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FATIGUE LIFE EVALUATION OF BULK CEMENT TANK TRAILER FRAME BASED ON HOT SPOT STRESS APPROACH USING THE COMBINED FE/MBD METHOD

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Abstract. The bulk cement tanker trailer frame is the main load-bearing component, and it is manufactured by the welding method. Therefore, it is necessary to evaluate the fatigue strength of the trailer frame. In this study, the fatigue stress of this structure is determined by using the hot spot stress approach. First, a combined method of finite element (FE) analysis and multi-body dynamics (MBD) simulation is used to analyse the structural stress. Considering the factors of speed and road surface class in operating conditions in Vietnam, MBD simulation is used to determine the dynamic load acting on the trailer frame when the trailer is excited by an uneven road surface. The nodal stress in the time domain is determined by structural dynamic analysis of the trailer frame with this dynamic load. The linear extrapolation of stress at the reference points is then used to determine the structural hot spot stress of the critical locations. Finally, the selected fatigue curve that corresponds to the related fatigue class (FAT) is used to calculate the fatigue life. In the fatigue analysis model, the cumulative fatigue damage value is chosen taking into account the durability degradation due to the thermal influence of the welded structures.

Keywords: bulk cement tanker trailer frame, welded structure, fatigue life, hot spot stress approach, finite element analysis, multi-body dynamic simulation.

1. INTRODUCTION

The frame component of the bulk cement tanker trailer is the main load-bearing structure, has an intricate shape, and is manufactured by the welding method. It is well known that welding is an efficient and economical method of permanently joining metal structures. However, due to the thermal influence, it causes geometrical deformation, stress concentration, and changes in the properties of the parent metal. This also reduces the durability of the welded structures [1]. On the other hand, the trailer frame is often subjected to dynamic loads due to uneven road surfaces during the movement of the trailer, which causes cyclic stresses and can lead to fatigue damage. Therefore, when assessing the durability of the trailer frame, it is important to prioritize evaluating the fatigue strength of the welded joint and adjacent parent metal region. Structural fatigue analysis is generally based on fatigue stress data and classified S-N curves of material. There are many different methods to determine the fatigue stress of a welded joint, such as nominal stress, hot spot stress, effective notch stress, etc. [2, 3]. For structures with complicated geometry and loads that make it difficult to estimate the nominal stress, the hot spot stress approach is often used as an effective method to determine the fatigue stress in the crack initiation period [4, 5]. The "hot spot" is simply the critical location where the initiation of the fatigue crack is likely to occur, which for a welded joint is at the weld toe. The stress at this point is known as the hot spot stress, which is also referred to as structural or geometric stress. When applying the FE method to analyze structures, meshing elements according to the proposed rule by the hot spot stress approach also facilitates the determination of nodal stress at reference points to calculate the hot spot stress.

This paper presents a combined method utilizing FE analysis and MBD simulation for structural analysis in the time domain [6, 7, 8]. The MBD model of the full vehicle is built with the object of the trailer frame transferred from the modal neutral file of the FE model. The dynamic loads acting on the trailer frame due to random excitations of uneven road surfaces were obtained through MBD simulation results. Under the impact of these dynamic loads, a structural dynamic analysis of the FE model was conducted to determine the nodal stress-time histories for the trailer frame. The hot spot stress is calculated from the stress values of reference points based on the extrapolation rule according to IIW recommendations [2]. The fatigue curve for the related fatigue class (FAT) and statistical characteristics of stress cycles are used to determine the fatigue life of critical locations in the trailer frame structure. Additionally, the durability degradation brought on by the thermal influence of welded structure is partially resolved by appropriately choosing the cumulative fatigue damage value.

2. METHODOLOGY

2.1. Finite element model

The research object for this paper is a V-type bulk cement tank trailer as shown in Figure 1. The basic specifications of the trailer are described in Table 1. The trailer frame component is divided into the front frame and the rear frame, as shown in Figure 2. The frame structure is mainly made of JIS-G3106 SM490A steel plate, which is equivalent to Q345C steel.

When building the FE model with ANSYS software, the following assumptions are made: disregarding the components such as side guardrails, fenders, air pipes, etc. and other parts that have little effect on the bearing capacity of frame structure; the welds are not modelled. The Shell63 elements with varied real constants of thickness are used to mesh nodes and elements as shown in Figure 3. In this FE model, 11 interface nodes (INF.#) are created and connected to the nodes on the frame by rigid regions. These nodes are used as connection points to other objects in the MBD model. The "*ANSYS-ADAMS interface feature*" is used to create a modal neutral file (*.*mnf*). This file contains the structural parameters of the trailer frame, such as mass, center of mass, moment of inertia, etc.

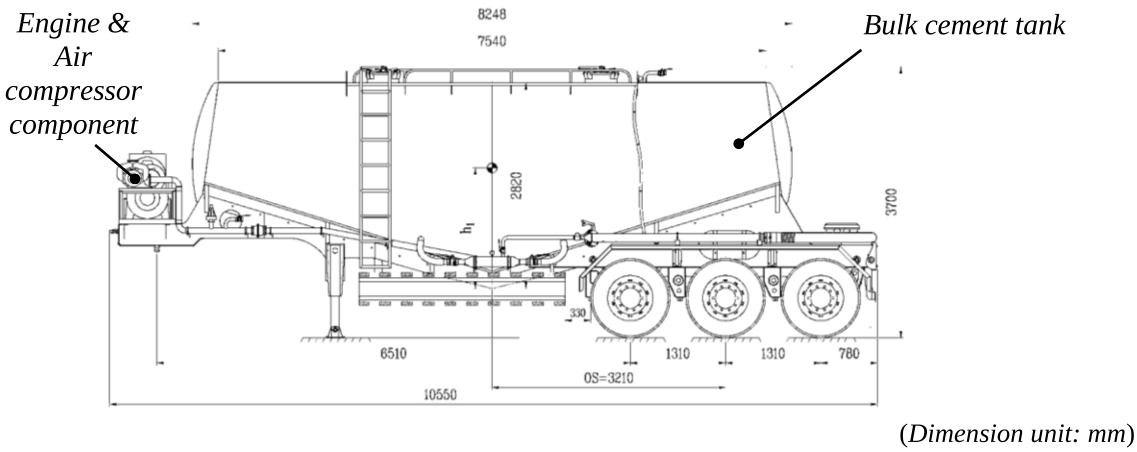
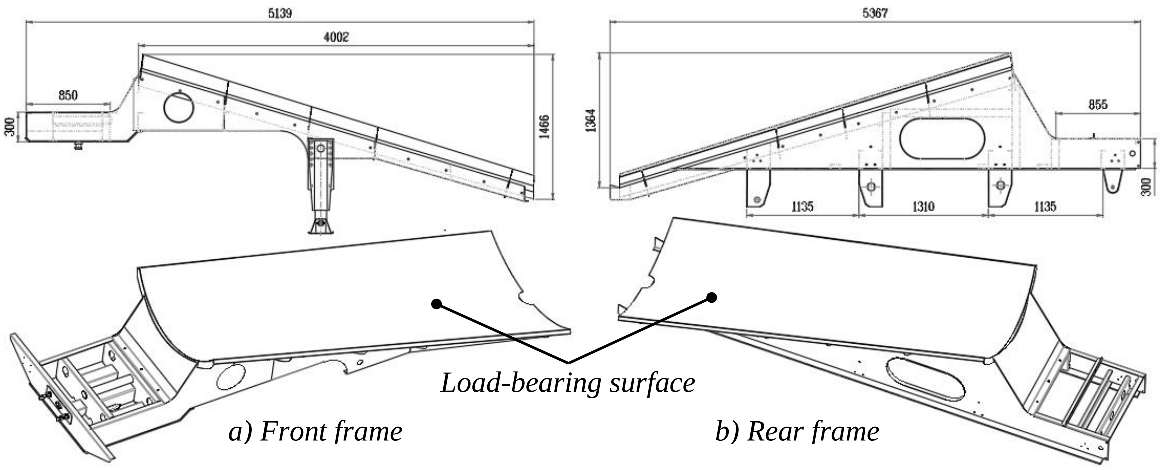


Figure 1. Bulk cement tank trailer configuration.

Table 1. The basic specifications of the trailer.

Specifications	**Value (*unit*)**
Model	V-shaped of tank
Size: *L*×*W*×*H*	10.55×2.49×3.70 (*m*)
Tare weight	7,730 (*kg*)
Tanker capacity	29,3754 (*l*)
King pin	JOST 2.0 bolting type
Axle number	03
Tire size	11.00-20
Payload	31,260 (*kg*)
Total weight	38,990 (*kg*)



(*Dimension unit: mm*)

Figure 2. Trailer frame component.

Figure 3. FE model of trailer frame.

2.2. Multi-body dynamic model

ADAMS software is used to build an MBD model of the 5-axle full vehicle, including the tractor and bulk cement tank trailer. The object of the trailer frame is created in this model by importing the modal neutral file (*.*mnf*), and the other rigid objects are connected to the trailer frame using various constraint types of joints. When simulating a vehicle moving in a straight line with constant speed, it is assumed that uneven road surfaces are the only source of excitation causing oscillations in the system. Considering the operating conditions in Vietnam, the road surface selected for simulation is D class, as defined by ISO:8608-2016 [9], which corresponds to the worst quality urban or extra-urban highways [10, 11]. Road roughness is numerically simulated using the Inverse Fast Fourier Transform method [12, 13] with the vehicle speed set to 60 *km/h* (16.67 *m/s*) and the time increments set to 0.01 seconds. The road roughness random excitation in the time domain of D class is shown in Figure 4.

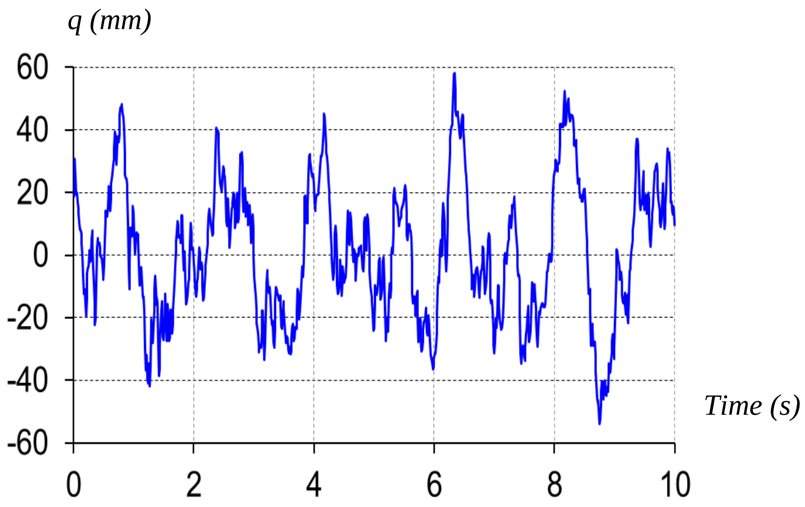


Figure 4. Road roughness in the time domain of *D* class with vehicle speed of 60 *km/h*.

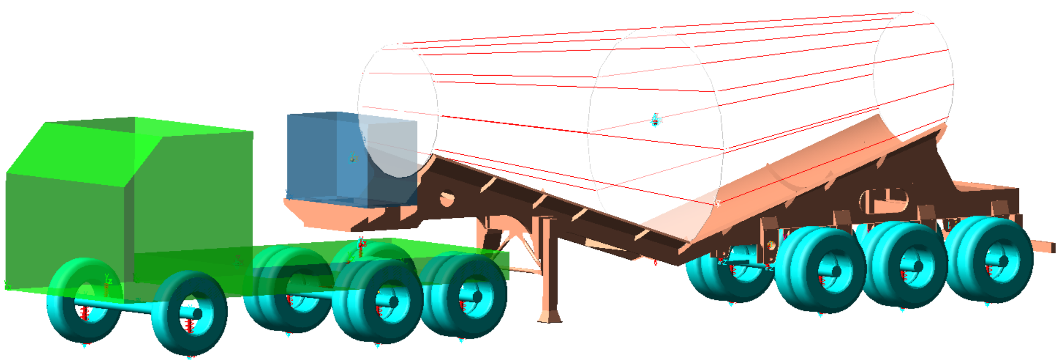


Figure 5. MBD model of the full vehicle.

The MBD model of full vehicle with 19 degrees of freedom (DOF) is built as shown in Figure 5. The DOF of each object in this model is described specifically in Table 2.

Table 2. The DOF of the MBD model.

Component	Object	Degrees of freedom
Tractor (*Tr*)	Sprung mass	Vertical displacement y_{SP}^{Tr}, and pitch angle φ_{Z-SP}^{Tr}.
	Front axle	Vertical displacement y_{AX1}^{Tr}, and roll angle φ_{X-AX1}^{Tr}.
	Rear axle	Vertical displacement y_{AX2}^{Tr}, roll angle φ_{X-AX2}^{Tr}, and pitch angle φ_{Z-AX2}^{Tr}.
Bulk cement tank trailer (*BCT*)	Trailer frame	Vertical displacement y_{TF}^{BCT}, and pitch angle φ_{Z-TF}^{BCT}.
	Tank with full load	Fixed to the trailer frame.
	Engine & Air compressor	Fixed to the trailer frame.

	Each axle of the trailer	Vertical displacement y_{AXi}^{BCT}, and roll angle φ_{X-AXi}^{BCT}, (i = 3, 4, 5).
	Equalizer arm between axles	Pitch angle φ_{Zj}^{BCT}, (j = 1, 2, 3, 4)

2.4. Fatigue life analysis model

Hot spot stress calculations are based on linear or quadratic extrapolation of the stress from two or three reference points at some distance from the weld toe. If the weld is not modelled, extrapolation to the structural intersection point is recommended in order to avoid stress underestimation due to the missing stiffness of the weld. The number and spacing of reference points and extrapolation equations are selected depending on the weld structure, plate thickness and meshing rules. In this paper, the hot spot stress (σ_{hs}) is calculated based on linear extrapolation from Equation (1) with $m = 0.5t_1$ and $n = 1.5t_1$ [2], as shown in Figure 6.

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

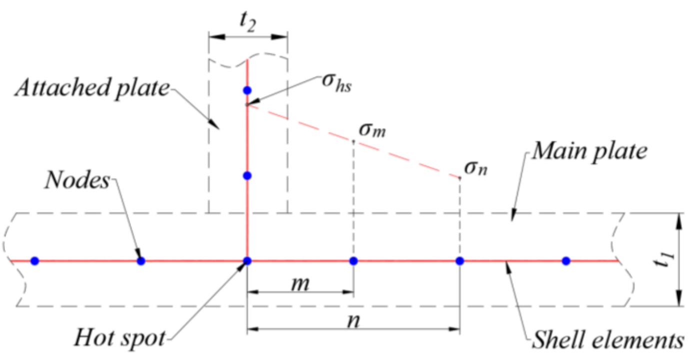


Figure 6. Model for calculating hot spot stress.

Based on the hot spot stress range ($\Delta\sigma$) and the geometry of the weld, fatigue curves ($\Delta\sigma - N$) are established using Equation (2) to calculate the fatigue life of the welded structure:

$$N = \begin{cases} \dfrac{C_1}{\Delta\sigma^{m_1}} & if \quad \Delta\sigma_e < \Delta\sigma \\ \dfrac{C_2}{\Delta\sigma^{m_2}} & if \quad \Delta\sigma < \Delta\sigma_e \end{cases}. \quad (2)$$

Where, N is number of cycles to failure; C is the constant coefficient;. 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 ($\Delta\sigma_e$); m_i is the exponent of fatigue curve, $m_1 = 3$. The IIW recommendations suggest correcting the fatigue curve with $m_2 = 2m_1 - 1$ in consideration of the influence of $\Delta\sigma < \Delta\sigma_e$ causing fatigue damage due to the high-cycle cyclic load of the structure. After correction, the fatigue curves corresponding to the fatigue classes are shown in Figure 7 [2].

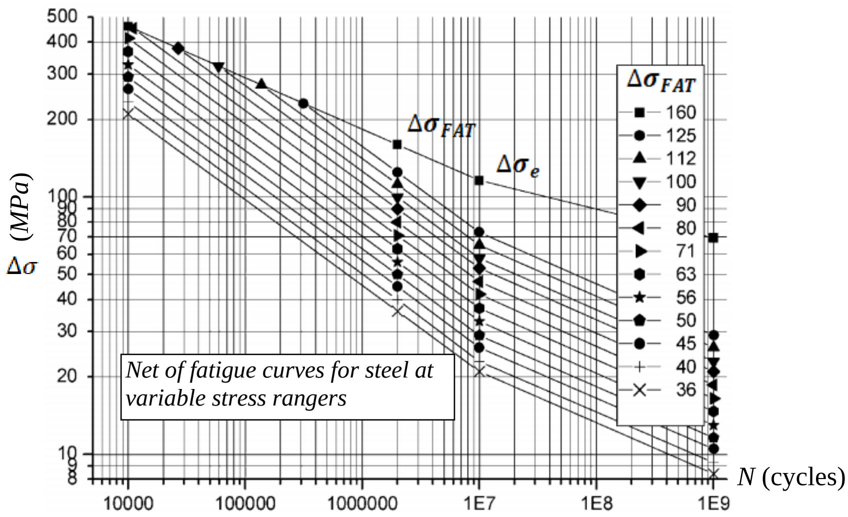


Figure 7. Fatigue curves correspond with the fatigue classes (FAT) [2].

The Rain-flow Counting algorithm [14] is used to count the statistical characteristics of stress-time histories for different stress ranges. This includes the number of stress cycles (n_i) in the stress range ($\Delta\sigma_i$), which corresponds to the number of cycles to failure (N_i). It makes it possible to calculate the cumulative fatigue damage (D_f) from Equation (3) using Palmgren-Miner's rule [15].

$$D_f = \sum D_i = \sum \frac{n_i}{N_i} . \tag{3}$$

3. REULTS AND DISCUSIONS

3.1. Hot Spot Stress Calculation

The dynamic load acting on the trailer frame in the time domain with 500 load steps was obtained by performing MBS simulation for 5 seconds. Structural dynamic analysis of the FE model of the trailer frame was carried out using this dynamic load. The analysis results show that some typical critical locations have high stress concentrations, as shown in Figure 8 and described in Table 3. Figure 9 shows the hot spot stress-time histories of the critical locations are calculated from the nodal stress data of reference points based on Equation (1).

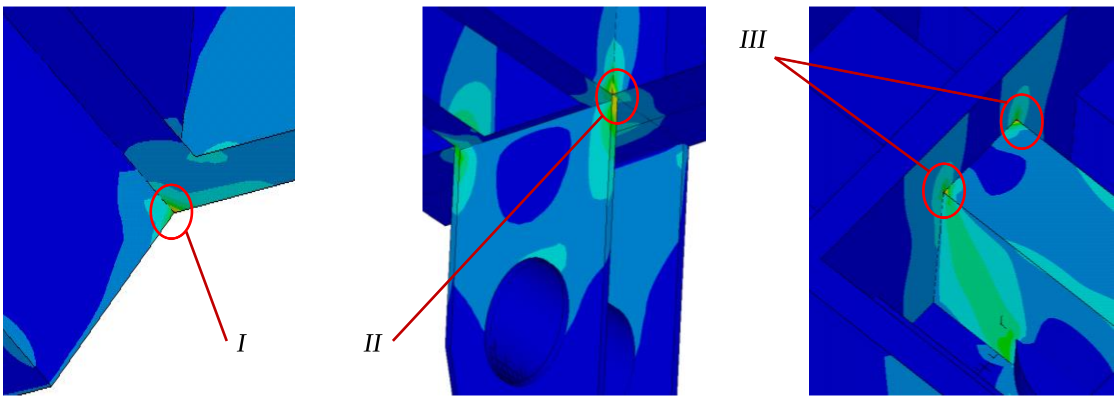


Figure 8. Equivalent stress distribution of typical critical locations.

Table 3. Description of critical locations.

Location	The welded joint positions with concentrated stress
I	Between 4th crossmember and main longitudinal beam
II	Between 2nd suspension hanger, transverse beam and main longitudinal beam
III	Between 2nd crossmember and longitudinal reinforced beam of mounting bracket of traction pin

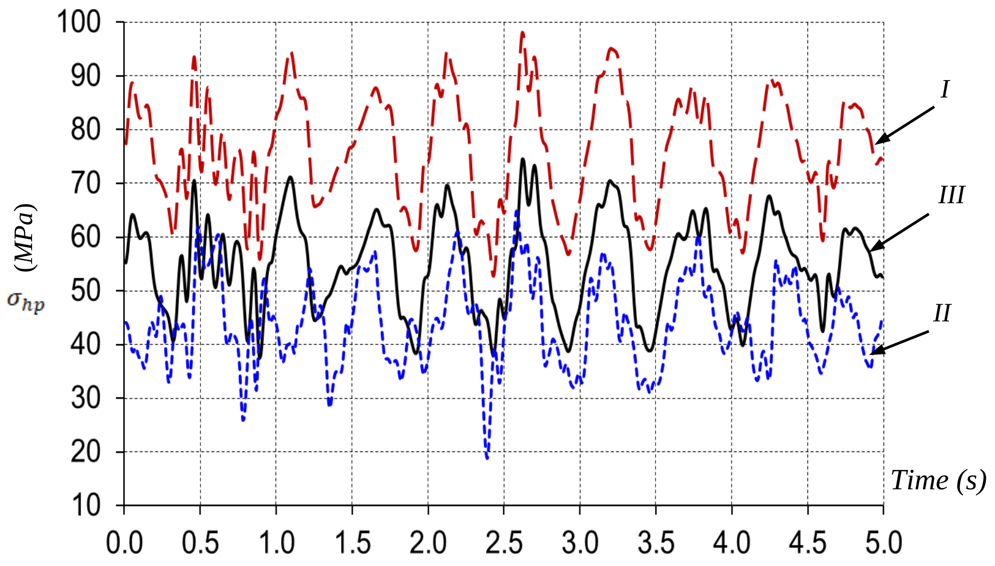


Figure 9. Hot spot stress-time histories of the critical locations.

3.2. Fatigue Life Analysis

The statistical characteristics of the hot spot stress-time histories of the critical locations with 500 load steps are as shown in Figure 10. Based on the weld structure of the critical locations, the fatigue curve corresponding to FAT100 is selected to calculate the fatigue life according to Equation (2) with $\Delta\sigma_e$ = 58.5 *Mpa*, C_1 = 2.0×10^{12}, and C_2 = 6.851×10^{15} [2]. For metallic materials, it is generally assumed that fatigue crack initiation occurs when D_f = 1, as indicated by Equation (3). But due to thermal influence that reduces the durability of the welded structures, D_f = 1 could not be sufficient for the fatigue design. The value D_f = 0.7 is suggested here as a partial solution to this problem.

Table 4 provides a summary of the fatigue life analysis results for the critical locations of the trailer frame, converting the fatigue life cycles (N) into the travel distance (L) of the trailer. The minimum fatigue life of $N_{min} \approx$ 8.28×10^7 (*cycles*) at location I corresponds to a travel distance of $L \approx$ 6.91×10^5 (*km*). Considering the average travel distance of a bulk cement tank trailer is 50,000 km per year in full load condition, it means that the service life (S) of the trailer frame is about 13.8 years. This is acceptable under operating conditions in Vietnam.

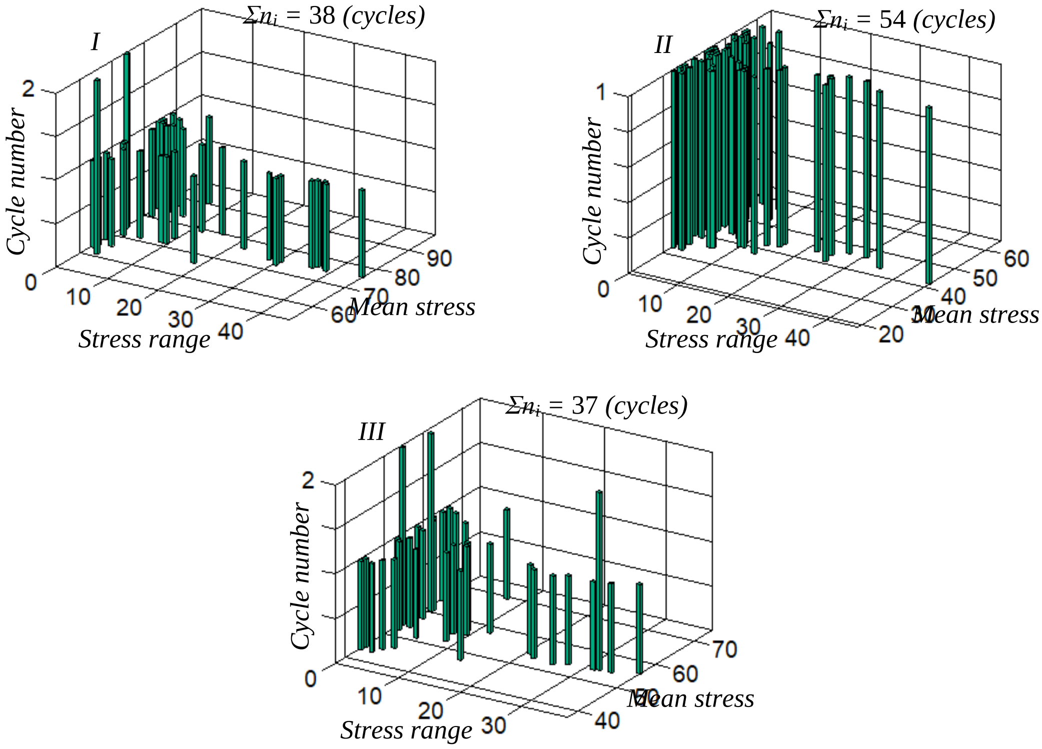


Figure 10. Statistical characteristics of hot spot stress-time histories.

Table 4. Fatigue life analysis results.

Location	Fatigue life, ***N*** (***cycles***)	Trailer travel distance, ***L*** (***km***)	Service life, ***S*** (year)
I	8.28×10^{6}	6.91×10^{5}	13.8
II	1.41×10^{7}	1.18×10^{6}	23.6
III	2.01×10^{7}	1.67×10^{6}	33.5

4. CONCLUSION

The structural characteristics of a bulk cement tank trailer include heavy loads, intricate shapes, and its parts are permanently connected by welding. For this reason, the hot spot stress approach is used to calculate the fatigue stress of the welded structure. The nodal stress-time histories of the trailer frame are to be determined using the combined method of FE analysis and MBD simulation. In accordance with IIW recommendations, the hot spot stress is calculated using the linear extrapolation rule from the stress values of two reference points. A selected fatigue curve that corresponds to the fatigue class of FAT100 is used to calculate the fatigue life of the typical critical locations. Additionally, the cumulative fatigue damage value, D_f = 0.7, is chosen to account for the durability degradation of the welded structures due to thermal influence. Assuming the operating conditions of the trailer at 60 km/h on a bad road surface of D class, the calculation results show that the minimum fatigue life of the trailer frame structure is 8.28×10^{6} cycles. This value corresponds to a travel distance of 6.91×10^{5} kilometers, or a service life of about 13.8 years. Under Vietnamese operating conditions, this is acceptable.

Enhancing the fatigue resistance of welded structures through techniques including structural optimization, the use of appropriate materials, or the improvement of the weld profile and residual stress condition is the next research direction of the author.

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