

Strength-deformation analysis of wheel reducer for metro cars

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ABSTRACT

Railway transport requires high reliability and safety in operation, which places high demands on the elements of the gear boxes. A particularly important role is played by the wheel reducers, which ensure the transmission of torque from the traction electric motor to the wheelsets of the rolling stock, as well as the braking torque during electrodynamic braking applied to the same wheelsets. In this work, a strength-deformation analysis of a wheel reducer for metro cars used in the Sofia Metropolitan is carried out. The main objective of the study is to find weak points in the structure through qualitative and quantitative analysis of the acting loads to increase the reliability and operational stability of the transmission mechanism of the bogies in the rolling stock of the Sofia Metropolitan. A review of the transmission mechanisms used in the rolling stock of the metro trains is carried out, considering their design features and operational characteristics. The operational condition of the considered node was analyzed, in which characteristic failures in the elastic membrane coupling EZK-MEM 250-1, related to stress concentrations and installation inaccuracies, were identified and analyzed. The conclusion provides recommendations for improving the design, installation, maintenance, repair and operation of this important for traffic safety node.

KEYWORDS

Wheel reducer, Metro cars, Strength-strain analysis, Finite element method, Operational reliability, EZK-MEM coupling.

1. INTRODUCTION

Transmission mechanisms are the mechanisms that transmit to the wheelsets a driving torque from the shaft of a traction electric motor or from the output shaft of a mechanical, hydraulic or other transmission system, without violating the freedom necessary for movement for relative movement of the wheels in relation to the bogie frame and of the bogie frame in relation to the wagon frame. The structural elements of the transmission mechanisms are:

- Reducers;
- Shafts;
- Joints;
- Supports;
- Couplings and others.

The technical and economic parameters of the railway vehicle significantly depend on the transmission mechanisms. This is the reason for a few requirements to be made to them. In summary, the most important of them are expressed in the following:

- The operation of the transmission mechanism should not be accompanied by the appearance of high-value dynamic forces and should not limit the operating modes;
- The reliability of the mechanism should be high and meet the requirements for economic efficiency;
- Ensure high operational economy;
- Do not reduce the space intended for installation of the traction motor as much as possible;
- The design should be simplified and allow accessibility to the mechanism for inspection and repair. The design should allow for the location of the traction motors, in which they are accessible for inspection and repair, as well as protected from snow, moisture and dust. Transmission mechanisms transmit torque from the electric motor to the wheels it drives (when the motor is in traction mode) and vice versa (when the motor is used for braking).

The power transmissions of the railway rolling stock must meet the following general requirements:

- To be safe in operation;
- To have as simple a design as possible;
- To be accessible for inspection and repair;
- To be light and compact;
- To provide optimal operating conditions for the engine.

The type and design of the power transmission is determined by the type, power and properties of the electric motor, the method of its suspension, its location in relation to the longitudinal axis of the metro car and the type, purpose and maximum speed of the metro car itself.

2. CLASSIFICATION OF TRANSMISSION MECHANISMS

2.1. According to the Number of Wheelsets, Which Are Simultaneously Driven:

- Power Transmissions for Individual Drive of the Wheelsets;
- Power Transmissions for Group Drive of the Wheelsets.

2.2. According to Their Regulation Properties:

- Non-adjustable (i.e. constant gear ratio) power transmissions – light, simple and cheap (in production, operation and repair) power transmissions. They belong to the category of mechanical power transmissions, as they transmit torque through gearing, lever systems or power chains;
- Adjustable (i.e. with variable gear ratio) power transmissions – relatively complex and expensive, but unlike the non-adjustable ones, they allow the adjustment of the engine characteristics in accordance with the changing operating conditions of the railway vehicle. They are mechanical (created based on a multi-speed gearbox with gear engagements); hydraulic and combined.

2.3. According to the Value of Unsuspended Masses:

- First class transmission mechanism – axle-mounted traction motor and axle-mounted reducer;
- Second class transmission mechanism – bogie frame-mounted traction motor and axle-mounted reducer;
- Third class transmission mechanism – frame-mounted traction motor and frame-mounted reducer. The traction motor, together with the wheel reducer, transmits its mass to the bogie frame and is part of the sprung parts.

3. STRUCTURAL LAYOUT AND FEATURES OF THE AXLE REDUCER OF ROLLING STOCK TYPE 81 – 740.2/741.2 AND 81 – 740.2B/741.2B

These wagons have two motorized two-axle bogies with individual drive of the axles - front, rear and one non-motorized two-axle bogie - intermediate. Motor bogies are an element of the running gear of the wagons and guide the movement along the rail track, ensuring minimal resistance and the necessary smoothness of the run, distributing and transmitting all loads from the body to the track, and forming and realizing the traction and braking forces for their propulsion. The suspension of the traction drive is of the third class, i.e. frame-mounted traction motor and frame-mounted reducer.

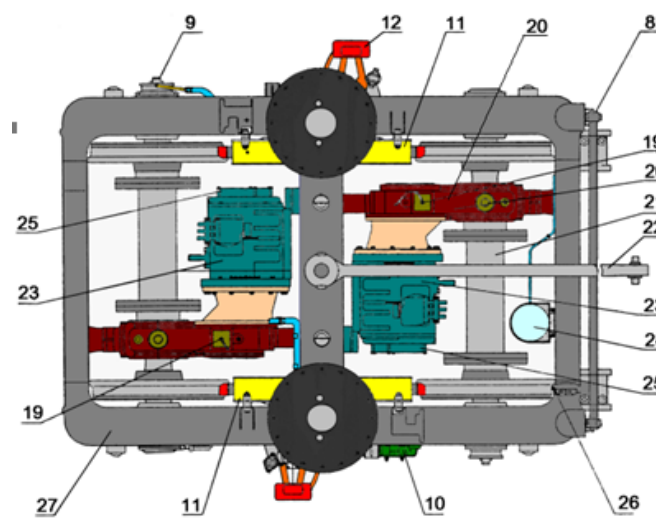


Figure 1:

It consists of the following main components, assemblies and mechanisms: frame 27; two axles 29; traction electric motor 23, reducers 20, transmission mechanism 21 and other devices for transmitting rotation (Fig. 1). The axles belong to the unsprung masses and are one of the main units of the running gear and all undercarriage equipment. The axles of the motor bogie consist of an axle 8, two wheels 2 and 10, axle boxes 1 and 11, transmission mechanism 7 and reducer 4 (Fig. 2).

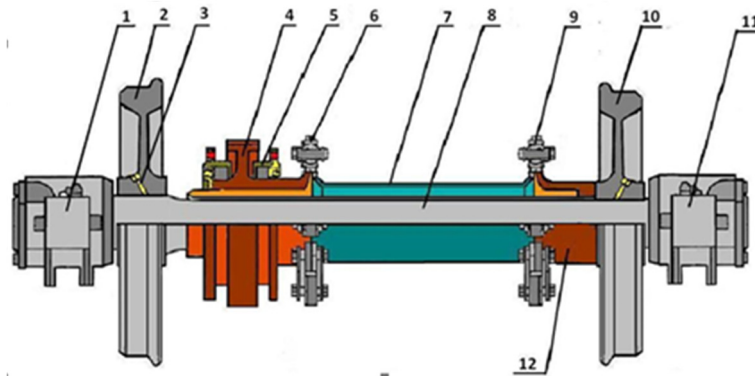


Figure 2:

The traction drive consists of a traction electric motor, a reducer and other elements that provide the transmission of torque from the electric motor to the wheelsets. The kinematic diagram of the drive from the electric motor to the wheels is shown in Fig. 3. The torque transmission is carried out according to the following scheme: electric motor rotor shaft 1, drive hub 2, gear housing 3, elastic ring 4, gear housing 5, driven hub 6, small gear shaft 7, small gear 8, parasitic gear 9, output shaft with large gear 10, flange of the output shaft of the reducer 11, flange of the hollow shaft of the transmission mechanism 12, hollow shaft 13, flange of the transmission mechanism 14, flange of the second wheel 15.

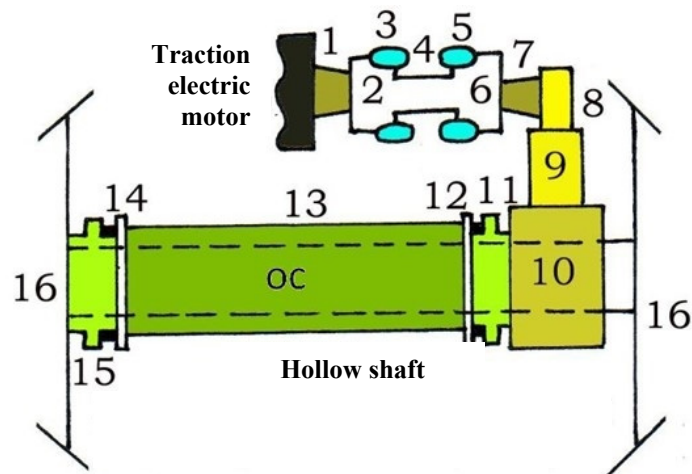


Figure 3:

The gearbox is two-stage and consists of a detachable housing of two parts - upper and lower crankcase. It is equipped with a shaft with a small gear 22, a shaft 20 with an intermediate gear 11 and an output shaft 16 with a gear ring. The shafts with the bearings are closed on both sides with covers. All gears of the gearbox have straight teeth. This prevents axial loading of the bearings and the housing (Fig. 4).

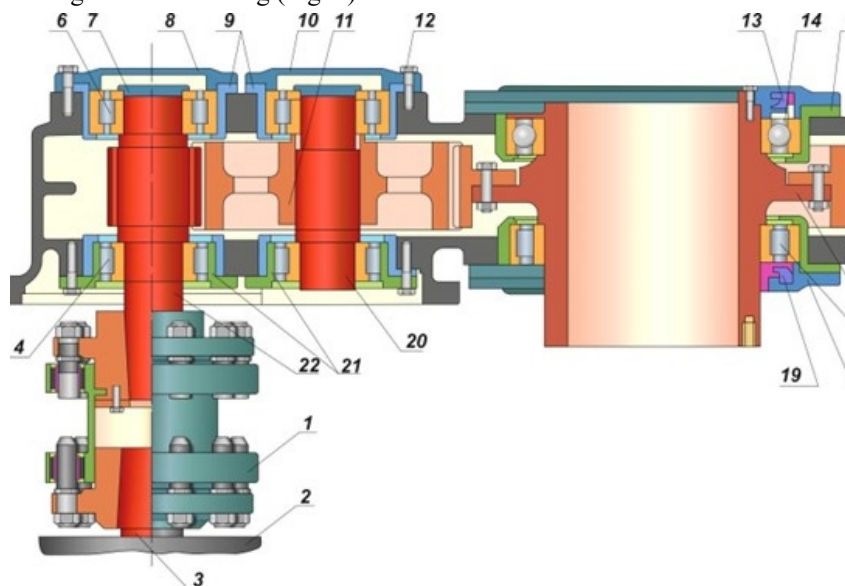


Figure 4:

4. ANALYSIS OF THE OPERATIONAL CONDITION OF THE UNIT

4.1. Unit Status Snapshot

After a detailed and thorough analysis of the structural layout and features of the transmission system of the metro cars, as well as after discussions with employees responsible for the maintenance and repair of the metro trains, it was established that the power transmissions of the trains are generally reliable in operation. The power transmissions in the metro cars have a simple design, are accessible for inspection and repair and provide optimal conditions for engine operation.

4.2. Problems Encountered in the Operation of the Unit

After in-depth research and statistical processing of the results obtained, it was found that for the period of the last four years, the most frequent registered malfunctions were in the coupling of the metro cars under consideration.

The problems are mainly concentrated in the elements that make up the elastic coupling, and more specifically in the flanges connecting the coupling halves: breakage of the housing of one coupling half, presence of cracks on the coupling half or a twisted coupling half.

4.3. Elastic Membrane Coupling EZK-MEM 250-1

The clutch is manufactured by the German company “KWD – Kupplungswerk Dresden” with No. 9981 5400. Its purpose is to transmit torque from the electric motor to the gearbox by means of opposing teeth meshing with each other through an elastic gear wheel that smooths out dynamic shocks.

4.3.1. Clutch Structure

The clutch consists of two half-clutches and an elastic gear ring. The half-clutches have the same design, each of them consists of a hub 2, a gear housing 3. The torque is transmitted from the traction motor through hub 2, the gear housing 3, the elastic ring 1 and the shaft of the small gear wheel of the reducer (Fig. 5÷10).

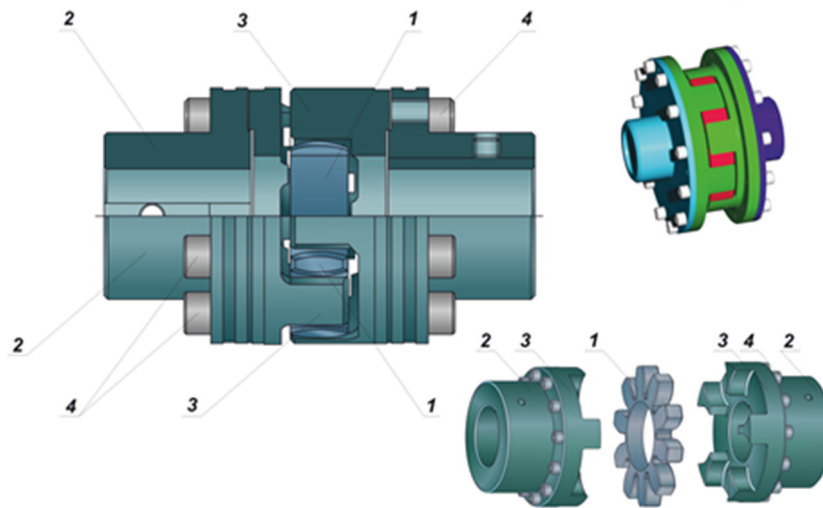


Figure 5:



Figure 6:



Figure 7:

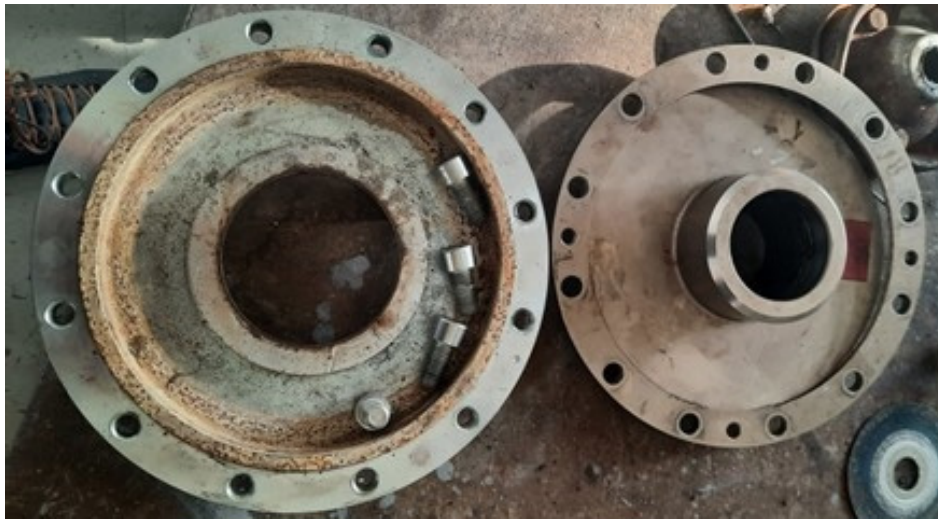


Figure 8:



Figure 9:



Figure 10:

4.4. Common Faults in the EZK-MEM 250-1 Elastic Diaphragm Coupling

According to the conducted statistical study and observations of the studied unit, it was found that the most common damages to the elastic membrane coupling are rupture of the housing of one coupling part (Fig. 11), presence of cracks on the housing part (Fig. 12) and twisting of the coupling part (Fig. 13).



Figure 11:



Figure 12:



Figure 13:

4.5. Causes of Clutch Damage

4.5.1. Damage to the EZK-MEM250-1 Elastic Coupling Caused by the Suspension of the Traction Motor and Gearbox

The suspension of the traction motor and the reducer is a support arm with transmission of torque to the axles through a hollow shaft with articulated guides with sleeves. The TED is fastened to the reducer by a transition flange around the small gear (Fig. 14). The flange is fastened to the TED and the reducer with bolts.



Figure 14:

In the lower part of the transition flange there is an opening connected by a tube to the lower part of the reducer. This helps to return excess oil from the housing of the compensation sleeve to the reducer. The suspension of the reducer has a similar bracket in its rear part on the side of the small gear; it is attached with the universal bracket with a suspension to the central cross member of the bogie frame. On the side of the output shaft of the reducer to its housing there is a bracket mounted by bolts. The bracket with the help of two bolts passing through it, nuts and lock nuts is connected to the metal-rubber joint of the universal bracket. The metal-rubber joint in its upper part has a thread on which an adjustment sleeve is screwed (Fig. 15).



Figure 15:

In the upper part of the adjustment sleeve, the thread of an analogous metal-rubber hinge is wound, which, through two detachable "stones", is attached to a special thickening of the end crossbeam of the bogie frame. The adjustment of the vertical distance between the output shaft of the gearbox and the axle of the wheel axle is carried out using an adjustment sleeve (Fig. 16).

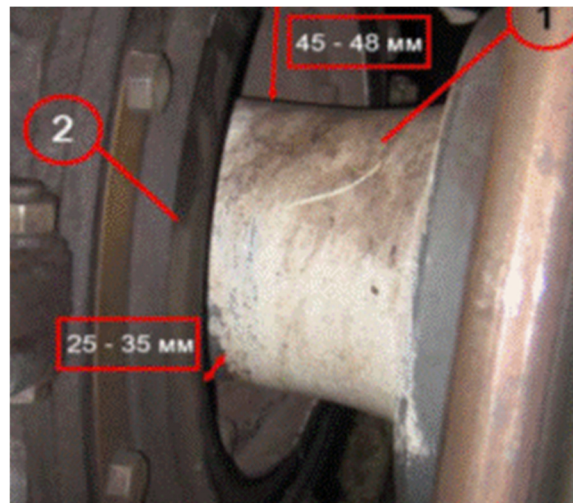


Figure 16:

4.5.2. Damage to the EZK-MEM250-1 Flexible Coupling Caused by Incorrect Assembly of the Coupling's Connecting Parts.

After conducting observations and analyzing the operational condition of the unit under consideration, it was found that the main cause of damage to the elastic membrane coupling is the coupling installation method. This is most likely due to the practice in the depot of lowering the traction motor with a crane. This method leads to inaccuracy and imprecision, as the positions of the shaft, gearbox and motor are not within the tolerances for each installation. When installing with unacceptable tolerances, misalignment occurs, with one half pressing the other, which during operation causes breakage or cracks to appear on the housing of one half. When installing the half coupling with the shaft, good contact must be obtained between the coupling hub and the traction motor shaft or the gearbox shaft. If the required contact spot is not achieved, the fitting (rubbing) is carried out with grinding paste. Clutch slippage is due to a contact spot with an area of less than 75% and poor fit (grinding) with the grinding paste on one clutch half.

5. STRENGTH-DEFORMATION ANALYSIS OF CONNECTING FLANGES USING THE FINITE ELEMENT METHOD

5.1. Method of Performing Analysis

The strength-strain analysis was performed using the finite element method. This is a numerical method for solving a wide range of problems in mechanics, in which, based on known relations between forces and displacements for individual elements of the structure, an analysis of the behavior of the entire structure is carried out. The goal of any such study is to determine the main characteristics of the field, namely the distribution of stresses or displacements, the values of stresses and displacements at individual points in the field, the extreme values of these quantities or their gradient, etc. Three-dimensional finite elements were used for the study.

5.2. Creating a Model

To perform a qualitative and realistic analysis using the finite element method, it is first necessary to create a 3D model that recreates the geometric dimensions and physical characteristics of the studied element as accurately as possible. For the study, a model was created that is as close as possible to the actual operating part, namely the coupling plates that connect the two halves of the coupling. The first plate is attached to the rotor shaft of the traction electric motor, and the second - to the shaft of the small gear from the reducer of the transmission mechanism.

5.3. Defining the Structural Load

The accuracy of the solution largely depends on the skillful development of the computational model. This requires the structure to be analyzed, the main supporting elements to be identified and a decision to be made on their appropriate representation by means of appropriate finite elements. The model is developed based on the load scheme of the real structure. This brings it as close as possible to it and the results are as close as possible to those operating in a real environment. The actual design of the coupling consists of two coupling plates, fastened with 12 bolts to the two half-couplings, one of which is loaded with the torque created by the traction electric motor, and another which is transmitted to the input shaft of the reducer. The two plates are pressed onto the rotor shaft of the traction motor and the input shaft of the reducer, respectively, by means of a conical press fit. The first plate, mounted on the rotor shaft of the traction

motor, is loaded with the torque that the motor creates and transmits it to the following elements of the reducer, and the second plate receives this torque and in turn transmits it to the input shaft of the reducer.

Thus, in the modeling, the first plate is loaded with torque in the hub and is fixed along the periphery in the bolt holes (Fig. 17), and the second is loaded with torque in the bolt holes and is fixed in the hub (Fig. 17). This also determines the differences in the results obtained in the analysis of the two elements.

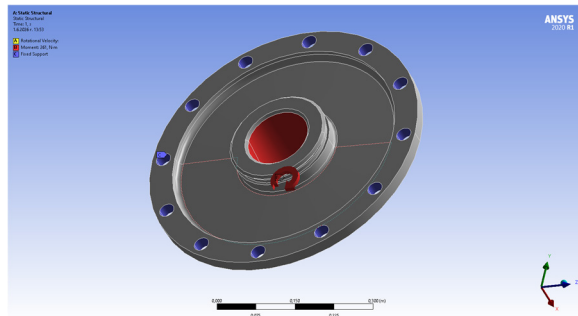


Figure 17:

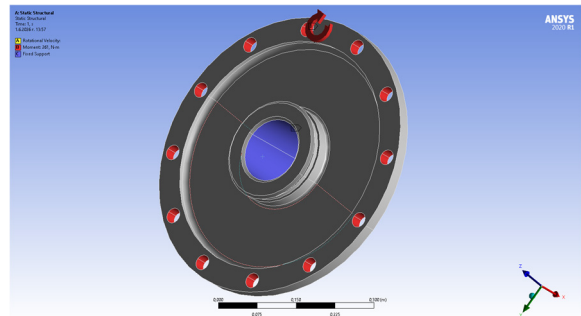


Figure 18:

The torque applied to the plates is maximum at start-up and decreases with increasing speed, with its minimum value at the design speed of the train. This dependence is key to determining operating conditions that are as close as possible to the actual ones. The maximum torque realized between the two plates is 261 Nm, realized at start-up and up to about 40 km/h, and the maximum angular velocity of the plates is 613.66 s^{-1} at the design speed. This somewhat relieves the load on the structure and must be considered.

5.4. Results Obtained

5.4.1. Load with Maximum Torque When Starting and Driving at Relatively Low Speed:

Guide plate: the maximum stress obtained in the guide plate is $\sigma=939.18 \text{ MPa}$ (Fig. 19), obtained in the transition from the hub to the membrane on the inside of the plate. The maximum relative elastic elongation in turn is $\varepsilon=4.71 \cdot 10^{-3} \text{ mm/m}$ in the same section. The safety factor is sufficiently high, uniform throughout the entire volume, which indicates that the part is sufficiently overprotected throughout its volume. The resource is evenly distributed throughout the volume and guarantees failure-free operation for $1 \cdot 10^6$ cycles (Fig. 20).

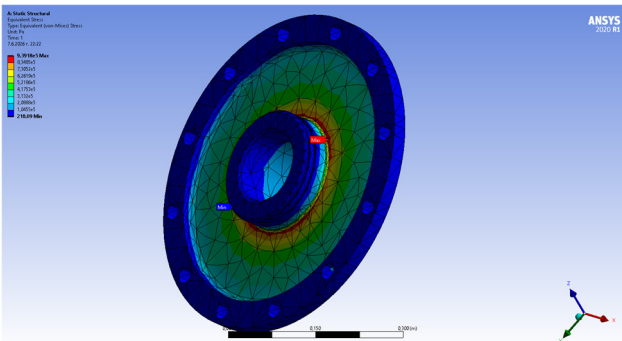


Figure 19:

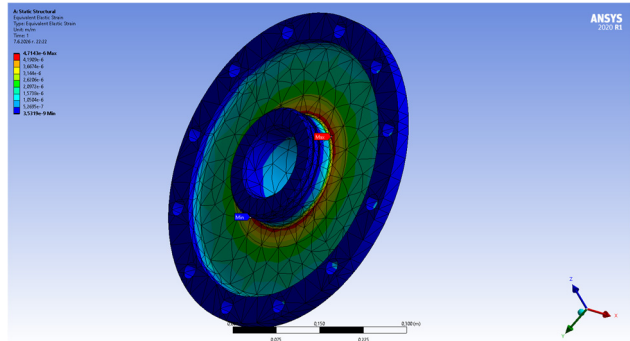


Figure 20:

Guided plate: the maximum stress is $\sigma=953.25 \text{ MPa}$, again obtained in the transition from the hub to the membrane on the inside of the plate, i.e. slightly higher than that in the guide plate (Fig. 21). The maximum relative elastic strain is also located in the same place, its value being $\varepsilon=4.782 \cdot 10^{-3} \text{ mm/m}$, also close in value to the guide plate. The maximum total deformation is obtained along the periphery of the plate, in the flange where the connecting bolts are located, and its value

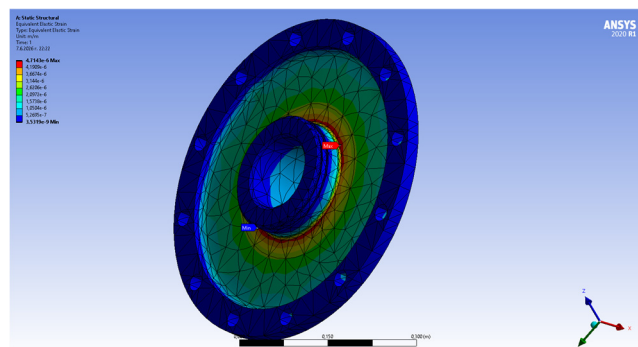


Figure 21:

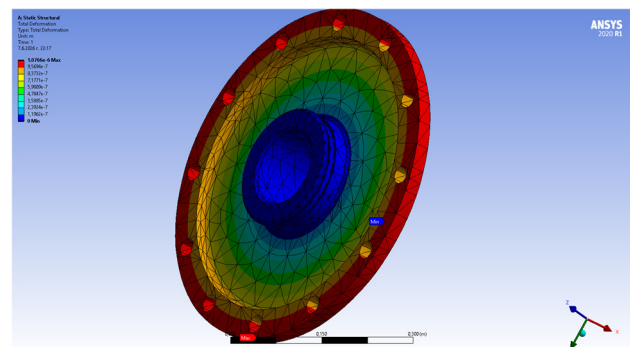


Figure 22:

is $1.0766 \cdot 10^{-3}$ mm, a value significantly higher than that in the guide plate (Fig. 22). The values of the safety factors do not differ from the first plate, i.e. the guided plate is also sufficiently well overprotected.

5.4.2. Load When Driving at Maximum Speed:

Guide plate: the maximum stress is $\sigma=5378$ MPa, located at the transition between the hub and the membrane on the inside of the plate (Fig. 23). This value cannot be considered authoritative because it appears at a node and is a result of excessive accumulation of values. More important in this case is the average stress value, which is 937.14 MPa. However, it can be responsibly said that it is the maximum value that has the greatest impact on the damageability of the plate (Fig. 24) and on its resource (Fig. 25). The maximum value of the relative elastic strain is $2.74 \cdot 10^{-2}$ mm/m, and the maximum total deformation is concentrated in the hub and has a value of $1.5315 \cdot 10^{-2}$ m. The minimum safety factor is $4.6 \cdot 10^{-2}$, obtained at the transition between the hub and the membrane on the inside of the plate, and the fatigue safety factor is $1.6 \cdot 10^{-2}$, obtained at the same location (Fig. 26).

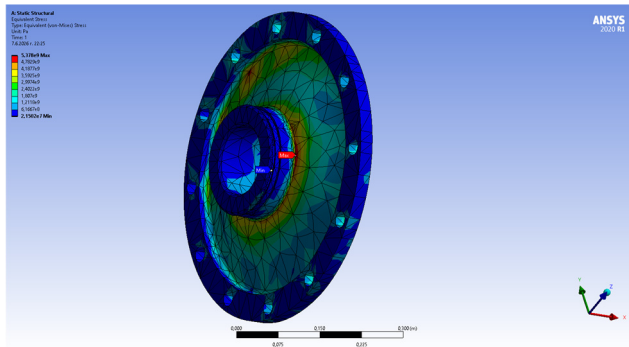


Figure 23:

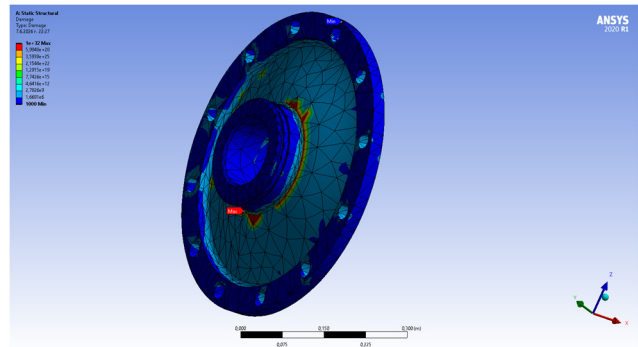


Figure 24:

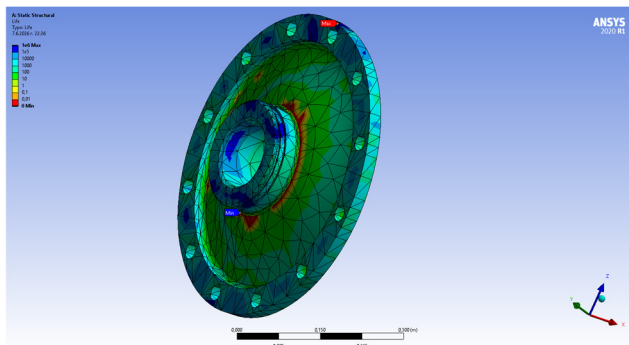


Figure 25:

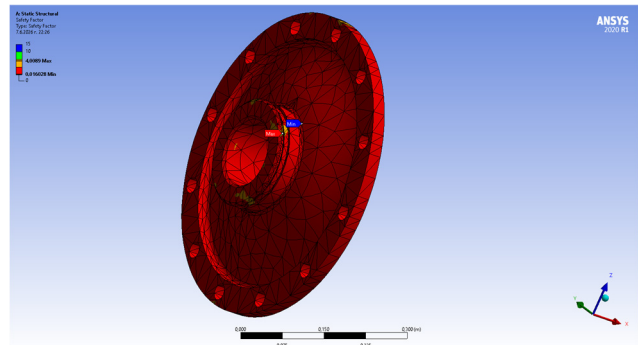


Figure 26:

Guided plate: the maximum stress is 8639 MPa, located at the same location (Fig. 27). The relative elastic elongation is $4.38 \cdot 10^{-2}$ mm/m. The safety factor is $2.89 \cdot 10^{-2}$, and the fatigue safety factor is $9.978 \cdot 10^{-3}$ (Fig. 28). The damageability and resource reach minimum values at the same location.

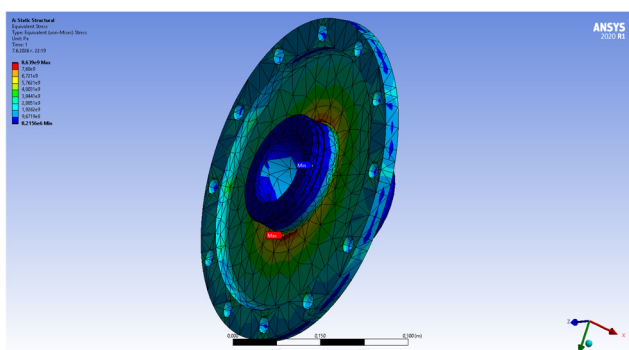


Figure 27:

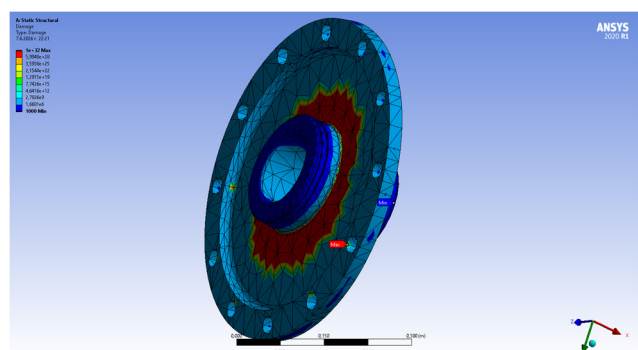


Figure 28:

5.5. Conclusions

- Obviously, the weakest section of the two coupling plates is the transition between the hub and the membrane on the inside of the plate;
- The maximum values of stress, respectively the safety factors, are not reached in starting process when the torque is the greatest, therefore the torque transmitted by the traction motor is not the most loaded element, mainly due to its relatively low value;

- The maximum values of all indicators of the state of the two elements are reached at maximum speed of movement, therefore the speed of movement, respectively the angular velocity of the rotating parts, is the most loaded indicator affecting the plates.
- When the train starts, the torque is maximum, the more loaded plate is the leading one, with the differences in the loads being minimal compared the driven one;
- When moving at maximum speed, the more loaded plate is the driven one, with the values of the loading indicators being significantly higher than those of the leading one.

5.6. Recommendations

- The elasticity of the material from which the plates are made can be increased, in order to withstand mainly the fatigue load, which is caused by their cyclic loading;
- In the comparative analyses conducted, it was found that the radius of curvature in the most endangered section does not have a significant impact on the results;
- Additional research is needed to improve the qualities of the connecting plates;
- The installation work performed when inspecting and replacing some of the elements must be carried out precisely to avoid frontal and radial runout when driving at high speeds.

5.7. Interference

The unit considered shows sufficiently high reliability in operation, but additional measures are needed to improve it, which include constructive and technological improvements in the design, as well as precision in performing assembly work on the unit.

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