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THE TRUCK TRAILER SUSPENSION AXLES FAILURE ANALYSIS AND MODELLING

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Abstract. The purpose of trucks is very diverse, but the main purpose is freight transportation. When cargos are transported, the truck's suspensions are heavily loaded, so failures also occur most often in the suspension elements. For axles of trailers – tubular construction failures occur, they crack. Axle failure investigations are required to determine the cause of the failure. The paper analyses three-axle truck trailer suspension. Axle failure analysis and axial deformation modelling were performed to determine trends and causes of truck trailer suspension axle failures. Different cases with axles of tubular construction with wall thicknesses of 9 and 11 mm were modelled. The paper presented visual failure analysis of truck trailers suspension axles and finite element modelling results of axle's deformation of different geometrical parameters. The results were discussed and conclusions were drawn.

Keywords: truck, trailer, axle, load, failure, finite element method, finite element analysis.

Notations

CAD – computer-aided design;
FEA – finite element analysis;
FEM – finite element method;
EMD – empirical mode decomposition;
ENN – Elman neural network;
HHT – Hilbert–Huang transform;
IMF – intrinsic mode function;
TDE – three-dimensional energy.

Introduction

Trucks are designed for the transportation of goods and are therefore loaded with a variety of static and dynamic loads on all their structural components. The axle of the truck trailer is one of the most loaded elements, since it is an intermediate link between the road and the frame of the trailer. Therefore, the trailer axle of the truck is a very important element of the chassis.

The axes are classified into modular and integrated. Modular chassis require periodic and timely inspections and maintenance to check the performance of semi-trailer braking systems and suspension parts, paying particular attention to U-bolt tightness. Unscrewed and unlocked bolts loosen release the axles more often. The parallel axes then distort and break other chassis components. Integrated axle is constructed as one-piece unit, which is simpler, more reliable and requires simple maintenance. However, failures occur, and the axle fractures are one of them.

The main properties of the axle are the following it must be strong, lightweight, and reliable to withstand various static and dynamic loads. Truck trailer axles are reliable, but you should still regularly check them for damage. Although axles are reliable under difficult operating conditions, they often experience fatigue failures.

When developing new products, the growing needs and environment must be taken into account. Today, the transport industry is more than ever confronted with ever-increasing costs and increasingly complex conditions, including additional requirements for vehicle safety and reliability. Thorough research and assessment of potential damage could help to find solutions to prevent defects and ensure product quality, reliability and cost-effectiveness.

This is a global problem and it does not matter whether the axle is used in a tractor, bus or truck trailer. Failures are similar for all means of transportation. After determining the problem in one construction, similar solutions

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can be applied in another construction. There has been a great deal of research carried out on this topic, but as new needs emerge, new solutions and new problems have to be investigated as well.

In the paper by Jafari *et al.* (2006) stress analysis of front axle of JD 955 combine under static loading conditions resulted from the applied modifications was performed by using FEM. The commercial finite element software ANSYS (version 9.0) was used for the solution of the problem. Numerical results showed that the calculated value of factor of safety is very low and the front axle of JD 955 combine is not strong enough to be installed on the modified combine.

In the paper by Aloni and Khedkar (2012) FEA approach is used to modify existing rear axle of tractor trolley. Fatigue failure of the rear axle finite element model was predicted after the dynamic load was imposed on it. The FEA of existing rear axle of tractor trolley revealed the stresses distribution on rear axle. In this work, the effort is made to modify the design of existing rear axle along with change of material so that advantage of weight reduction along with safe stress can be obtained.

The paper by Manasa and Reddy (2013b) deals with static analysis of tractor trolley axle. Analysis is done using ANSYS workbench. In paper, an attempt has made by replacing rectangular cross section with circular section. Further static analysis is done to determine von-Misses stress, equivalent elastic strain, maximum shear stress, total deformation. Finally, the results of rectangular section axle with circular section axle are compared which result in reducing the 20% weight of the circular axle.

In the paper by Odanovic *et al.* (2015) railway axles light on the causes of fracture occurrence is investigated. Detailed analyses were conducted on the axle fracture surface and mechanical properties. In addition, microstructure of the axle material, as well as on exploitation conditions and stress state was examined. Calculations indicated that, apart from working load impact, the influence of press fit joints, especially of the one between the labyrinth seal and the axle is of crucial importance for the analysis of railway axle stress state. The entire numerical-experimental analysis has shown that the considered axle failure was caused by inadequate maintenance, insufficient axle strength and adverse stress state in the railway axle critical cross-sections.

The paper by Bhagoria *et al.* (2017) deals with the various analysis incorporated in the testing and inspection of the axle shaft. The axle shaft is one of the prime components of an automobile and provides greater turgidity and balance to the same. The paper reviews the various works that have been reported on the safety and working of this prime component, which is chiefly subjected to the torsional and sudden shocks in its working.

In study by Paul *et al.* (2013), existing trolley axle was redesigned considering the static and dynamic load conditions. Based on finite element analysis, redesign of axle was carried out for reducing the cost and weight and maintains the mechanical strength with easy manufacturability and cost reduction. Results of static, modal and transient analysis of proposed axle under loading due to modified combination showed that the proposed model was suitable to install on trolley. This paper described the optimization of the hollow axle for the ultimate value so that the strength should be maintained with the reduction in cost and weight and it was founded that the weight was reduced from 40 to 60%.

The paper by Zhou *et al.* (2018) presented a new method for classifying railway vehicle axle fatigue crack Acoustic Emission (AE) signal. The method was developed by integrating self-adaptive EMD with ENN. The method first used EMD to decompose the signals into six IMFs and one residual. From the IMFs and the residual obtained by EMD, a TDE feature vector consisting of energy entropy, energy distribution ratio, and interval average energy were computed by HHT. The result showed that this method was better than other EMD energy domain classification method on identifying railway vehicle axle fatigue crack AE signal.

The paper by Náhlík *et al.* (2017) presented methodology for the residual fatigue lifetime prediction of the railway axle based on the linear elastic fracture mechanics concept. The methodology contained estimation of the critical position of initial crack, prediction of the fatigue crack front shape development during crack propagation, separation of the bending and press-fitting contributions to the axle load, experimental measurement of the crack growth kinetics of EA4T steel and subsequent estimation of the residual fatigue lifetime of railway axle. Part of the presented study was also devoted to the probability aspects of determination of material characteristics describing fatigue crack propagation and retardation effects caused by existence of plastic zone ahead of propagating fatigue crack.

In study by Bansal and Kumar (2012), existing trolley axle was redesigned considering the static load conditions. A CAD model was prepared using ANSYS (version 12.0). Improved cross-section for the axle was calculated which resulted in the 11.5%. The design was optimized, based on the manufacturing cost of the axle.

In the paper by Manasa and Reddy (2013a) a static analysis was conducted on a tractor trolley axle. The solid modelling of axle was developed by CATIA-V5. Analysis was done using ANSYS workbench. Most of the tractor trolley axle used today is rectangular cross-section type, which in turn leads to increase in the weight of tractor trolley and axle. In this paper, an attempt has been made by replacing rectangular cross-section with circular one, which resulted in reducing the weight of the axle and the cost.

In the paper by Katore *et al.* (2015) the axle stress strain analysis was presented.

In the paper by Shad and Ul Hasan (2018) a number of wheel axles of MF-240 tractors, which had broken after unusually short times in the field, had been presented. The fracture surface showed typical fatigue fracture that had initiated from a circular crack in the induction-hardened layer at the "neck" region of the axle. The paper presented research, which determined the cause of their failures.

In study by Ramachendran *et al.* (2016), trolley axle was redesigned considering the static and dynamic load conditions. Based on FEA, redesign of axle was carried out for reducing the cost, weight and maintained the mechanical strength with easy manufacturability and cost reduction. Results of static, modal and transient analysis of proposed axle under loading due to modified combine showed that the proposed model was suitable to install on trolley. The design is optimized based on the manufacturing cost of the axle. The failure analysis is performed on the axle of trolley used in agricultural area. These results provide a technical basis to prevent future damage to the axle.

In the paper by Lemberg *et al.* (2017) the failure analysis of a trunnion axle on a hard suspension multi-axle trailer was presented. All reported failures have occurred in an unloaded state very shortly after being put into service at or near the top of the trunnion axle in close proximity to a welded round plate. Analyses indicated a pre-existing flaw in the heat-affected zone near the weld. The unloaded state of the trailer, which may have exacerbated the dynamic loading, coupled with the limited damping provided by the hard suspension was likely the driving force for this failure.

The research can help to identify the causes and possible axle defects, find rational solutions and make recommendations to manufacturers. The most frequent research issues of separate certain parts occur in various vehicle suspension. The FEM based on the application of ANSYS or SolidWorks software was used for the research. Research publications on vehicle suspension elements such as the analysis and modelling mean that the topic is relevant and important.

The purpose is to determine the nature and causes of failures of the suspension axles of truck trailers and to perform modelling of the suspension axle deformations using the FEM.

1. The object of the research

The object of the research is an axle of the truck with a three-axle trailer (Figure 1).

Every component of the truck is manufactured according to the requirements. The axle photo is presented in Figure 2 (Čepukė *et al.* 2016).

The maximum speed of the truck is 105 km/h, external diameter of axle d_e = 146 mm and external loading of axle will be described below.

The axle cross-section is tubular with various thickness of the wall (Figure 3). Thickness t depends on truck's exploitation geographical region and quality of the roads.

The company produces axles from tube with external diameter d_e and internal diameter d_i (Figure 3) with thickness t = 9.0 mm and t = 11.0 mm. The inside diameter depends on the different wall thickness t.

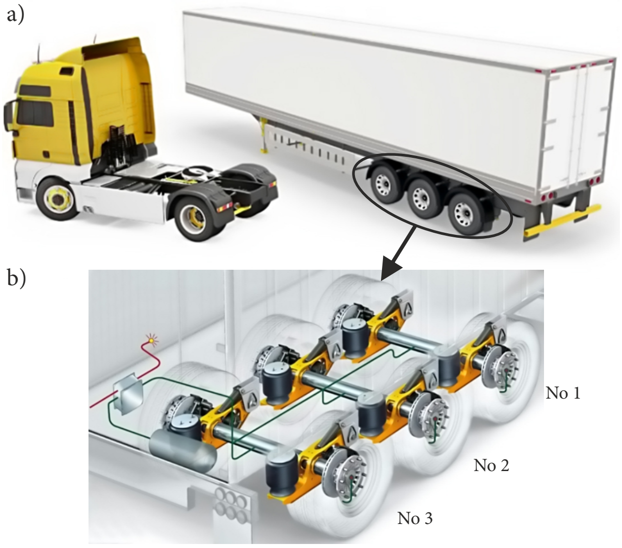

Figure 1. Truck with trailer: a – general view; b – trailer suspension

Figure 2. Object of research

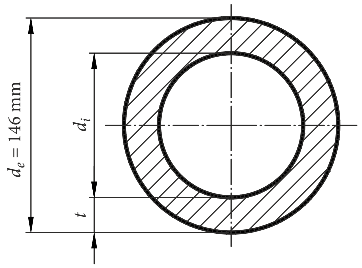

Figure 3. Geometrical parameters of the axle cross-section

The authors of the paper met some difficulties – there was absolutely no information from producer about axle presented: neither information about steel material and its properties, nor information about geometry, as well as no reasons of the fracture were mentioned, etc.

2. The axle's failure analysis

Dynamic loads have been applied according to research by Buhari *et al.* (2013). The factors influencing the vertical dynamics include the mass and stiffness distribution of the vehicle's structure, payload mass distribution, suspension and tires, road surface's longitudinal profile, and the speed of the vehicle. Dynamics coefficient values of less than 8% indicate moderately smooth pavements, greater than 10%

is considered to indicate moderately rough pavement, and higher than 15% indicates very rough pavement surfaces (Buhari *et al.* 2013). In this paper, the authors accepted that the dynamic loads are higher than 15% and dynamics coefficient is approximately equal 1.2.

During the operation, an axle undergoes static and cyclic loading, including random loading, bending about horizontal and vertical axes, as well as welding influence and climate temperatures (Yasniy *et al.* 2013).

In order to reduce the number of faults on truck trailer axles, it is first necessary to perform a fault analysis. In most cases, axial failures develop gradually. Sudden failure of truck trailer axles is rare. The speed of cracks depends on many factors. Figure 4 shows the undamaged axle of the truck trailer. Axle failures are presented in Figures 5 and 6.

After some exploitation, axle primary failures appeared (Figure 5a). Axle failure began to develop from minor cracks in crack focus (Figure 5b).

As the truck is exploited further, the cracks progress (Figure 6a) (Čepukė *et al.* 2016) till total failure of axle occurs (Figure 6b).

From the photos (Figures 5 and 6), it is visible that minor faults (small cracks in Figure 5) turn into serious failures (Figure 6).

When using a trailer with a cracked axle, the fault develops to fractures.

Figure 4. New truck trailer axle fragment

It was observed by drivers of the trucks that only first and second axles turned to fracture. The third axle was always without cracks. Hence, we may conclude from practical observation, that loading of axles No 1, No 2 and No 3 (Figure 1b) is different (Čepukė *et al.* 2016). In accordance with our results and observations, the axle No 1 (Figure 1b) is tend more to fracture, because it experiences the highest loads.

The crack growth mechanisms acquire ductile character, which makes preconditions for the increased strain localization. An increase in the level of plastic deformation causes the localization of plastic strains in the vicinity of the microstructure elements. With an increase in the crack length, the influence of inclusions and disperse particles on the fatigue crack propagation mechanisms increases (Yasniy *et al.* 2013; Sorochak *et al.* 2015).

On the basis of these studies mentioned above the mechanism of crack development will be described. The visual examination of the focal lengths and fractures of the axis crack (Figures 5 and 6) showed that the crack nucleus is the most often formed at the weld seam of the axis joint (Figure 5b).

To prevent malfunctions, you need to know the causes of the malfunctions.

The causes of trailer axle failures can vary widely, but the root causes may include:

- »» carrying load overload;
- »» poor road surface;
- »» low quality production;
- »» poor load distribution in the trailer;
- »» the axis is made of poor metal quality.

Fault assessment methods are the following: visual inspection; chemical analysis of metal, fractographic research, mechanical tests (tensile test, impact strength test, hardness test), microstructure study (microhardness tests), computational analytical model, FEM with ANSYS software, FEM with SolidWorks software.

In this paper truck trailers axles transformation research used FEM with ANSYS software (Katore *et al.* 2015).

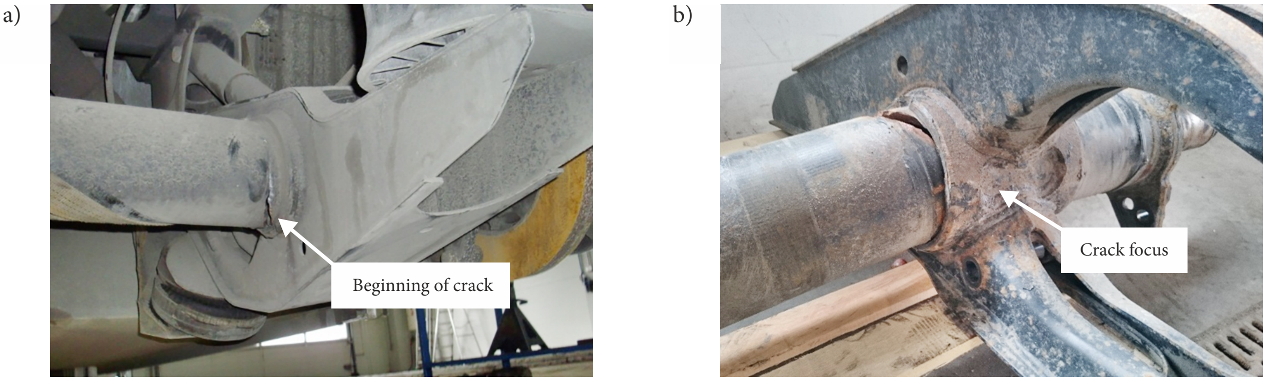

Figure 5. Axles: a – the beginning of the crack; b – crack at the mounting position

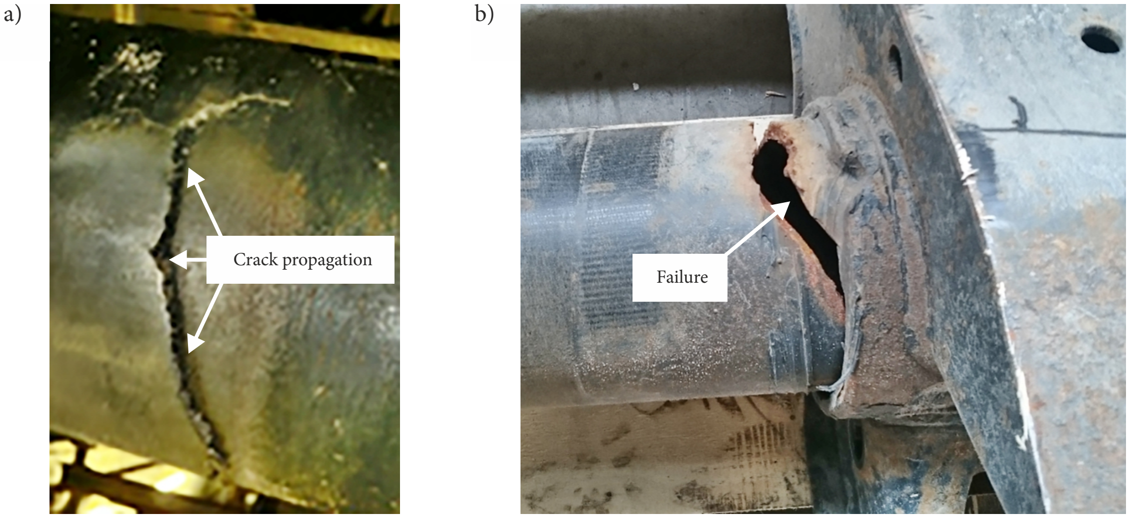

Figure 6. Axles: a – crack not at the mounting position, visible fracture split; b – crack not at the mounting position, total failure

3. Static analyses of strength of the axle by FEM

First of all, the main problem is an identification and calculation of the internal forces. Some of them could be in static and dynamics – bending moment about horizontal axle. Other – bending moment about vertical axle (in sudden braking) and torsion (road with defects) – only in dynamics.

In the paper, only static deformation has been analysed, because it is enough for checking of the finite element models quality. Full analyses with dynamics and fracture investigation will be performed in the future.

The loads of the axle were defined according to Koval' (2017) and transportation case with fully loaded trailer (Figure 7) with permissible loads was taken into account. According to Figure 7 performance axle capacity for solutions and modelling is 9000 kg. Certainly, this load is not exact, because the dynamics effect in roads with defects will increase this value. For this reason, different loads for different axes are not defined.

As it is shown in Figure 7 that the trailer axle loads are the same. Taking into account (Čepukė *et al.* 2016) from statics equilibriums equations of the two support (Figure 8) beam and method of sections extremal internal forces are:

- »» shear force $V_y = 78.8$ kN;
- »» bending moment $M_{\max} = 40.6$ kN·m.

Truck axles No	1	2	Truck trailer axles No	1	2	3
Empty [t]	6.2	3.4		1.6	1.6	1.6
Equivalent [10 t]	0.15	0.01		0.00	0.00	0.00
Total empty [t]	14.4					
Regular [t]	7.1	8.2		4.9	4.9	4.9
Equivalent [10 t]	0.25	0.45		0.06	0.06	0.06
Total common [t]	30.0					
Full load [t]	7.4	10.7		7.3	7.3	7.3
Equivalent [10 t]	0.30	1.31		0.28	0.28	0.28
Permissible	10.0	11.5		9.0	9.0	9.0
Total full load [t]	40.0					

Figure 7. Loads distributions to axles

Two types of 3D meshing technique have been explored for modelling of axle as 3D body. The mapped mesh (Figure 9a) may be considered as a regular mesh with homogeneous structural solid elements, the second type of mesh presents curvature or irregular mesh (Figure 9b) with structural elements having spatial prismatic orientation. The quality of the finite element models with different mesh grid size (Figure 9) was tested by comparing a deflection of the central point by analytical formula (Čižas 2008). In aggregate 4 different meshes with thickness $t = 9.0$ mm were tested. Two of them are show in Figure 9: regular mesh and curvature mesh. The 3D element, which is used in modelling and analyses, has plasticity, large deflection and large strain capabilities. The ANSYS code is used for analysis (Katore *et al.* 2015).

The structure is loaded by applying the two concentrated loads in points C and D (Figure 8) of a conservative character. Geometric boundary conditions restricting displacement are given on the axles ends (points A and B) (Figure 8), while one of them modelling with free displacement according Z axis. The material is assumed to be homogeneous and isotropic. The Young's modulus $E = 204$ GPa was obtained from experimental curve of tensile test of the steel, while Poisson ratio $\nu = 0.30$, which is standard for steel was taken.

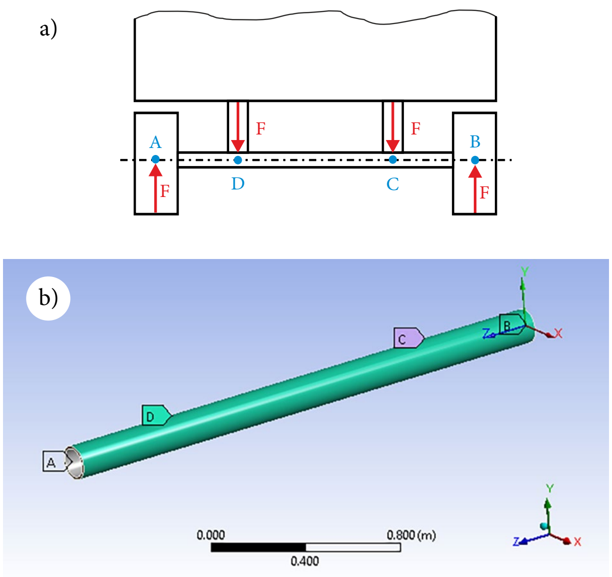

Figure 8. Axle loads:
a – principal scheme with the load; b – FEM

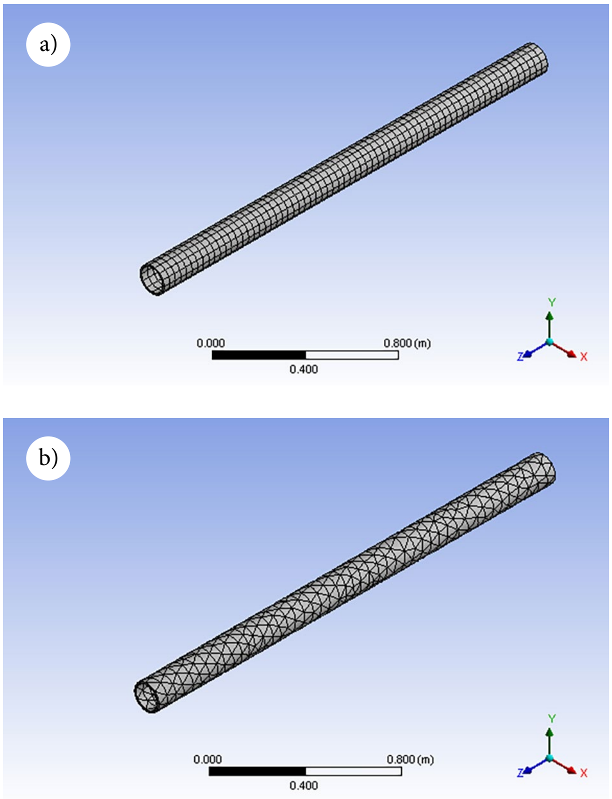

Figure 9. The finite element meshes of the axle:
a – regular mesh; b – curvature mesh

The quality of finite element models was checked by comparing numerical results with analytical solutions. The density of the mesh depends on number of elements (Table). The results of the test as displacement of the central point is presented in Table.

Errors between analytical and FEM research results are presented in graph (Figure 10).

Table. The results of the test

Mesh size function	Number of nodes	Number of elements	Displacement [mm]	
			FEM	Analytical
Curvature	6472	3192	13.608	13.827
Curvature	4829	2387	13.864	13.827
Curvature	6529	1156	14.252	13.827
Regular	42282	6612	14.250	13.827

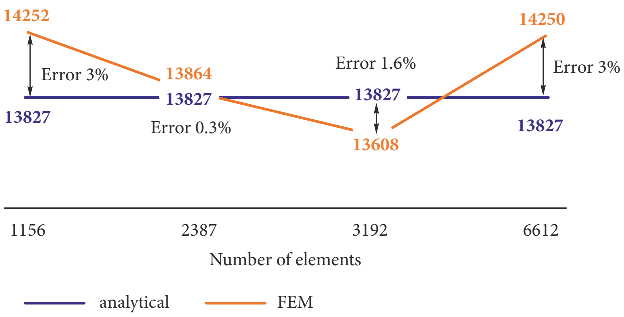

Figure 10. Errors between analytical and FEM research results

As it can be seen from Figure 10, errors between the analytical and FEM results are between 0.3 and 3.0%.

Numerical and analytical data on obtained deflections results shows quite good coincidence. It can be observed that type of irregular mesh with number of elements 2387 (Figure 10) gives accuracy 0.3% and this model will be used for simulating deformation behaviour of the axle.

4. The results and discussion

Therefore, model with thickness t = 9.0 mm was tested with curvature mesh (Figure 11) too and displacement of 13.8 mm gives 0.3% error comparing with analytical result. Model with t = 11.0 mm (Figure 12) gives displacement of 12.1 mm.

Both finite element models with different thickness were investigated. Distribution of stress has been obtained according to von-Misses stress given in Figures 13 and 14. The most important zone occurs in the central region of the axle and spreads along the axle until loads impact region.

Their absolute values 366 MPa (Figure 13) of the model with thickens t = 9.0 mm and 325 MPa (Figure 14) of the model with thickens t = 11.0 mm only depend on bending moment about horizontal axis. The static analyses of developed FEM illustrate that with a decrease thickness of axle walls from 11.0 to 9.0 mm von-Misses stresses increase till 11% and the amount 366 MPa.

Shear stresses of the model with thickens t = 9.0 mm are 48.9 MPa (Figure 15) and maximal values spread near the ends of axles. The analytical maximal value of shear stresses without concentration effect is 40.7 MPa (Čepukė *et al.* 2016). The finite element analyses performed with concertation effect shows 20% increasing of shear stress values.

The dynamics compound stresses for two-dimensional stress state by maximum-shear-stress theory for axle with t = 9.0 mm in most simple cases rise in the centre 440 and 118 MPa in the end of the axle. The dynamics compound stresses by maximum-shear-stress theory are 392 MPa in the load impact region. The yield stress of the constructions steels in transport engineering are approximately 500…800 MPa, so overloading of the axle up to 28% achieve 500 MPa. It shows the necessity to investigate axles full dynamic stress state in area of loads impact region, etc. estimate torsion and bending moment about vertical axis and properties of the axle's steel.

Future investigations of the axle will include full dynamics effect, all internal forces, fracture, cyclic loading and experimental investigation of the material of the axle.

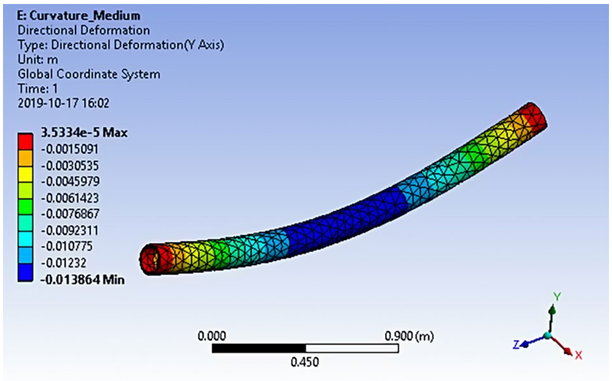

Figure 11. Axle displacements, when axle wall thickness is t = 9.0 mm

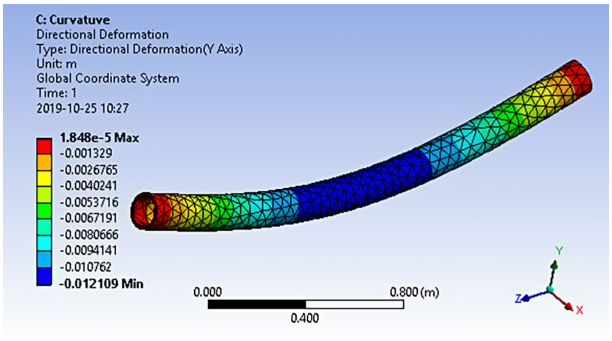

Figure 12. Axle displacements, when axle wall thickness is t = 11.0 mm

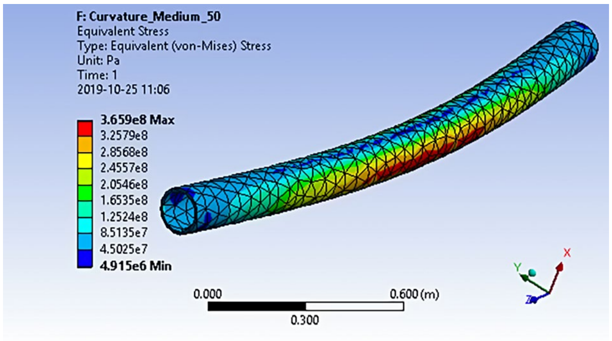

Figure 13. Axle von-Misses stress distribution, when axle wall thickness is t = 9.0 mm

Conclusions

Errors between analytical and FEM research results is from 0.3 to 3.0%. The model with irregular mesh with 2387 elements has shown the best accuracy 0.3% and was used for finite element analyses.

The bending static analyses of developed FEM illustrate that in the axle with thickness of 9.0 mm von-Misses stresses increased to 11%. The deformation occurs in the central region of axle and spreads along the axle until loads impact region.

Shear numerical stresses of the model spread near the ends of axle, shows 20% increasement comparing with analytical value and are 48.9 MPa.

The dynamics compound stresses for axle wall thickness with t = 9.0 mm in the centre of axle rise 440 MPa and 392 MPa in the most important load impact region. Overload of the axle by 28% would cause of yielding of steel. It shows the necessity to investigate and estimate full dynamic stress state including torsion and bending moment about vertical axis in area between maximal normal and shear stresses, etc. of loads impact region.

Further research results can help to identify the causes and possible locations of axle defects, find rational solutions and make recommendations to manufacturers.

The presented research is methodical and its results can be used for other similar future investigations.

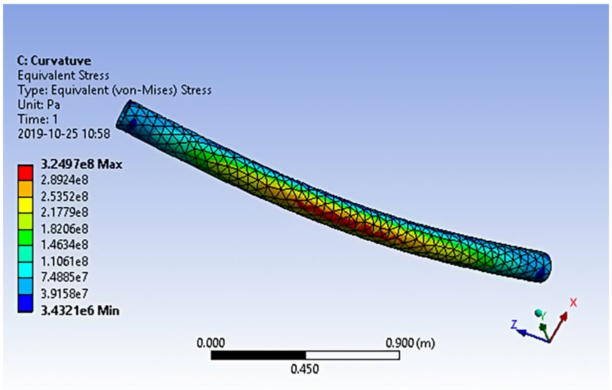

Figure 14. Axle von-Misses stress distribution, when axle wall thickness is t = 11.0 mm

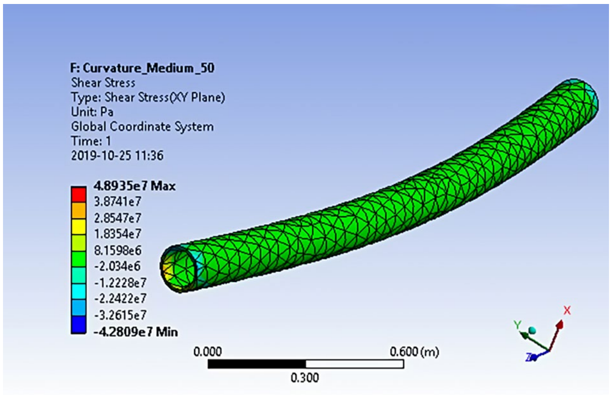

Figure 15. Shear stresses, when axle wall thickness is t = 9.0 mm

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