software.*

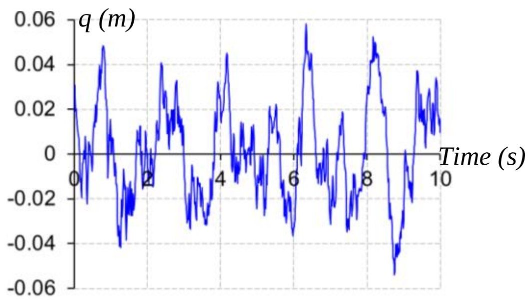

Figure 5*. Road roughness of D grade with vehicle speed of 60 km/h.*

2.4. Fatigue life analysis model

The fatigue strength of the welded joints are expressed as fatigue curves based on the structural stress range ($\Delta\sigma$) and the geometrical type of the welded structure. According to the IIW recommendations, the following equation is used to establish the fatigue curve ($\Delta\sigma - N$ curve):

$$N = \frac{C}{\Delta\sigma^{m_1}}. \tag{3}$$

Where, C is the constant coefficient; m is the exponent of $\Delta\sigma - N$ curve, m_1 = 3; N is number of cycles to failure. Each fatigue curve of the constant stress range at N = 2.0×10^6 cycles is the fatigue class (FAT or $\Delta\sigma_{FAT}$) and at N_e= 10^7 cycles is the fatigue limit ($\Delta\sigma_e$).

Considering the influence of the constant stress range lower than the fatigue limit causing the fatigue damage due to the high-cycle cyclic load of structure, the IIW recommendations proposes to correct the fatigue curve with $\Delta\sigma < \Delta\sigma_e$: the slope of the fatigue life curve from fatigue limit must be extrapolated beyond it at the shallower slope of $m_2 = 2m_1 - 1$. From Equation (3), the number of cycles to failure is calculated:

$$N = \begin{cases} \dfrac{C_1}{\Delta\sigma^{m_1}} & if \quad \Delta\sigma_e < \Delta\sigma \\ \dfrac{C_2}{\Delta\sigma^{m_2}} & if \quad \Delta\sigma < \Delta\sigma_e \end{cases}. \tag{4}$$

For variable stress ranges, the Rainflow-counting algorithm [15] is used to count the number of stress cycles (n_i) of constant stress range ($\Delta\sigma_i$) whose number of cycles to failure at constant stress range ($\Delta\sigma_i$) is N_i. It allows the application of Palmgren-Miner's rule [16] to calculate the cumulative fatigue damage (D_f):

$$D_f = \sum \frac{n_i}{N_i}. \tag{5}$$

After correction, the fatigue curves corresponding to the fatigue classes ($\Delta\sigma_{FAT}$) are shown in Figure 6 [3].

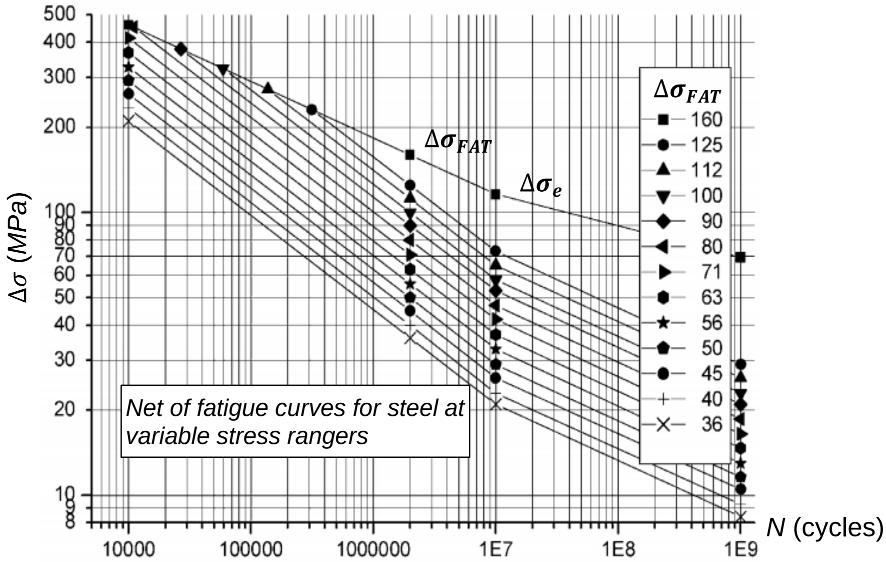

Figure 6. *Fatigue curves correspond with the fatigue classes ($\Delta\sigma_{FAT}$)*

III. REULTS AND DISCUSIONS

3.1. Structural Hot Spot Stress Calculation

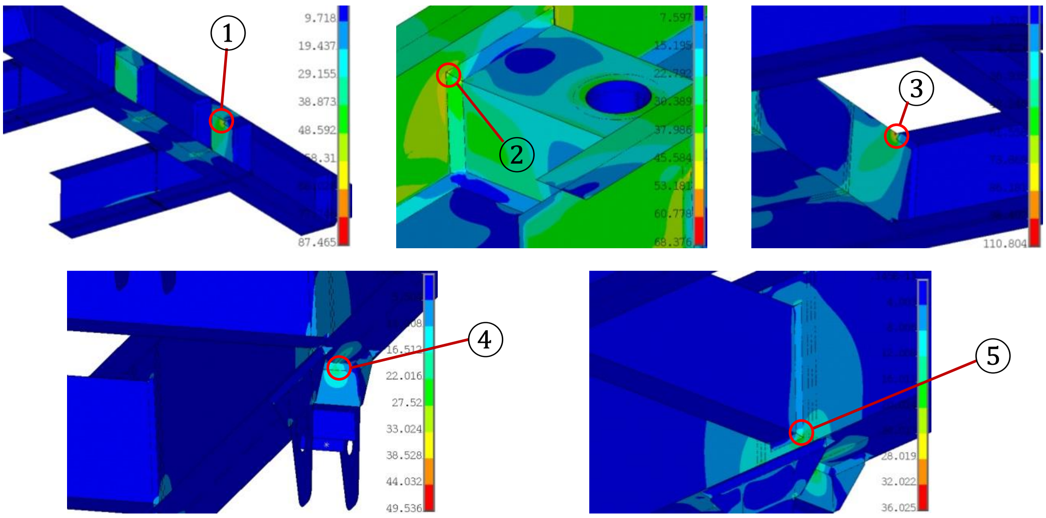

Figure 7. *Equivalent stress distribution of typical critical locations*

After performing the MBDS, using the Export FEA Loads feature in ADAMS to export the dynamic loads acting on the chassis frame to a load file (*.*lod*), which includes forces, moments, angular velocities, linear and angular accelerations in three directions. The load file is imported into the FE model of the chassis frame and the nodal stress-time histories are calculated from FE dynamic analysis of structure. The equivalent stress distribution of the typical critical locations which have been observed at the welded toe of the welded connections as shown in Figure 7 and described in Table 2.

Table 2. Description of critical locations

Location	The welded connections between components:
①	The front bolster and the main I beam
②	The longitudinal reinforced beam and the mounting bracket of traction pin.
③	The transverse reinforced beam and the main I beam
④	The 2nd suspension hanger and the main I beam
⑤	The 7th crossmember and the main I beam

On the basis of Equation (1) and element size at the critical locations, the hot spot stress are approximate calculated using the equivalent nodal stress of the reference points. Figure 8 shows the hot spot stress-time histories of the critical locations with 150 load steps and 0.01 second per step.

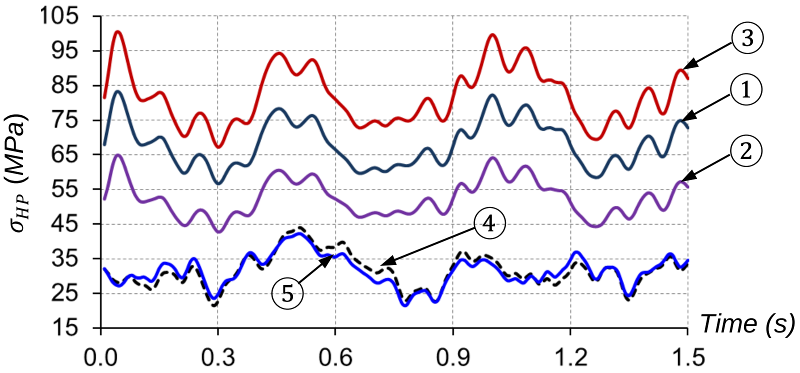

Figure 8. *Hot spot stress-time histories of the critical locations.*

3.2. Fatigue Life Assessment of Fillet Welded Structures

In order to determine the fatigue life of the fillet welded structures of semi trailer's chassis frame, it is necessary to calculate the statistical characteristics of the hot spot stress-time histories, including the number of stress cycles (n_i) corresponding to the stress range ($\Delta\sigma_i$), etc. The statistical characteristics of the hot spot stress-time histories with 150 load steps are as shown in Figure 9. From the geometry of fillet welded structure of critical locations, FAT90 ($\Delta\sigma_{FAT}$ = 90 *Mpa*) is proposed as design fatigue curve, as shown in Figure 6. The calculated results show that the maximum values of the stress ranges are smaller than the fatigue limit ($\Delta\sigma_e$ = 52.70 *MPa*) of FAT90. Therefore, the parameters of Equation (4) are chosen as follows: m_2 = 5, C_2 = 4.064×10^{15}. In general, the fatigue failure occurs when cumulative fatigue damage of D_f = 1, as defined in Equation (5). However, recent research indicates that assuming D_f = 1 may not be satisfactory for fatigue design of welded joint structures. Here, this problem is partially solved by recommending a value of D_f = 0.5 [3].

Table 2 summarizes the fatigue life analysis results of the critical locations of fillet welded structure on the chassis frame of semi trailer using the hot spot stress approach. Were, the fatigue life values of N (cycles) were converted into the travel distance (L) of vehicle. It can be seen that:

the maximum values of stress ranges and the number of cycles at the location ④ are both greater than those at the location ②. But the fatigue life at the location ② is less than that at the location ④. This is explained by the influence of the mean stress value: the mean stress value of the stress cycles at location ② is greater than that at the location ④.

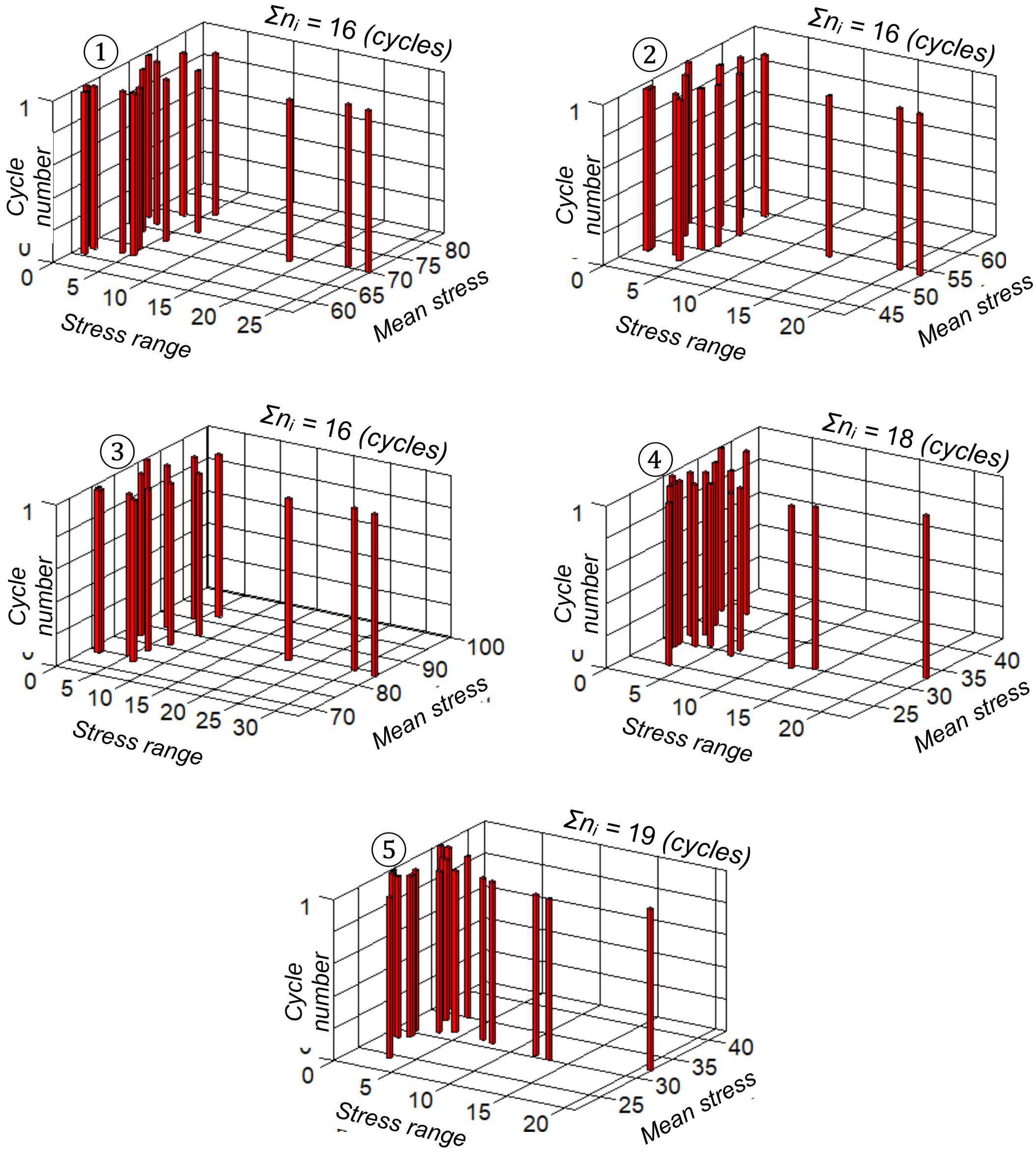

Figure 9. *Statistical characteristics of hot spot stress-time histories with 150 load steps*

The results of fatigue life analysis also show that: the minimum fatigue life of $N = 2.94{\times}10^7$ at location ③ is greater than the number of cycles of the fatigue limit ($N_e = 10^7$), which indicates that the fillet welded structure of semi trailer's chassis frame meet the fatigue strength requirements. On the other hand, considering the average vehicle travel distance of around 45,000 kilometers per year in the case of full load, that means about 15 years can be expected for the service life of semi trailer, which is consistent for the conditions of use in Vietnam.

__Table 2.__ Fatigue life analysis results

Location	$\Delta\sigma_{max}$ (MPa)	Fatigue life, N ($cycles$)	Vehicle travel distance, L (km)
①	26.43	8.93×10^{7}	2.23×10^{6}
②	21.91	2.37×10^{8}	5.94×10^{6}
③	33.07	2.94×10^{7}	7.36×10^{5}
④	22.50	3.06×10^{8}	7.65×10^{6}
⑤	20.73	4.50×10^{8}	1.13×10^{7}

IV. CONCLUSIONS AND PERSPECTIVES

Mechanical structures such as automotive welded structures usually have complicated geometry and loads. That is the reason for applying the hot spot approach to the fatigue life assessment of welded structures. In this paper, the combined method of the FEA and MBDS is proposed to analyse structural stress-time histories of the chassis frame of semi trailer, which was locally manufactured in Vietnam. In FE model, both the stiffness and geometry of welded structures are considered by using shell element. The structural hot spot stress is calculated by the linear extrapolation of stress at the reference points. The fatigue life of the typical critical locations of fillet welded structures is determined using the hot spot stress approach with selected fatigue curve corresponding to the fatigue class of FAT90 according to IIW recommendations.

The fatigue life analysis of fillet welded structures is performed under the conditions of the vehicle operating on the bad road surface level of *D* grade, vehicle speed of 60 *km/h*. The calculation results show that: the fillet welded structures of the chassis frame meet the fatigue strength requirement with the minimum fatigue life of 2.94×10^{7} cycles. This number of cycles corresponds to the vehicle travel distance of 7.36×10^{5} kilometers or the vehicle service life of about 15 years in the conditions of use in Vietnam.

ACKNOWLEDGMENT

This research is funded by University of Transport and Communications under grant number T2020-CK-009.

References

[1]. *Richards K. G.*, Fatigue strength of welded structures. Welding Institute, Cambridge, 1969.

[2]. *Niemi E.*, Stress Determination for Fatigue Analysis of Welded Components. The International Institute of Welding, IIW doc. IIS/IIW-1221-93, 1995.

[3]. *Hobbacher A.*, Recommendation for fatigue Design of Welded Joints and Components. The International Institute of Welding, IIW-1823-07 ex. XIII-2151r4-07/XV-1254r4-07, 2008.

[4]. *Savaidis G., Vormwald M.*, Hot-Spot Stress Evaluation of Fatigue in Welded Structural Connections Supported by Finite Element Analysis. International Journal of Fatigue, Vol. 22 (2), 2000, pp. 85-91.

https://doi.org/10.1016/S0142-1123(99)00119-X.

[5]. *Lee J. M., Seo J. K., Kim M. H., Shin S. B., Han M. S., Park J. S.*, Mahendran M., Comparison of Hot Spot Stress Evaluation Methods for Welded Structures. International Journal of Naval Architecture and Ocean Engineering, Vol. 2 (4), 2010, pp.200-210. https://doi.org/10.2478/IJNAOE-2013-0037.

[6]. *Fayard, J., Bignonnet, A., Dang Van, K.*, Fatigue Design Criterion For Welded Structures. Fatigue & Fracture of Engineering Materials & Structures, Vol. 19(6), 1996, pp.723-729. https://doi.org/10.1111/j.1460-2695.1996.tb01317.x.

[7]. *Goes K. C., Camarao A. F., Pereira M., Batalha G. F.*, A Fatigue Life Prediction Model of Welded Joints under Combined Cyclic Loading. AIP Conference Proceedings (AMPT2010), 24–27 October 2010, Paris, France, Vol. 1315 (1), 2011, pp.801-806. https://doi.org/10.1063/1.3552548.

[8]. *Chattopadhyay, A., Glinka, G., El-Zein, M., Qian J.*, Formas R. A., Stress Analysis and Fatigue of Welded Structures. Welding in The World, Vol. 55, 2011, pp.2-21. https://doi.org/10.1007/BF03321303.

[9]. *Wu J. D.(Dat Tuan Vu), Dong D. W., Yan B., Wang Y. W.*, Dynamic Response Analysis and Bogie Frame Fatigue Life Prediction of Hydraulic Modular Trailers. Machine Design & Manufacture, Vol. 276 (2), 2014, pp. 69-72, (in China). https://doi.org/10.19356/j.cnki.1001-3997.2014.02.022

[10]. *Bennebacha M., Klein P., Kirchner E.*, Several Seam Weld Finite Element Idealizations Challenged in Fatigue within A French Industrial Collaborative Workgroup. Procedia Engineering, Vol. 213, 2018, pp.403-417. https://doi.org/10.1016/j.proeng.2018.02.040.

[11]. *Miao B. R., Zhang W. H., Zhang J. H., Jin D. Ch.*, Evaluation of Railway Vehicle Car Body Fatigue Life and Durability Using Multi-Disciplinary Analysis Method. International Journal of Vehicle Structures & Systems, Vol. 1(4), 2009, pp.85-92. http://dx.doi.org/10.4273/ijvss.1.4.05.

[12]. *Wu J. D.(Dat Tuan Vu), Dong D. W., Yan B., Wang Y. W., Sun Y. H.*, Dynamic Response Characteristics and Swing-Arm Fatigue Analysis for A Hydraulic Modular Trailer Based On Rigid-Flexible Coupling Simulation. Journal of Vibration and Shock, Vol. 33(7), 2014, pp.37-44, (in China). https://doi.org/10.13465/j.cnki.jvs.2014.07.007.

[13]. *GB/T7031-2005*: Mechanical Vibration - Road Surface Profiles - Reporting of Measured Data. Chinese National Standard, 2005.

[14]. *Liu X. D., Deng Zh. D., Gao F.*, Research on The Method of Simulating Road Roughness Numerically. China: Journal of Beijing University of Aeronautics and Astronautics, Vol. 29 (9), 2003, pp.843-846, (in China). https://doi.org/10.13700/j.bh.1001-5965.2003.09.021.

[15]. *HBM-nCode*. ANSYS 15.0 nCode DesignLife - DesignLife Theory Guide. HBM United Kingdom Limited, 2013.

[16] *Fatemi A., Yang L.*, Cumulative Fatigue Damage and Life Prediction Theories: A Survey of the State of the Art for Homogeneous Materials. International Journal of Fatigue, Vol. 20(1), 1998, pp.9-34. https://doi.org/10.1016/S0142-1123(97)00081-9.