FATIGUE TESTS AND NUMERICAL ANALYSES OF THE PAWO AUTONOMOUS ELECTRIC VEHICLE

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Abstract

The following article presents fatigue testing and FEM numerical analysis of an autonomous electric vehicle, PAWO autonomous operational support platform. The purpose of the study, which was carried out in the ŁUKASIEWICZ – Automotive Industry Institute, was to verify the structure of the platform by forcing in three axes on the position: a table with six degrees of freedom "MAST", as well as conducting fatigue numerical analyses, allowing to determine places critical for fatigue endurance. This will be the starting point for the modification of the structure, and also will allow you to identify places that you need to pay attention to during tests and subsequent operation. The results of these tests allow us to determine critical places due to fatigue strength and possible intervention before starting field tests with a complete vehicle, as well as to detect places that should be noted during tests, inspections and tests, and in development versions of the vehicle.

Keywords: fatigue; finite elements method; finite elements analyses, autonomous electric vehicle, strength tests

1. Introduction

The research object was the autonomous operational support platform – PAWO (Figure 1), designed to navigate in unknown terrain to perform operational tasks. Project is funded by the National Center for Research and Development (Narodowe Centrum Badań i Rozwoju – NCBiR) as part of a program for young scientists for National Defence and Security.

The properties that the designed platform should have were delimited in the prism of specific tasks that it would perform. Nevertheless, analysing the utility properties of the vehicles presented in the previous section and the tendency to equip military subunits and uniformed services with high mobility equipment that supports them in effective operation in particularly difficult conditions, it is assumed that utility in field operations

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requires that the autonomous platform that is the subject of the project be characterized very high off-road mobility, which can be ensured thanks to off-road suspension, all-wheel drive and low unladen weight. Other features that a platform should have include the ability to carry small loads and move at speeds of several dozen km/h. An important aspect are also the dimensions of such a device that will ensure the required high mobility, convenient loading/access to equipment and trouble-free transport by known means. Given that the platform will be equipped with a number of advanced sensors, an undoubted advantage for their smooth operation will be the suspension, which will minimize vibrations and bounce of the vehicle when driving on uneven ground. This feature will also be very beneficial when transporting delicate loads. When transporting goods, it will be very useful to equip the platform with transport handles and a hook to pull additional equipment [12].

Considering that this vehicle will be used in difficult terrain, a very important aspect of the structure design process is the potential for fatigue phenomena. The frame structure of the PAWO vehicle is welded from steel profiles and the joints are the places where stress concentration can be expected, and thus after some time of operation, permanent deformations and fatigue cracks may occur. In the case of the structure under consideration, we are dealing with a complex spectrum of loads, stretching, compression, torsion, and bending. These loads vary over time, pulsate on both sides, so this is the most critical load model. Therefore, the allowable stress must take into account the high strength reserve. Under various assumptions, practice and experience, the allowable stress value will be at the level of 12% of the yield strength Re. Therefore, being aware of the threats to the strength of the structure, a series of analyses and tests should be carried out to capture dangerous places at the initial stage of the structure's development and, if necessary, to introduce necessary changes before starting the tests and production.

Fig. 1. 3D CAD model of the PAWO autonomous high mobility platform

2. Fatigue of materials

Equipment and machine components often work under variable load conditions (cyclical, periodically variable, random) [2, 4]. This causes changes in stresses and strains corresponding to given loads, hereinafter referred to as stresses or fatigue strains. Consequently, after exceeding a certain effort and a certain limit number of cycles (corresponding to the threshold of fatigue stress), this leads to a complex convolution of phenomena and changes called material fatigue (fatigue changes) [5, 6, 13]. The micro-fissures created as a result of variable loads gradually develop and accumulate, leading to fatigue cracking and destruction of the element or device. Two characteristic phases can be distinguished in the fatigue process:

1) crack initiation – in which local effects (fissures, cracks) occurring regarding the grains of the material (mesoscopic scale),

2) the development of cracks and destruction – in which the resulting changes are observable on a macroscopic scale.

The element's lifetime depends on the level of fatigue stress. Durability is usually calculated in millions of cycles and three ranges can be distinguished – the Wöhler chart:

I) $N_f < (10^3\text{-}10^4)$ cycles – quasi-static cracking (quasi-static strength). The destructive stress is assumed to correspond to static strength. The destruction process is usually plastic (static) and cracking occurs at the marginal plastic deformation. This deformation is comparable to that which would occur for a static load. An example of such damage is e.g. ratcheting.

II) $N_f \subset (10^3\text{-}10^5)$ cycles – low cycle fatigue (low cycle endurance). This type of damage is characterized by the occurrence of plastic deformations caused by high stress levels (alternating plasticity, plastic shakedown).

III) $N_f \subset (10^5\text{-}10^7)$ cycles – high cycle fatigue (high cycle strength). With high cycle fatigue, the scrap has the character of a brittle fracture, which is caused by a low level of fatigue stress. On the macroscopic scale, there are no plastic deformations. They can occur only within the grains of the material (mesoscopic scale). The range above $N_f > 10^7$ cycles is called the area of unlimited fatigue strength that occurs with most steels (not with aluminum alloys).

In the scope of unlimited fatigue strength, fatigue stresses are less than the stress limits (so-called fatigue strength) determined for a specific material and nature of the load (bending, torsion, etc.). It should also be remembered that the values of both allowable stress and fatigue limit N_f depend not only on the type of material but also on: the structure of the material resulting from the treatment (e.g. heat, mechanical, manufacturing technology), geometrical, dynamic features and surface condition. Additionally, taking into account the random or pseudo-random nature of the load and environmental impact (corrosion, radiation, temperature influence), fatigue should be treated as a stochastic issue.

At present, the understanding of both high cycle fatigue and low cycle fatigue is based on the same hypothesis: part damage and lifetime can be calculated as a stochastic result of surface nucleated cracking followed by part propagation [7, 8].

The phenomena of fatigue are characterized by three mandatory aspects:
- stress cycle,
- tensile stress,
- plastic deformation.

If one of these aspects does not occur, fatigue failure will not occur. Based on the material's initially observed condition, fatigue solutions are generally characterized in one of two ways for a homogeneous material:
- safe life: the material is free from initial visible defects,
- damage tolerance: the material contains an initial defect or crack.

The Stress – Life (SN) method is suitable for high cycle fatigue when the material is subject to cyclic stresses that are always in the elastic range. Structures in such stress ranges should typically survive over 100,000 cycles.

The Strain – Life (EN) approach should be used in the case of low-cycle fatigue, in which plastic deformation is a key factor contributing to fatigue damage.

The curve of the dependence of deformation on life is a logarithmic graph of plastic and elastic deformation components together with the total deformation and the dependence of deformation amplitude from inversion to damage.

Nucleation of cracks is the first step in the breakdown of fatigue in part:
- crack nucleation is a highly localized plastic deformation in the structure of the part,
- nucleation of cracks is usually a surface phenomenon,
- crack nucleation is a stochastic process.

Surface condition is an extremely important factor affecting fatigue strength, because fatigue damage occurs on the surface. Surface finishing and machining parameters are factors correcting the difference between the tested material and the material used in operation [9, 10].

In addition to the above-mentioned factors, there are many other factors that can affect the fatigue strength of a structure:
- notch and stress gradient effect,
- size effect,
- loading type.

3. Scope of research

During the examination on the effector of the M.A.S.T device (Figure 2), on which the platform was placed on special brackets, forced mapping driving on the actual road surface was recorded and the achieved acceleration values in three directions were recorded using an acceleration sensor (three axis) located at the agreed measuring point on the platform structure.

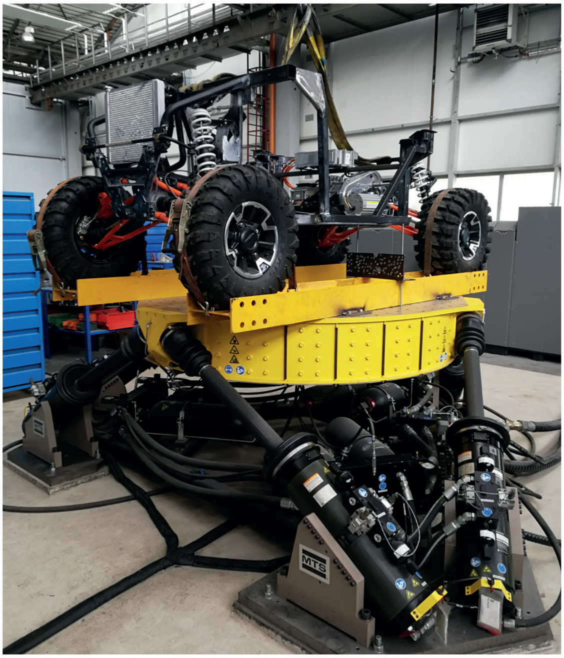

Fig. 2. Platform construction during the test at the M.A.S.T. stand

To the M12 mounting holes, located in the vibrating table of the M.A.S.T device, brackets made of profiles (leveling the displacement of the wheels in the transverse direction) were mounted. The PAWO platform was attached to the brackets with securing straps surrounding the platform wheels in such a way as to prevent their displacement during the test.

Figures 3-5 present signals registered during road tests, which were then used as input signals to the station during the platform test. The duration of forcing the input signal was about 300 s.

The study consisted of giving cyclical excitations for 8 hours (480 min.). The acceleration signal was recorded in three directions every 60 min., giving 24 acceleration runs. Comparison of the acceleration diagrams recorded for the first and last measurement is presented in Figures 6-8.

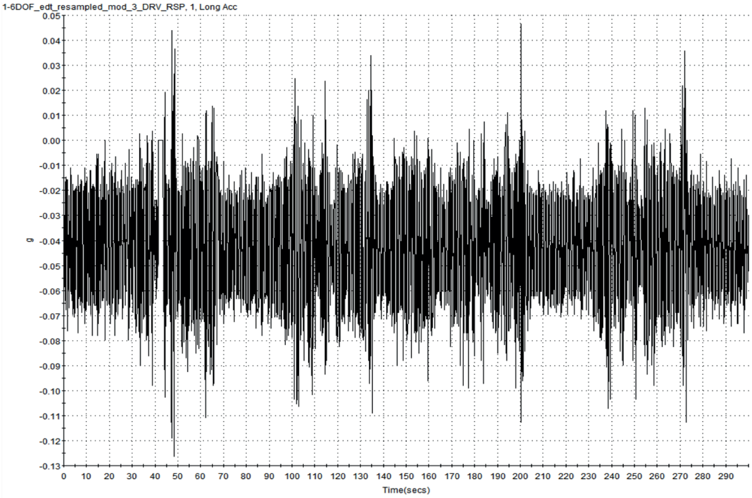

Fig. 3. The waveform of the input signal in the X direction

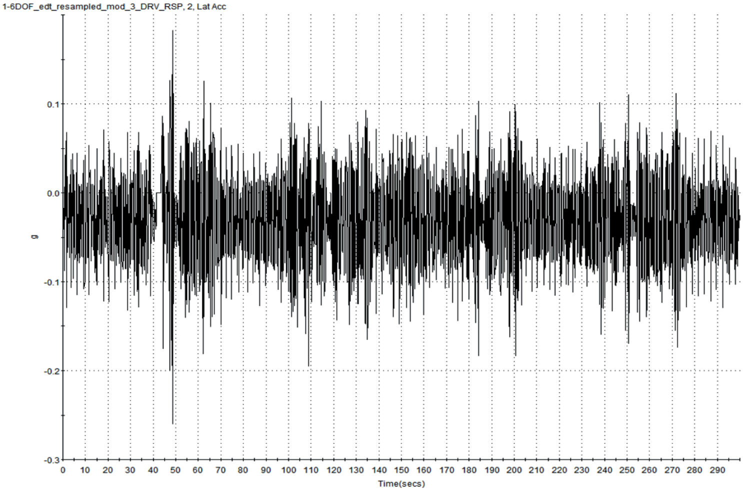

Fig. 4. The waveform of the input signal in the Y direction

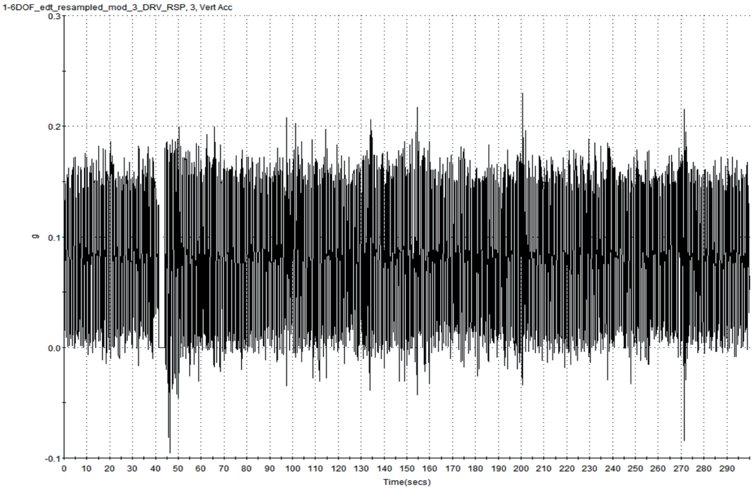

Fig. 5. The waveform of the input signal in the Z direction

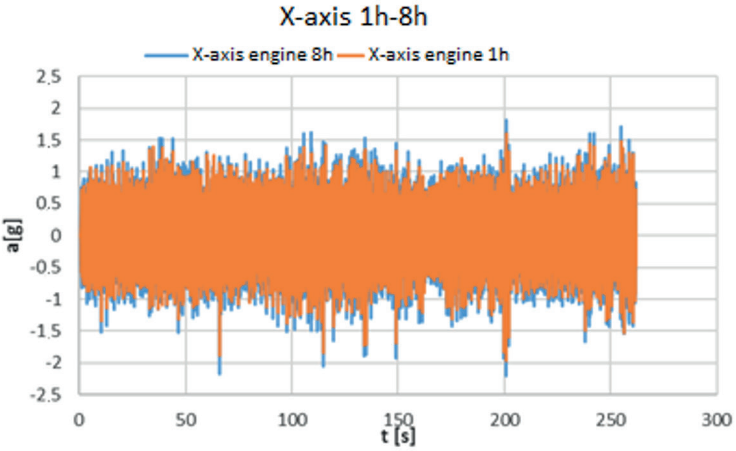

Fig. 6. Comparison of accelerations recorded in the X direction for measurements taken for 1 hour

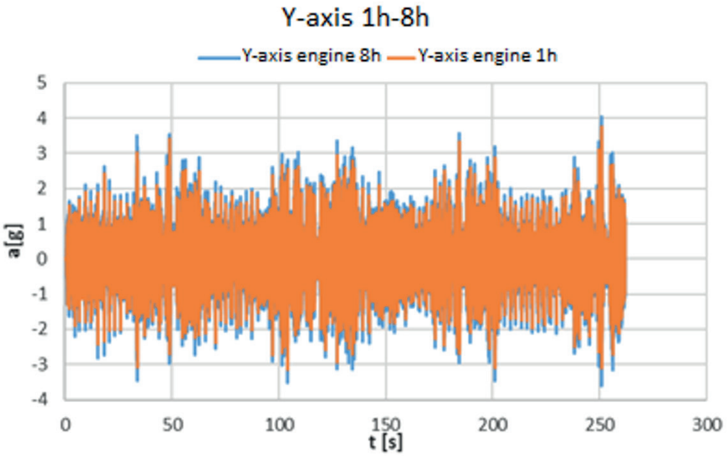

Fig. 7. Comparison of accelerations recorded in the Y direction for measurements taken for 1 hour and for 8 hours of the test

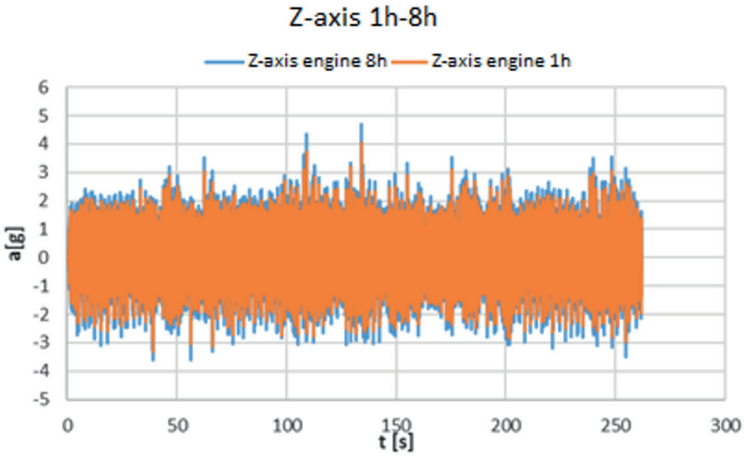

Fig. 8. Comparison of accelerations recorded in the Z direction for measurements taken for 1 hour and for 8 hours of the test

The RMS values calculated on the basis of recorded accelerations for the three directions are presented in Table 1.

Tab. 1. Calculated values of the RMS indicator [g]

RMS value [g] for the direction:	1 h	2 h	3 h	4 h	5 h	6 h	7 h	8 h
X	0.36	0.35	0.38	0.38	0.40	0.38	0.40	0.40
Y	0.63	0.63	0.68	0.67	0.71	0.67	0.71	0.70
Z	0.75	0.76	0.81	0.81	0.84	0.81	0.84	0.85

4. Summary of test results

As a result of testing the platform at the stand: the table with six degrees of freedom "M.A.S.T", the test object was loaded with extortion in three axes (X, Y, Z) reflecting the ride on the actual surface.

The platform was assembled in accordance with the structural assumptions. Based on the test, correct assembly can be determined: no permanent deformations, cracks or mutual collision of platform components were found.

Lower acceleration values were observed for the first hour of the test compared to the last hour of the test, which may indicate that the platform components during the dynamic loads at the stand "arranged" to the position consistent with the structural assumptions.

During the test, the shock absorber springs warmed up to the temperature reached during intensive work. No negative impact of temperature increase on suspension operation was observed. The study showed that the platform suspension works correctly, in line with the constructor's assumptions.

5. Numerical fatigue analysis

Below is a report on the numerical studies (FEM) carried out in the framework of the Autonomous Operational Support Platform PAWO.

Based on materials in the form of 3D CAD models and additional information such as: names of anticipated materials, anticipated ways of joining elements, a discreet frame model of the Autonomous Operational Support Platform was prepared [3, 11].

Fig. 9. 3D CAD model of the frame PAWO autonomous high mobility platform

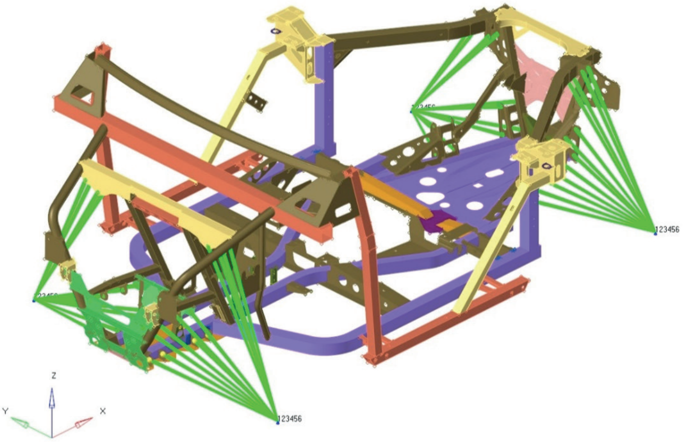

Fig. 10. FEM model

The works carried out included:

- analysis of the 3D CAD model of the frame structure,
- development of computational models based on the 3D model,
- determination of attachment and other boundary conditions,
- development of the mesh in HyperMesh,
- defining connections using the dedicated functional elements of the numeric solver,
- fatigue analysis with the FEM finite element method of the vehicle frame based on complete 3D CAD models,
- analysis of the results from the calculations of the PAWO Autonomous Operational Platform framework.

Based on the 3D model (Figure 9), using the preprocessor in the form of HyperMesh software, the geometry and mesh of elements of the analysed assembly were developed. In the process of model discretization, a surface model was created using elements of the Quad and Tria type (Figure 10).

The developed discrete model of the vehicle frame geometry grid was confirmed in the wheel attachment points (all degrees of freedom were taken away) (Figure 10). The load spectrum was defined on the basis of data from tests carried out at the M.A.S.T. stand.

Durability

The Durability of a design is a key requirement in industry today, as customers expect a robust design. Altair HyperWorks provides load prediction, stress analysis, and fatigue prediction using stress-life or strain-life methods.

With increasing competition, durability is an important feature of a product. Late changes in the design cycle to respond to test results are expensive and create production delays and system risks. Simulating product durability can provide early results and tremendous insight into the design for the product development team while reducing cost and meeting deadlines.

The HyperWorks suite provides tools to prepare, generate and evaluate simulation results. Even without the extensive customization options HyperWorks fits perfectly in work environment. Ready to use automation templates make your work efficient and help you to focus on the essential goal to produce quality products.

Modelling

HyperMesh, OptiStruct and RADIOSS allow modelling and simulation of structures including complex automotive components, lightweight composite designs, and rugged industrial components.

Here are some functionality helping the durability engineer:

- HyperMesh customization framework allows users to create weld macros that enables them to build a complex finite element mesh according to requirement of various fatigue solvers.
- Fatigue Process Manager template allows users the setup analyses in the RADIOSS fatigue solver.
- OptiStruct solver supports combined static stress and fatigue analysis in a single run. It can perform industry standard stress and strain life predictions.
- Altair OptiStruct can perform fatigue optimization in a single environment.

Automation

HyperWorks Automate is an advanced process based tool that enables the creation of a repeatable, scalable process in the Altair HyperWorks desktop environment. It includes several building blocks that can be assembled into a sequence that can be executed several times. Own building blocks can be added, making it a powerful customization tool.

Key features:
- creation of reusable tasks,
- ability to assemble tasks,
- customization with little coding knowledge needed,
- fatigue Workflow.

Altair HyperLife is an easy-to-learn fatigue analysis software developed on a solver-neutral framework. It provides a comprehensive toolset for durability analysis, directly interfacing with all the major finite element analysis (FEA) results files. With an embedded material library, HyperLife enables prediction of fatigue life under repetitive loadings experienced in a wide range of industrial applications [1].

The analyzes were divided into two groups. One was based on the SN method, the other on the EN method. The curves for these two cases are shown below (Figures 11 and 12).

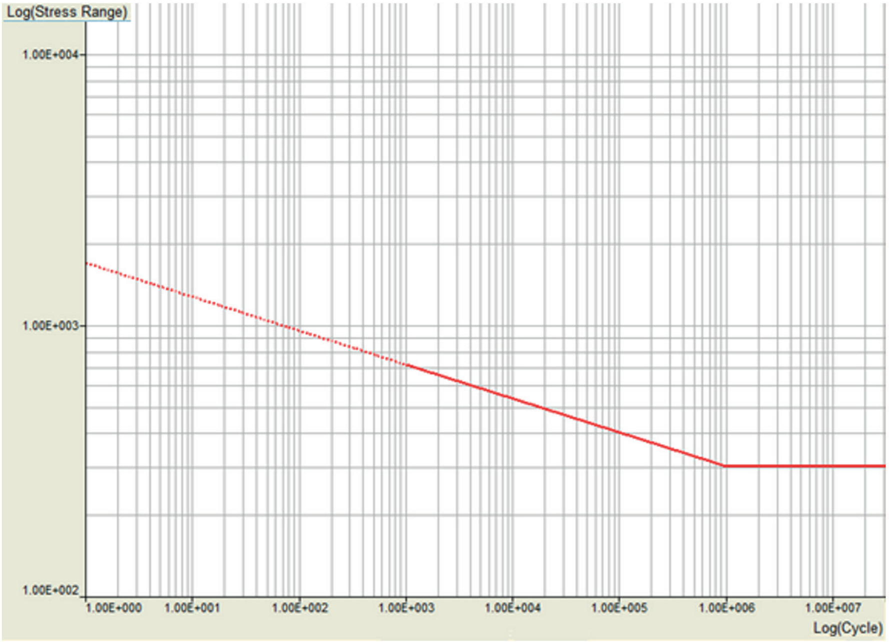

Fig. 11. SN curve

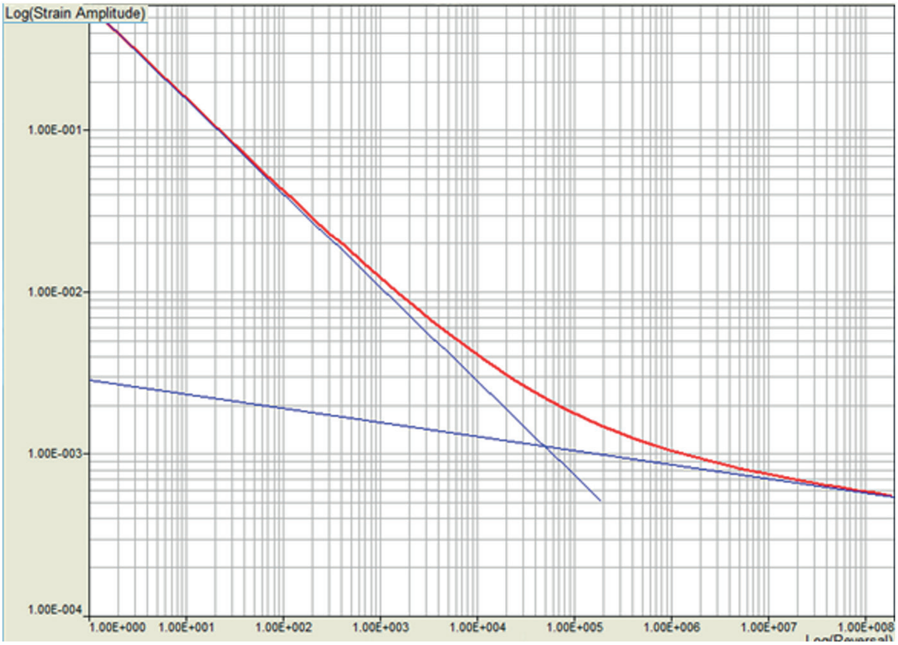

Fig. 12. EN curve

The following settings were used in the analysis based on the SN method:
Stress combination method: Abs. Max. Principal
Plasticity correction: NEUBER
Mean stress correction: GOODMAN
Rainflow type: STRESS
Certainty of survival: 0.5

The following settings were used in the analysis based on the EN method:
Stress combination method: Abs. Max. Principal
Plasticity correction: NEUBER
Mean stress correction: MORROW
Rainflow type: STRESS
Certainty of survival: 0.5

6. Results of fatigue analysis

The discrete model of the elements of the PAWO Autonomous Operational Support Platform, as agreed, was subjected to FEM fatigue numerical analysis. The results of the analyses are presented below (Figures 13-23).

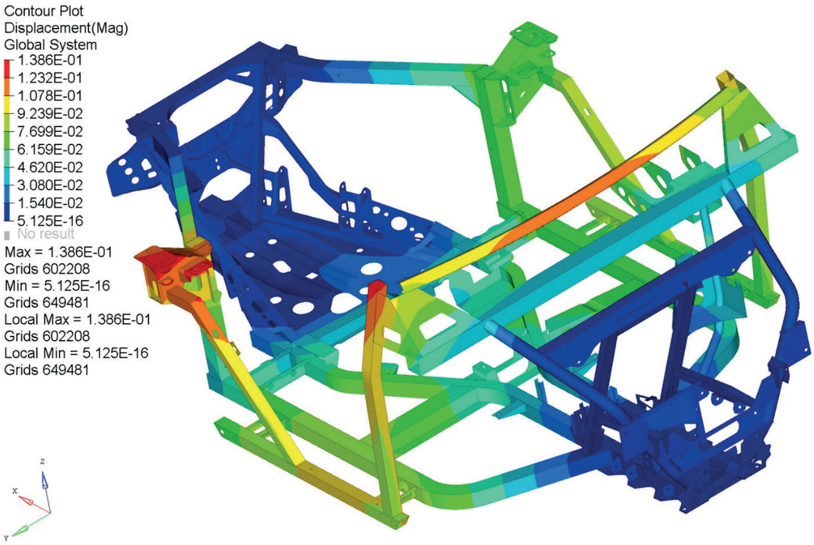

Fig. 13. Displacement [mm]

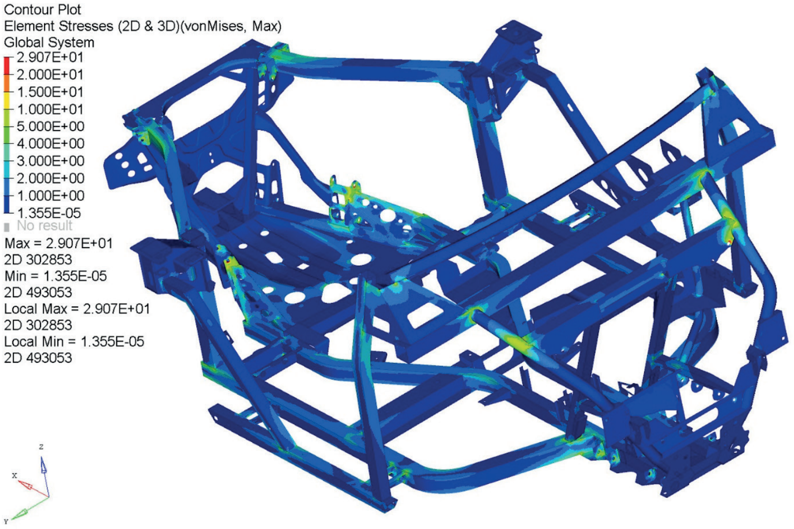

Fig. 14. Stresses (von Mises) [MPa]

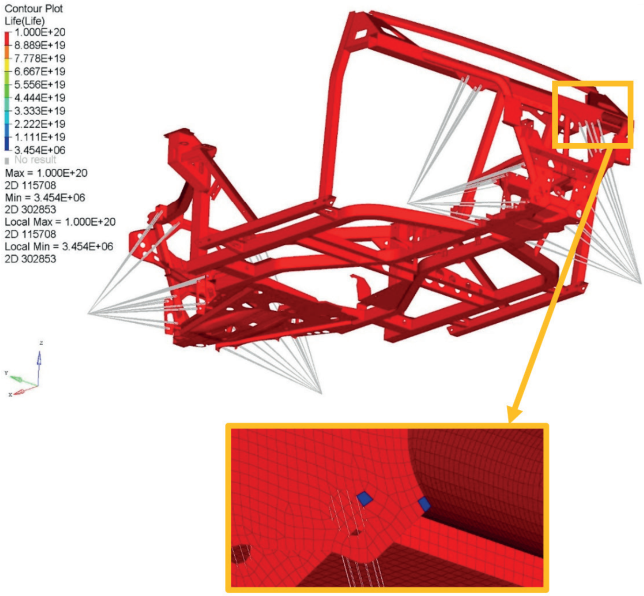

Fig. 15. Contour plot – Life (EN_AbsMaxPr_Morrow_Stress)

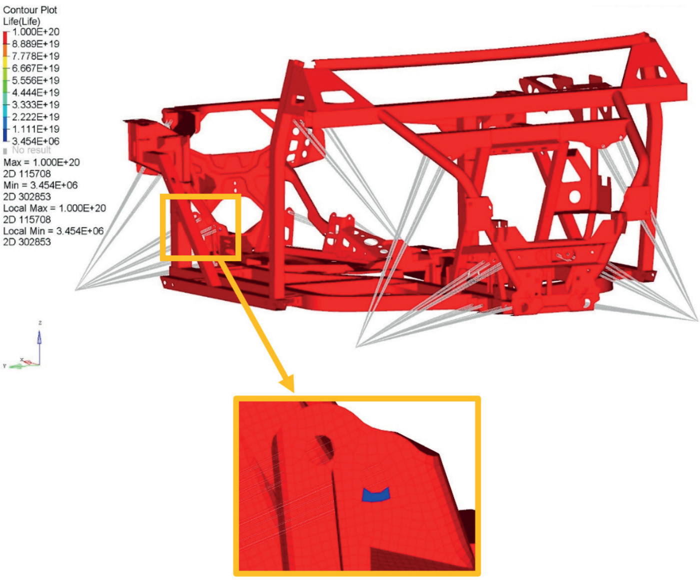

Fig. 16. Contour plot – Life (EN_AbsMaxPr_Morrow_Stress)

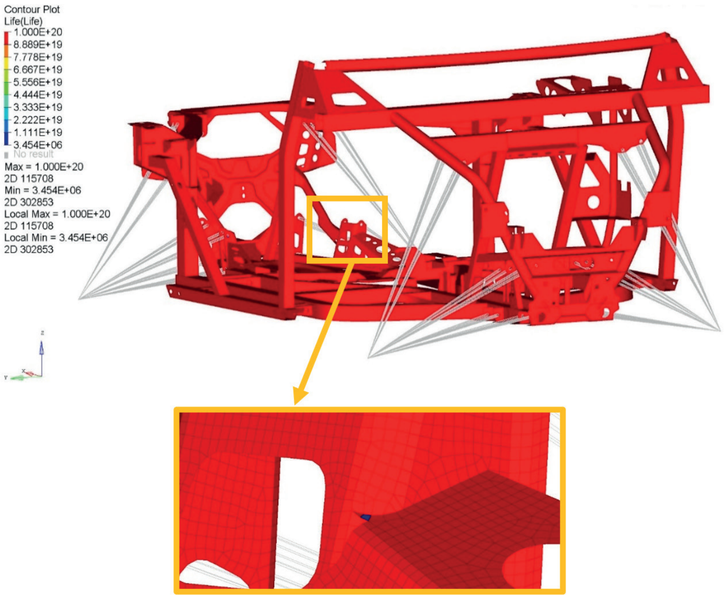

Fig. 17. Contour plot – Life (EN_AbsMaxPr_Morrow_Stress)

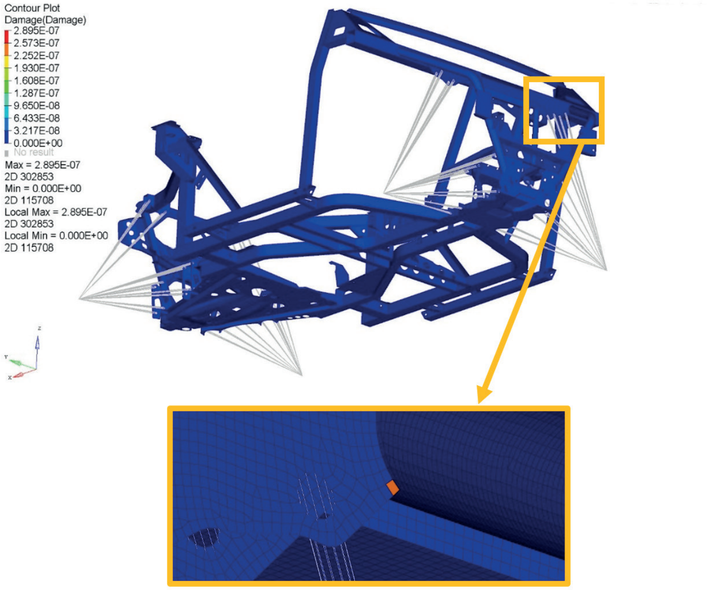

Fig. 18. Contour plot – Damage (EN_AbsMaxPr_Morrow_Stress)

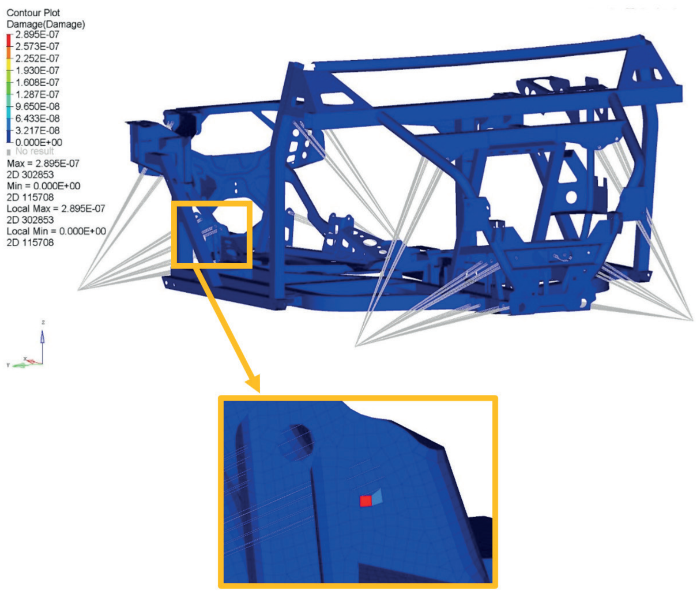

Fig. 19. Contour plot – Damage (EN_AbsMaxPr_Morrow_Stress)

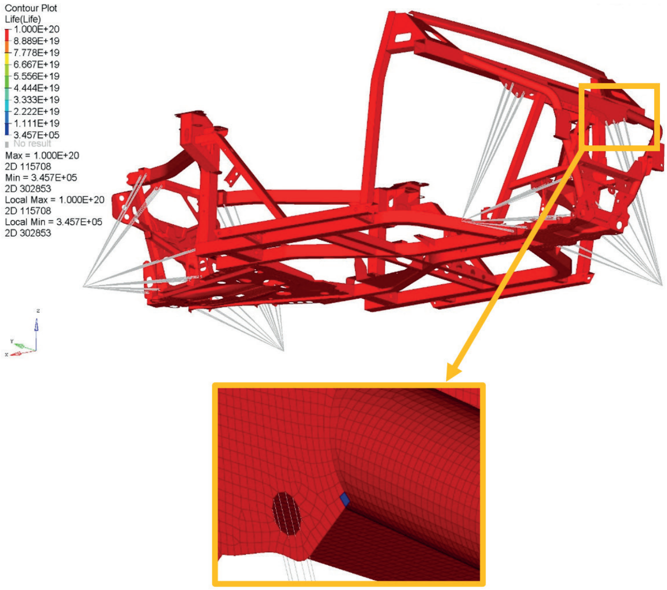

Fig. 20. Contour plot – Life (SN_AbsMaxPr_Goodman_Stress)

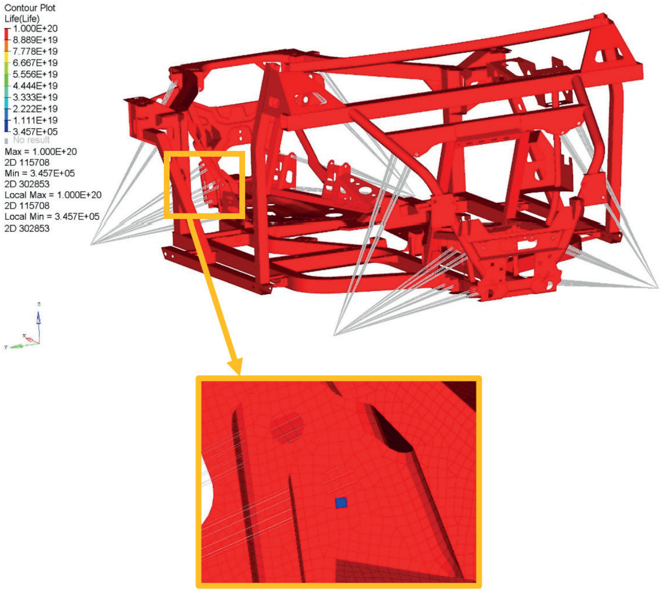

Fig. 21. Contour plot – Life (SN_AbsMaxPr_Goodman_Stress)

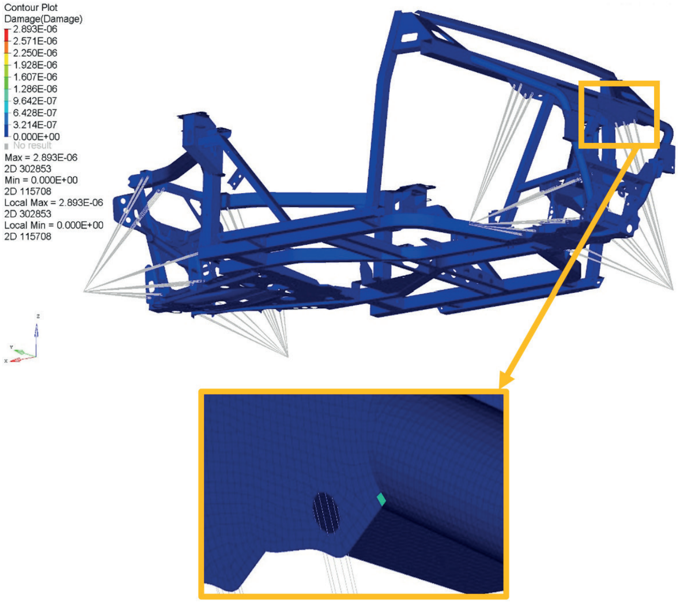

Fig. 22. Contour plot – Damage (SN_AbsMaxPr_Goodman_Stress)

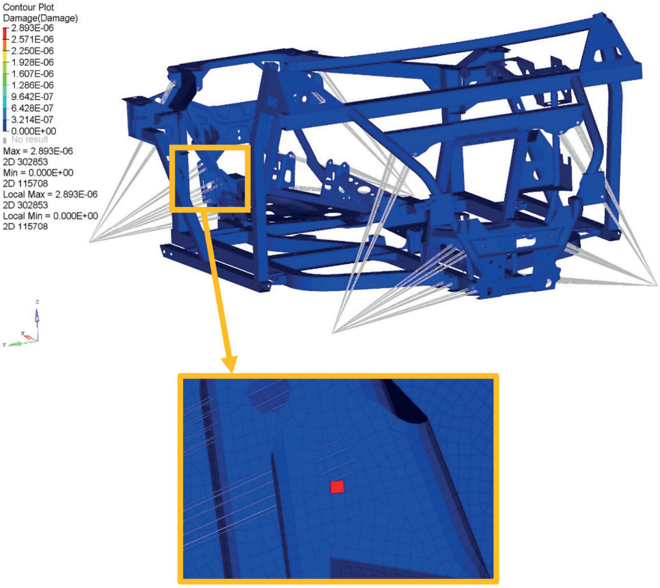

Fig. 23. Contour plot – Damage (SN_AbsMaxPr_Goodman_Stress)

7. Summary of analysis results

The results of the numerical analyses showed places particularly dangerous due to fatigue strength. As expected, they are around welded joints connecting the spatial frame profiles of the structure. They are also at the same time around the suspension attachment. The result of the numerical analysis in the place where the RBE element is embedded can be misleading due to the numerical nature of this connection. Therefore, this place of stress concentration should be treated with distance. However, the fact that such accumulation occurs at this point is noteworthy, because indeed in the physical, real structure the place of attachment of the suspension elements is critical for strength.

The results of FEM analysis can be the basis for modification of the structure, and thus lead to improved fatigue strength before serial production is implemented. The results of the analyses indicate critical places from the point of view of fatigue strength, which must be taken into account during testing and subsequent operation.

8. Conclusions

The results of both tests at the M.A.S.T. stand and numerical fatigue analyses allow the structure to be checked in laboratory conditions at an early stage of structure development. Be aware that the frame itself with the suspension is tested here, not the complete vehicle. For a complete structure, with sheathing and other components, the strength will increase. The results of these tests allow us to determine critical places due to fatigue strength and possible intervention before starting field tests with a complete vehicle, as well as to detect places that should be noted during tests, inspections and tests, and in development versions of the vehicle.

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