FATIGUE EVALUATION OF TANK SEMI-TRAILER FRAME MADE OF DUPLEX STEEL

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Abstract

The frames of tank semi-trailers are usually made of carbon steel. However, this steel is susceptible to corrosion. During the exploitation of the semi-trailer, the protective paint layer is damaged, and the frame is exposed to the atmospheric effects, road salts, and other reagents used in cold weather conditions. According to this metal forming company AB Astra LT aims to design and produce a lightweight tank semi-trailer for the food industry products, the production of which stainless steel would be used. For this purpose, LDX 2101 duplex steel was chosen. This steel not only looks good aesthetically but also has high corrosion resistance and high mechanical strength.

This paper presents the fatigue analysis of the frame of a tank semi-trailer. To accomplish this task the experimental fatigue tests of x-type specimen were conducted, and FEM simulations were performed. Experimental tests were used for the construction of the S-N curve of welded duplex steel. Later, this curve was used in numerical simulation. The FEM simulation was performed in several steps. First, the dynamic analysis of the whole semi-trailer frame with a tank was performed, imitating driving on an uneven paved asphalt road. This simulation allowed determining the most loaded section of the frame and the stress profile vs time at this section. The second model was the small portion of the most loaded part of the beam of the semi-trailer frame. Using the beam model, the experimentally determined S-N curve and the loading spectra were applied, and as a result, the total lifetime cycles were determined. Research has shown that the designed tank semi-trailer can travel up to 5.1 million km on uneven paved asphalt roads.

Keywords: Duplex steel, fatigue analysis, x-type specimen test

1. INTRODUCTION

Lithuanian metal forming company AB Astra LT aims to design and produce a lightweight tank semi-trailer for food industry products. The priorities of the newly designed semi-trailer would be weight reduction, increased durability, and attractive appearance. Naturally, the choice of the material was stainless steel. The stainless steel not only has good aesthetic looks but also has corrosion resistance. The most common choice in terms of material in food industry is AISI 304 and AISI 316 [1]. However, these steels are considered as mild steels and using them for the design of the semi-trailer frame would increase its dimensions, weight, and price. Therefore, the duplex LDX 2010 steel was selected for the design and manufacture of the frame. According to EN standard [2] LDX 2101 has ~2 times higher yield strength and at least 1.25 times higher ultimate strength compared to AISI 304 and AISI 316 steels. On the other hand, duplex has poorer weldability [3] and unknown durability of the weld joint. Deeper knowledge is needed on LDX 2101 weld joint cyclic strength to properly design the semi-trailer frame.

The aim of this works is to evaluate the fatigue of the tank semi-trailer frame and to predict its lifetime as a max driven distance. For this purpose, the fatigue experimental research of weld joint of duplex LDX 2010 steel was conducted, the evaluation of the maximal equivalent stress profile in the frame due to the trailer's response to the uneven (roughly) paved asphalt road was performed, and the prediction of the driven distance up to a significant fatigue damage was done.

2. RESEARCH MATERIAL AND EXPERIMENTAL TESTS

The main task of this research is the evaluation of the fatigue of the semi-trailer frame made of duplex LDX 2101 steel. LDX 2101 steel has yield strength $R_{p0.2}$ = 584 MPa and strength limit R_m = 759 MPa. However, the durability of the T-type weld joint is unknown. Therefore, an experimental campaign was conducted to construct the S-N curve of welded LDX 2101 steel and evaluate its resistance to cyclic fatigue. The semi-automatic MIG welding process and Cromacore DW 329A filler metal were selected for the weld. The weld metal's strength $R_{p0.2}$ = 601 MPa and strength limit R_m = 844 MPa. The modulus of elasticity E = 200 GPa and Poisson's ration v = 0.3 is the same for both materials.

According to the recommendations of the International Institute of Welding (IIW) [4] the x-type specimen was produced for the experimental testing of tee-type weld joint. The shape and dimensions of the specimen are presented in the **Figure 1**.

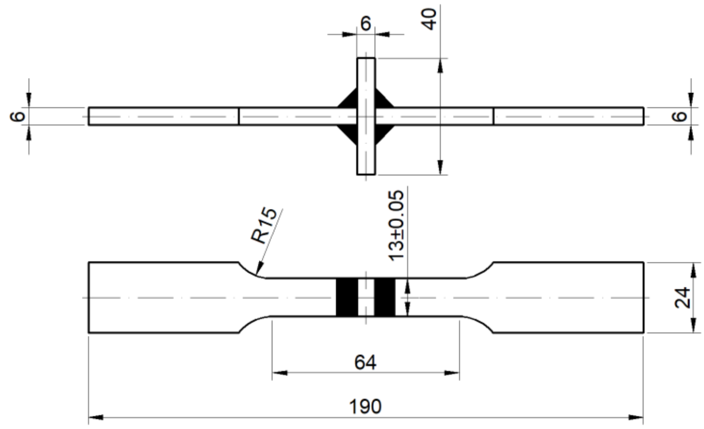


Figure 1 The sketch of x-type specimen

IIW [4] recommends conducting a minimum of 10 fatigue tests at different loadings for the construction of S-N curve and determining so called fatigue class (FAT). The fatigue tests of 19 specimens were conducted at different stress ranges in stress control conditions and stress ratio R = 0. Experimental testing was conducted at Instron Model 8801 test machine.

The welded connection fatigue strength is expressed in a logarithmic scale as:

$$logN = logC - m \cdot log\Delta\sigma \tag{1}$$

where:

N - number of cycles

C - constant of the curve

m - coefficient of the slope of the curve

$\Delta\sigma$ - the stress range (MPa)

The FAT class is determined as a stress range level $\Delta\sigma$ at the cycle number $N = 2 \times 10^6$. The experimental data and determination of S-N curve according to IIW is presented in **Figure 2**. Initially, the best fit line of experimental data was determined (line No 1) and the curve slope coefficient = 3.8 was determined. This line has the survival probability of 50 %. The second line of the S-N curve was determined with the increased survival probability up to 97.7 %. FAT 120 class of welded LDX 2101 steel was determined using the second line. However, it is recommended to consider, that residual stresses in small specimens are usually small and vice versa. Therefore, the determined result must be corrected to evaluate the residual stress effect in real constructions. it is recommended to reduce the determined FAT class by 20 % in case of the experiments conducted at cyclic loading stress ratio R = 0. The corrected curve is shown as line No., 3 and the determined fatigue class is FAT 96.

The S-N curves are assumed to stop decreasing at the fatigue limit, below which failure will not occur. In that case, the S-N curve becomes horizontal. Traditionally, the fatigue limit was determined at cycle number $N = 10^7$ for steel components. However, the research in this field, especially for welded joints, showed that this limit does not exist, and according to IIW the S-N curve over $N = 10^7$ point should continue with a 10 % decrease of the stress up to $N = 10^9$ cycles, which corresponds to a slope coefficient m = 22. According to that, the previously determined line No. 3 was extended up to $N = 10^9$ cycles with a 10 % slope and with the knee point at $N = 10^7$.

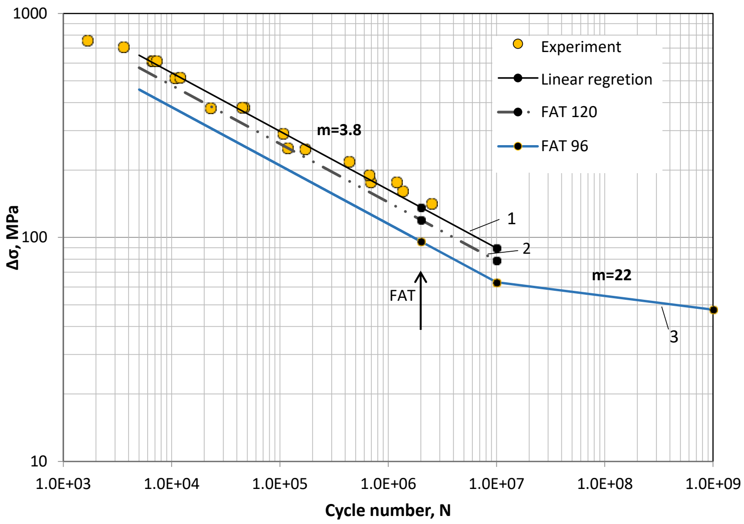


Figure 2 S-N curve of welded LDX 2101 steel x-type specimen

3. FATIGUE EVALUATION OF THE TANK SEMI-TRAILER FRAME

3.1 Dynamic analysis of the frame

The computer model of the tanker semi-trailer was created, and the analysis was performed using the modern finite element method (FEM) computer program Ansys Workbench. This model includes a tank, originally designed frame elements, and some standard components of a chassis and semi-trailer coupling mechanism. The static analyses evaluate various possible semi-trailer loading scenarios, such as driving up the hill, down the hill, driving on a road with high camber, through a pothole, etc. All these scenarios were used to correctly select the frame elements' dimensions. After the design was approved by static analyses, the dynamic analyses were done to evaluate the cyclic loading induced by the unevenness of the road.

A few types of road pavements were considered in the dynamic analysis, i.e. smooth asphalt, uneven asphalt, and gravel. The analysis showed that the highest cyclic loading is induced by the gravel paved road, while the smallest loading was determined by the smooth asphalt paved road. An example of the evaluation of the cyclic loading induced by the road paved with uneven asphalt is presented in this paper.

100 m long fragment of the uneven asphalt-paved road used in the dynamic analysis is shown in **Figure 3**. The figure shows the road profiles for the left and right wheel tracks/ruts. This fragment is the record of the real measurement of the road in Lithuania. The record was made by the measurement with the laser profilograph DYNATEST 5051 RSP [5].

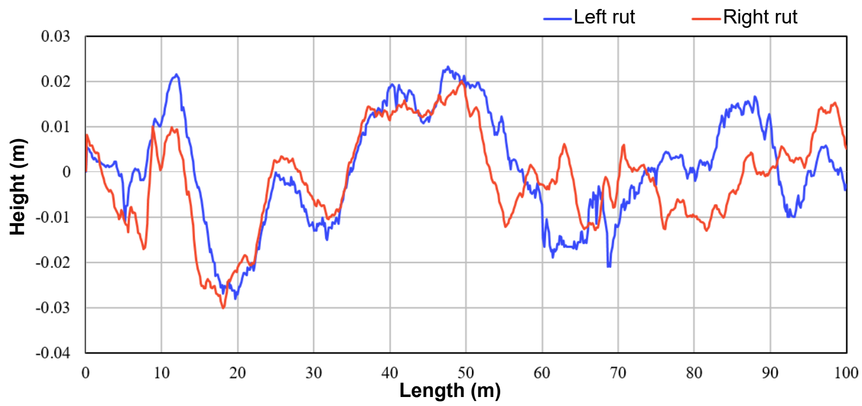


Figure 3 The fragment of the uneven asphalt-paved road longitudinal microprofiles for a left and right wheel tracks/ruts

The dynamic analysis of the tank semi-trailer frame was conducted on an uneven asphalt paved road when the driving speed was 70 km/h. The determined maximal equivalent stress profile is shown in **Figure 4**. As seen, the highest stress reaches 153.2 MPa while the lowest – 60.02 MPa, what means that the loading cycle stress range is $\Delta\sigma$ = 93.18 MPa.

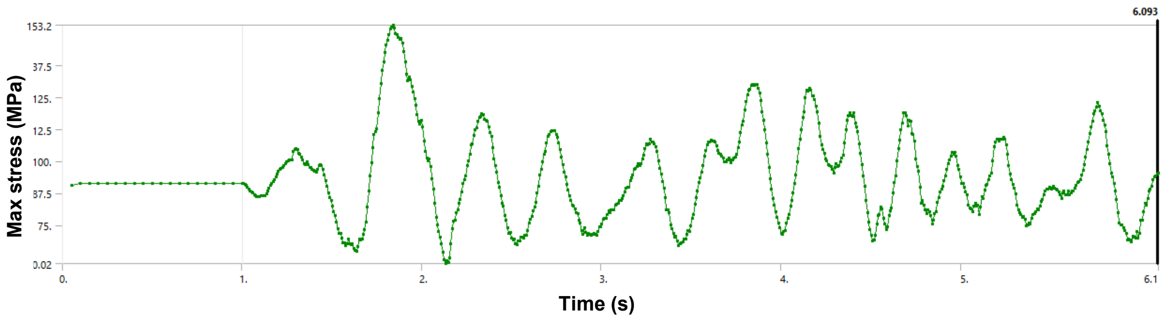


Figure 4 Maximal equivalent stress profile in the frame

The equivalent stress distribution in the main load-bearing beams of the frame at the time of 1.85 s is shown in the **Figure 5**. The highest stress was determined at the weld joint between the web and the flange of the main load-bearing beam of the tank semi-trailer frame. The separate FE model of the small section of the beam was analysed to evaluate the fatigue of the weld joint in this area. This analysis is presented in the next chapter.

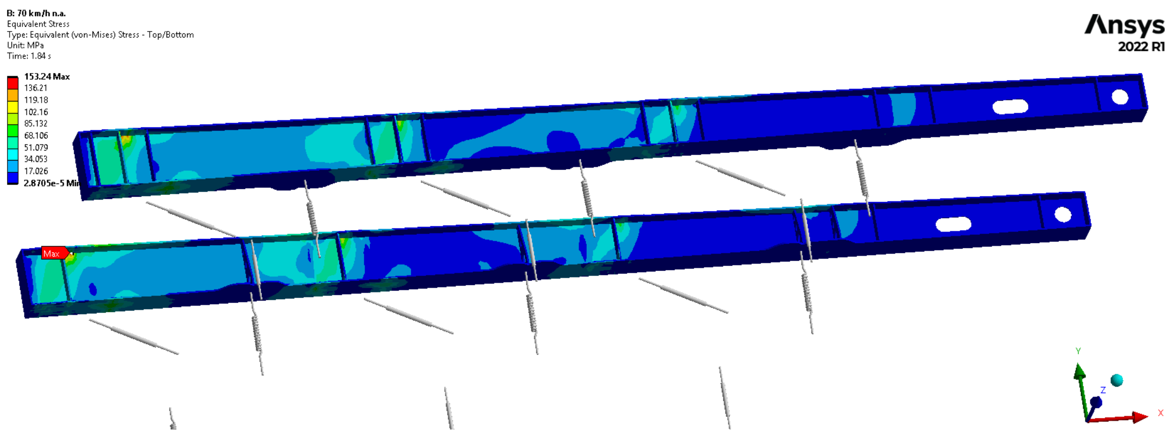
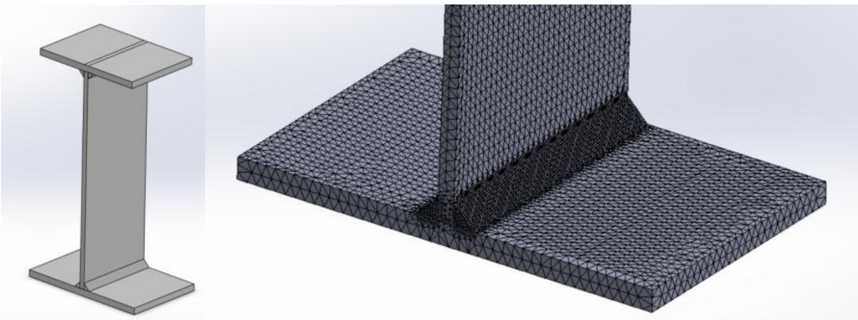


Figure 5 Equivalent stress distribution in the frame at max stress moment

3.2 Fatigue analysis of the beam section

SOLIDWORKS Simulation FE program was selected for the fatigue analysis of the beam section.

The section of a beam of the frame was selected for the analysis as it is the main load-bearing element of the semi-trailer. The numerical model of the beam segment created for the fatigue assessment of this element is shown in **Figure 6**. The finite element mesh is also shown in the figure. The BE mesh consists of 224628 elements and 335372 nodes. The material properties of LDX 2101 steel and weld material were used as described in Chapter 2.



a b

Figure 6 FE model of the semi-trailer frame section: a) numerical model; b) FE mesh

The max equivalent stress in the frame is 153.2 MPa (**Figure 4**) when the semi-trailer is driving on uneven paved asphalt at 70 km/h. Therefore, the beam section model was loaded in such a way that it reached the same stress of 153.2 MPa. The distribution of the equivalent stress is presented in **Figure 7**.

Once the stress distribution in the model has been determined, the fatigue evaluation was performed. The dynamic loading of the beam section was used as shown in **Figure 4**. The entire load variation shown in the figure was called a block and corresponds to a 100 m distance driven by the semi-trailer.

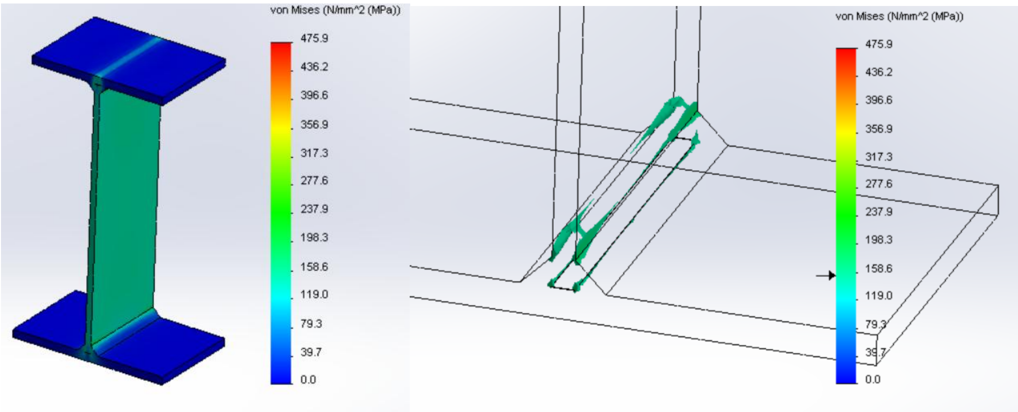


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Figure 7 Equivalent stress distribution in a beam section model: a) in the whole model; b) in the region where stresses are ≥153.2 MPa

The fatigue analysis results are presented in **Figure 8**. The results show that significant fatigue damage can occur after 5.1E+7 loading blocks. As one load block corresponds to 100 m of the road, the damage presented in **Figure 8** will occur at the tank semi-trailer frame after driving 5,100,000 km on the uneven paved asphalt road.

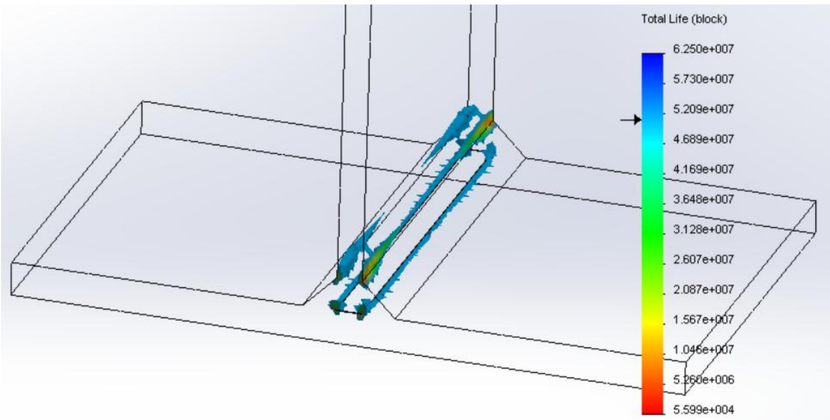

Figure 8 Finite elements of the I beam section model with a cyclic lifetime ≤5.1e7 loading blocks

4. CONCLUSIONS

The fatigue evaluation of the tank semi-trailer frame made of duplex LDX 2101 steel was performed in this study. According to the recommendations of the International Institute of Welding, experimental fatigue research was conducted, and the S-N curve as well as the fatigue class FAT 96 of the weld joint of LDX 2101 steel was determined. The fatigue evaluation was performed using the determined S-N curve and maximal equivalent stress profile in the frame of the semi-trailer. Analysis showed that the tank semi-trailer can safely travel up to 5,100,000 km on uneven paved asphalt roads at 70 km/h.

ACKNOWLEDGEMENTS

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