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Abstract: The non-drive automotive rear axle beam of a heavy commercial vehicle, 35T gross vehicle weight (GVW), 8×2 Truck, is undergoing bending failure on the field (failed axle beam). The failure is primarily due to the overloading of the vehicle by the customer. The paper analyses the failed rear axle shaft of the vehicle and highlights the regions of failure in the axle cross-section and its impact on performance and life. A three-dimensional (3D) computer-aided design (CAD) engineering model of the failed axle beam is modelled on Solid Works software. The 3D model is imported into finite element analysis (FEA) software, Altair Hyper Works to create a finite element model, carry out linear static, modal, and fatigue analysis and study the stress/strain induced in the failed axle beam. Based on the results obtained from the three analyses, the axle beam will undergo cross-sectional and material changes to eliminate the failure and improve product quality and life.

Keywords: non-drive automotive rear axle; bending failure; finite element model; fatigue analysis; stress concentration; CAD; computer-aided design; heavy vehicle; static analysis; materials.

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1 Introduction

In an automobile, an axle is a mechanical component that can be fixed/rotated and rotates the wheels mounted on it. The two types of axles in an automobile are Drive Axle and Non-Drive Axle, forming the vehicle Suspension System. The drive axle transmits the engine power to the wheels to move the vehicle, while the non-drive axle bears the load of the vehicle and cargo (if any). In heavy vehicles such as trucks, trailers, dumpers, there can be more than two axles such as the front axle, lift axle, rear-drive axle, rear non-drive axle, etc. The non-drive rear axle of a heavy vehicle is an important mechanical component, just like the other axles of a vehicle. The axle only carries the vehicle load, and any failure in this component would also directly impact the vehicle's product quality and performance. It can lead to wear and tear in the tyres, or it can cause damage to other components of the vehicle, thereby increasing the maintenance/repair costs of the vehicle for the consumer. Hence, while designing the non-drive rear axle beam for a heavy commercial vehicle, the consumer/vehicle usage trend should also be given equal importance in addition to the base specifications of the vehicle for which the axle is being designed. Over the past decade, several works focused on rear axle beams of different types of vehicles. Modal analysis is conducted on the rear axle beam of a three-wheeled vehicle to predict the failure based on the frequency and fatigue analysis is carried out to predict the failure close to a realistic situation (Verma et al., 2021). Through modal analysis, it is understood that combined bending and torsional vibration are more dangerous to failure. At the same time, in the case of fatigue analysis, it was concluded the variable amplitude loading degrades the working life cycle of the axle. The probability approach is applied (Kepka and Kepka, 2018) to predict the fatigue life of a trolleybus rear axle and the reasons for failure. The nCode software identifies critical regions (weld and radius pin joints) of the rear axle beam where the probability of failure is predicted high. Consequently, changes in loading patterns helped eliminate failure. Çiçek et al. (2021) demonstrated the heavy military vehicle dynamic analysis under the firing load condition and also performed parametric optimisation by using ANSYS Parametric design language. Thangapazham et al. (2020) investigated the stress analysis and stress concentration factors in the bogie bracket unit of the heavy-vehicle system, the computer-aided engineering (CAE) software was used to identify the forces which cause failure. Nataraj and Thillikkani (2020) explained the failure analysis of the heavy vehicle suspension leaf spring, the finite element analysis (FEA) was carried out to investigate the failure root cause of the leaf spring. Sun et al. (2011) focused on the casting methods used for the rear axle beam of a truck and the defects that are produced. The material is nodular cast iron. The results from the Z-CAST simulation software for casting are used to eliminate casting defects such as cold shut and mis run by altering parameters such as temperature, liquid flowing field, and geometry of ingates and runners. A four-point bending test is performed on the rear axle beam of a truck (Firat, 2011). It uses the Smith – Watson – Topper and Fatemi – Socie parameters to predict the fatigue life tests and crack initiations mainly near the housing dome of the rear axle beam. The above is done in conjunction with the local stress-strain approach, which used the cyclic plasticity model and notched stress-strain approximation scheme. Topaç et al. (2009) noticed that before the expected loading cycles during the vertical fatigue tests of a rear axle housing prototype, a premature failure occurs in a region close to the housing. Fatigue crack initiation cycle was noted, which was less than predefined resist load cycles. Accordingly, design changes such as increasing banjo transition area and thickness of reinforcement ring were proposed as minimum design criteria. Suresh Kumar and Kumaraswamidhas (2021) focus are on removing failure during the developmental testing of the fabricated rear axle housing of a 31T GVW vehicle. Adding an inner side weld at the central section of the axle helped resolve the stress concentration at the notch area and thereby passed in rig testing, and no failure was observed on the torture track (TT). Zhao et al. (2014) conducted fatigue analysis on a rear axle beam by modifying Miner's Rule to prepare a fatigue model which is used to analyse stress and strains for strengthening damage and loads below the fatigue limit. The paper demonstrates that there can be a significant improvement in the fatigue life predicted if damage and loads below the fatigue limit are taken into account. MTS Road simulator is used to verify the results. Concepts of Fracture mechanics to study the regions of initiation of cracks are also used. Walton et al. (1986) explained the fatigue failure analysis of the gear transmission drive through an interactive design program. Chaudhary et al. (2021) demonstrated the post-failure analysis of the rear axle shaft of a heavy vehicle through Fractography and ultrasonic testing. Gonzalo (2013) used a simulation model and an empirical equation to predict the failures that might occur in any of the systems of the rear axle beam of a heavy truck (mechanical, electrical, pneumatic, hydraulic systems). Parameters such as overloading, manufacturing/assembly process, maintenance, and lubrication are considered to predict the exact life of system underuse and perform the reliability analysis. Zhang et al. (2016) carried out a fatigue life analysis on the front axle beam of a heavy-duty truck. After determining the dangerous area of failure, structural improvements in the beam section are made for multi-loading conditions. Avikal et al. (2020) described the design and fatigue analysis is conducted on the front axle beam of a heavy-duty truck (TATA Tipper). The crack initiation regions, which are often in the end region of the axle where it comes into contact with the wheel, are predicted. Parameters such as deformation, fatigue life, and others that are also affected by the crack are effectively investigated for a wide variety of steel grades. Sharma et al. (2012) explained the design and analysis of the floating structures and ships also demonstrated the major challenges in the design of the industrial applications. Perumal et al. (2011) studied the influence of the forging process on the fatigue properties of the steel used to manufacture an axle. The Roll and Hot – Die-Forging process were compared to investigate the mechanical and microstructure properties of AISI 4140 steel. The different martensitic microstructures in both processes significantly brought changes in overall mechanical properties. It is further noticed that the fatigue life is 37% higher for roll forged beams in comparison to the hot-die forging. Wu et al. (2006) proposed experimental studies on air-cooled bainitic micro-alloyed steel materials are conducted that can be used for front axle beam. Mechanical Properties, cooling rates, and chemical composition of the alloy were important parameters used in the empirical formulas to carry out various calculations and arrive at the right chemical composition for the alloy. It is concluded that the air-cooled bainitic micro-alloyed steel with 0.003% bainite can be used to manufacture a safe front axle beam. Panachev and Kuznetsov (2015) demonstrated the stress and strains experienced in the rear axle beam of a Hauler.

A correlation is defined between the specific energy input and the mathematical expectation of the stress amplitude in the undercarriage of the Hauler. Data obtained from oscillograms regarding stress experienced is used as input for statistical models to improve the failure life of axle beams. Wang et al. (2012) explained linear static finite element model is prepared to simulate the vertical bending fatigue test for the BANJO housing of the rear axle. Factors such as the mass of the differential, damping ratio, loading frequency, and material properties of the rubber bushings are considered. Fatigue life prediction using the finite element model prepared to simulate the vertical bending fatigue test.

The main objective of this paper is to analyse a failed non-drive rear axle of a heavy vehicle undergoing bending failure and propose a safe design to eliminate failure. Section 2 describes the process of preparing the CAD and FE model of the failed axle beam to carry out FE analysis. The same process would be involved to carry out FE analysis for axle beams undergoing dimensional changes/material grade changes while developing a safe axle beam design. Section 3 describes the methodology adopted. The problem statement for the failed axle beam and the three load cases are also described in this section, an essential criterion for the FE analysis. Results and discussion are covered in Section 4 and Section 5 is the conclusion.

2 CAD and FE model preparation of the rear axle beam

The material properties and the dimensions of the failed rear axle beam are shown in Table 1. A truck garage visit was also done to measure the dimensions as seen in Figure 1.

Figure 1 Rear axle beam (see online version for colours)

The CAD modelling of the failed rear axle beam is prepared on SolidWorks software. The axle beam has two parts: A Circular Spindle and A Rectangular Axle Tube modelled separately and then assembled to prepare the complete 3D model of the failed rear axle beam. The 3D model of the axle beam is shown in Figure 2.

The CAD model of the failed rear axle beam was imported into the FEA Software Altair HyperWorks. The pre-processing, processing/solver and post-processing are carried out on HyperMesh, Optistruct, and HyperView, respectively.

Table 1 Material and dimensions of failed rear axle beam

Properties	*Value*
Material grade	STEEL E250
Material density of axle beam ρ (kg/m^3)	7900
Material Young's modulus E (MPa)	210×10^3
Material yield point σ_y (MPa)	250
Material UTS σ_u (MPa)	410
Designed capacity (kg)	10500
Circular section dimensions (mm)	135Ø×12THK
Rectangular section dimensions (mm)	135(W)×140(H)×12Thk
Total axle length (mm)	2049

Figure 2 3D model of the failed rear axle beam (see online version for colours)

2.1 Pre-processing

The first step involved in any FEA is to prepare the Finite Element Model, which involves CAD and Meshing. The CAD model of the failed axle beam is already ready on SolidWorks. The same model is imported into HyperMesh for meshing the CAD model. Meshing is mainly categorised into three types i.e., 1D Meshing, 2D Meshing, and 3D Meshing. Within 3D Meshing, there are different finite element geometry sizes and shapes, such as Quads, tria, tetra, penta, hex, pyramid, etc. For the rear axle beam model, 3D Tetra Meshing is done, which provides accurate results within an optimum solving time of the solver (Optistruct). Figure 3 shows the meshing of the different cross-sections of the axle beam.

After meshing the CAD model, boundary conditions need to be applied to the meshed model. Hence, two parameters i.e., constraints and load, need to be defined. An RBE2 constraint is applied to the spindle of the axle beam, thereby making 4 DOF's zero (two translational and two rotational). The load is applied on the axle tube in the region, where the chassis rests on the axle in an area of 105×55 mm^2 and at 450 mm from the axle end. As previously mentioned that the analysis is carried out for three load cases, we shall prepare a single FE model by applying a load of 1N in the pre-processing stage and derive the results for the three load cases in the post-processing stage from the same FE model. Figure 4 depicts the RBE2 constraint in the spindle, and Figure 5 shows the load applied.

Figure 3 3D tetra meshing of the non-drive rear axle beam (see online version for colours)

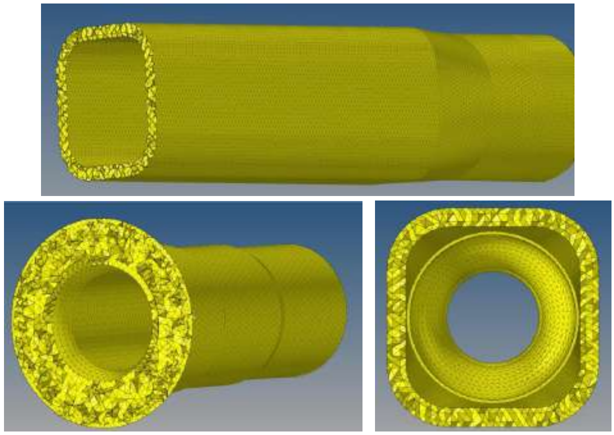


Figure 4 RBE2 constraint on one spindle (see online version for colours)

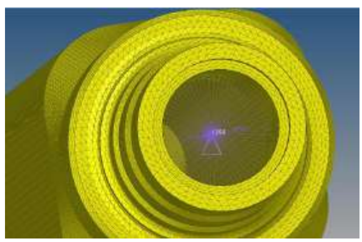
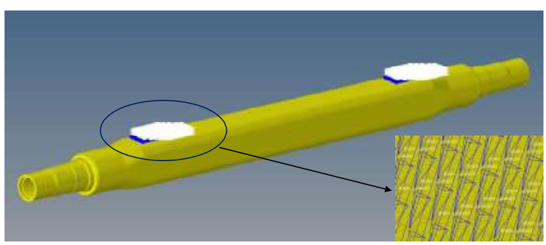


Figure 5 Load of 1N applied on the mesh nodes (see online version for colours)



The material assigned to the FE model of the axle beam is steel whose Young's modulus, Poisson's ratio, and density are defined in the pre-processing stage as 210 GPa, 0.3, and 7900 kg/m^3. The Yield Point and UTS will be input in the post-processing stage.

2.2 Processing/Solver

In this step, the solver (Optistruct) carries out matrix formations, inversion, multiplication, and solution to compute the analysis results, such as displacement, stress, strain, life, etc. There are three analyses carried out on Optistruct i.e., linear static analysis, modal analysis, and fatigue analysis. The equation of motion (Based on D'Alemberts principle) is given below,

$$[M]\ddot{x} + [C]\dot{x} + [K]x = F(t) \tag{1}$$

where $\ddot{x} = \frac{d^2x}{dt^2}$ = acceleration, $\dot{x} = \frac{dx}{dt}$ = velocity, x = displacement.

For Linear Static Analysis, $[M]\ddot{x} = 0$, $[C]\dot{x} = 0$, $[K]$ and $F(t)$ = Constant.

Thus, the equation for Linear Static Analysis reduces to

$$F(t) = [K]x \tag{2}$$

For modal analysis of a system without damping, $F(t) = 0$ and $C = 0$.

Thus, the equation of motion for modal analysis reduces to

$$[M]\ddot{x} + [C]\dot{x} = 0 \tag{3}$$

For fatigue analysis, calculations for the life of the structure are done based on $S - N$ curve (alternating stress vs cycles) or $\varepsilon - N$ (alternating strain vs cycles). The equation for alternating stress is given below.

$$\sigma_a = \frac{\sigma_{\max} - \sigma_{\min}}{2} \tag{4}$$

The solver (OptiStruct) takes matrix formulations and calculates the results using the above theoretical formulas.

2.3 Post processing

Post Processing is viewing the results of the analysis that has been completed and taking necessary design decisions to eliminate the failure (if any). The post-processing software used for viewing the analysis results of the rear axle beam is HyperView. The Yield Point and UTS for steel will be input into the software in this stage.

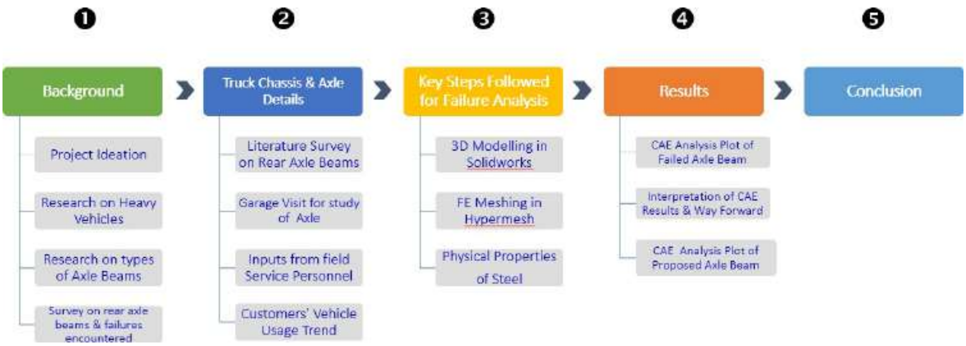
3 Proposed methodology

Considerable work is done to understand the various axle beams in an automobile, and the basis on the research/survey done, our field of work is focused on the non-drive automotive rear axle beam of a heavy vehicle. The survey revealed that the non-drive rear axle was bending within 6 months of operation. The bending failure modelled to high tyre wear on the inner side of the wheel and degraded the vehicle's performance. It was also noted that failures were negligible on highway running vehicles but high in the case of non-highway running vehicles where either the road is bad or overloading by the customer or a combination of both. With many consumers driving the vehicle with the 'lift axle' up, there was an increase in the load on the non-drive rear axle beam of the vehicle. Hence, basis the above information and the data obtained from a vehicle manufacturer, the analysis for the axle beam needs to be done for 3 load cases as described below.

- *Rated load*: Rated Load on the non-drive axle is 10.5T.
- *30% overload:* With the 'lift axle' up, the load on the non-drive axle increases by 2.5T, thereby making the total load equal to 13T.
- *60% overload:* In case of overloading of the truck by customers, load measurements (on weighbridge) have shown that loads on the non-drive axle can go up to 17T.

It is also understood that during running, the axle beam is subjected to G loads up to 3G. The objective of this paper is to analyse a failed non-drive rear axle of a heavy vehicle, highlight and understand the causes of failure in the axle beam, propose design changes to eliminate failure and verify that the new design is a safe axle beam design. The analysis will be done under the on-field usage of the vehicle. Therefore, the proposed methodology can be understood from the flowchart in Figure 6.

Figure 6 Flowchart for proposed methodology (see online version for colours)



4 Results and discussion

4.1 Linear static analysis

The design and material properties of the failed non-drive rear axle beam section are shown in table. Figures 7–9 describe the static analysis of the non-drive rear axle beam section.

Figure 7 Full axle beam linear static analysis CAE plots (see online version for colours)

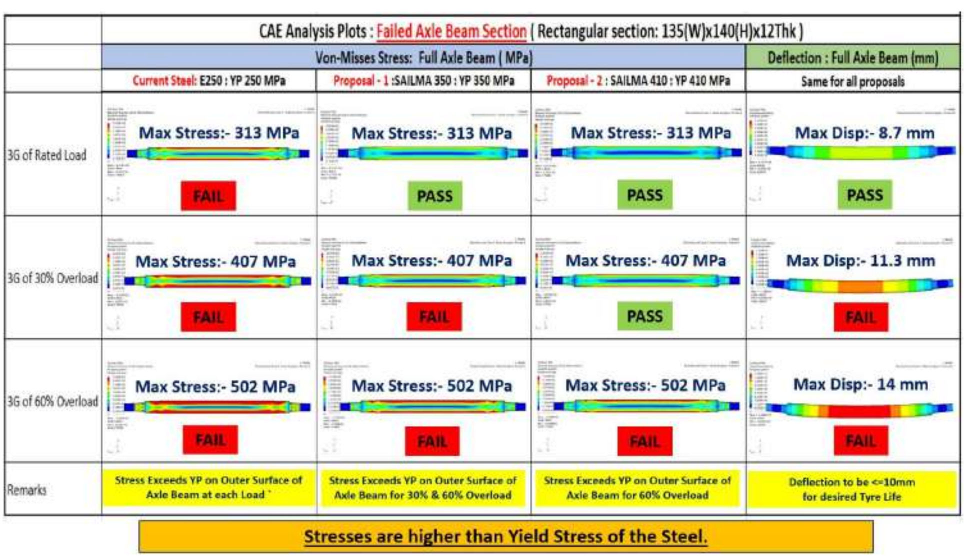


Figure 8 Circular section linear static analysis CAE plots (see online version for colours)

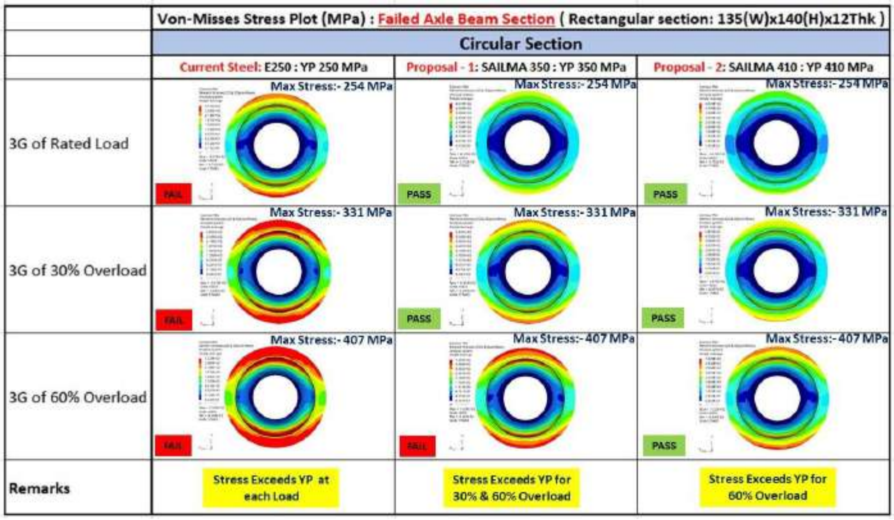
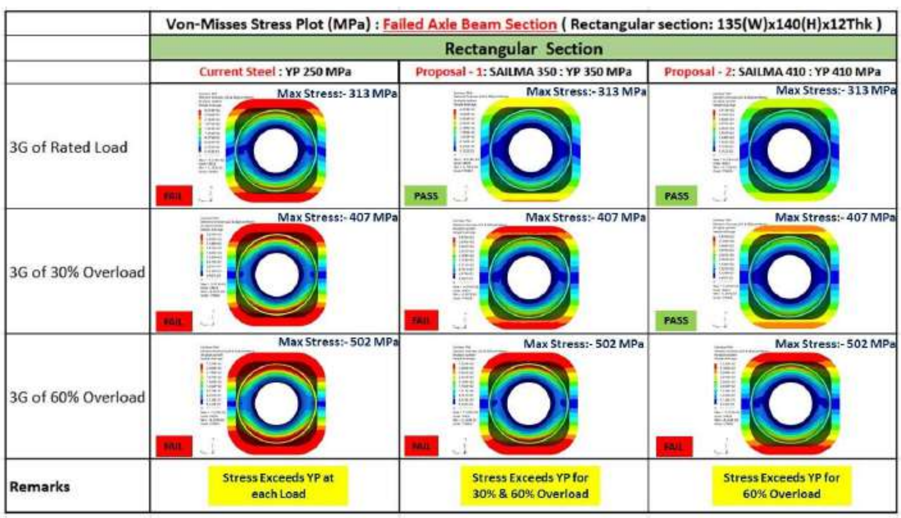


Figure 9 Rectangular section linear static analysis CAE plots (see online version for colours)



It is observed that in all three figures the current steel axle is going to bending failure under all three loading conditions. The produced maximum stresses are higher than the YP of 250 MPa. The maximum stresses in the circular region are 254 MPa, 331 MPa, and 407 MPa, respectively, which is higher than the YP, 250 MPa.

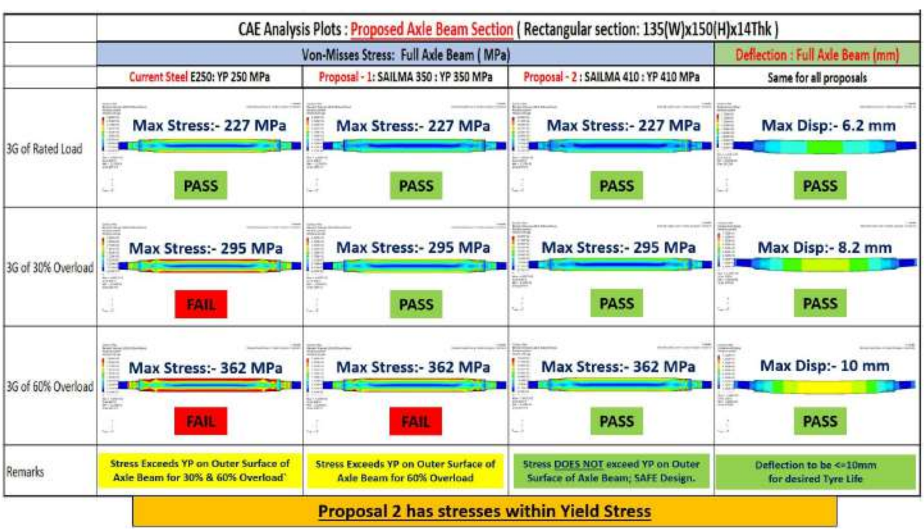
The region of failure in the cross-section is highlighted in RED colour in the CAE plots in the figures. As a result, a portion of the cross-section of the failed axle beam is undergoing a permanent set (plastic deformation), and hence, the design is tagged as 'FAIL' in the figures. The corresponding deflection in the axle beam is also higher than the permitted 10 mm deflection for desired tyre life, as seen in Figure 7. The maximum stresses in the rectangular section are 313 MPa, 407 MPa, and 502 MPa, respectively, which are higher than the YP, 250 MPa.

In Figures 8 and 9, it is also clearly seen that for the proposed material changes, SAILMA 350 and SAILMA 410, having YP 350 MPa and 410 MPa, respectively. T the region of bending failure in the axle beam section (RED coloured region) is comparatively decreasing, but still undergoing bending failure in one/two load cases. The 'Remarks' row and the tags 'PASS' and 'FAIL' in Figures 7–9 will help in understanding the Linear Static CAE plots of the failed non drive rear axle beam section.

It is clear now that, to eliminate bending failure, the axle beam section modulus also needs to be modified. The maximum stress in the axle beam section is lower than the YP of the material. Several trials for different section modulus were performed for the three materials, E250, SAILMA 350, and SAILMA 410. An optimum axle beam section modulus is determined in the process, which is discussed below.

Figures 10–12 go together with Figures 7–9. As seen in Figure 10 heading, the proposed axle beam rectangular section has dimensions 135(W) × 150(H) × 14 THK. This change has increased the section modulus, as a result, the maximum stress in the rectangular section has gone down. The maximum stresses in the axle tube are 227 MPa, 295 MPa, and 362 MPa, respectively, while the stresses in the circular section have negligible changes in stress values. The tags 'PASS' and 'FAIL' along with remarks row in Figures 10–12. The region of failure in the axle cross-section (RED coloured regions) indicates that the proposed axle beam section manufactured using material SAILMA 410 is a safe axle beam design that passes for all the 3 load cases. The deflection values in Figure 10 also within the defined deflection limits, confirm that the design is safe.

Figure 10 Full axle beam linear static analysis CAE plots (see online version for colours)



Hence, for linear static analysis, the following can be concluded. The summary of the Linear Static Analysis is given in Table 2.

Figure 11 Circular section linear static analysis CAE plots (see online version for colours)

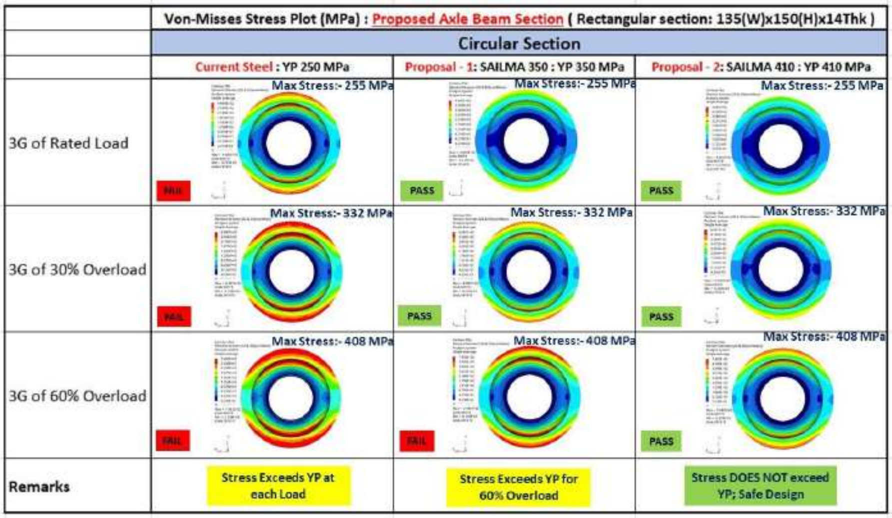


Figure 12 Rectangular section linear static analysis CAE plots (see online version for colours)

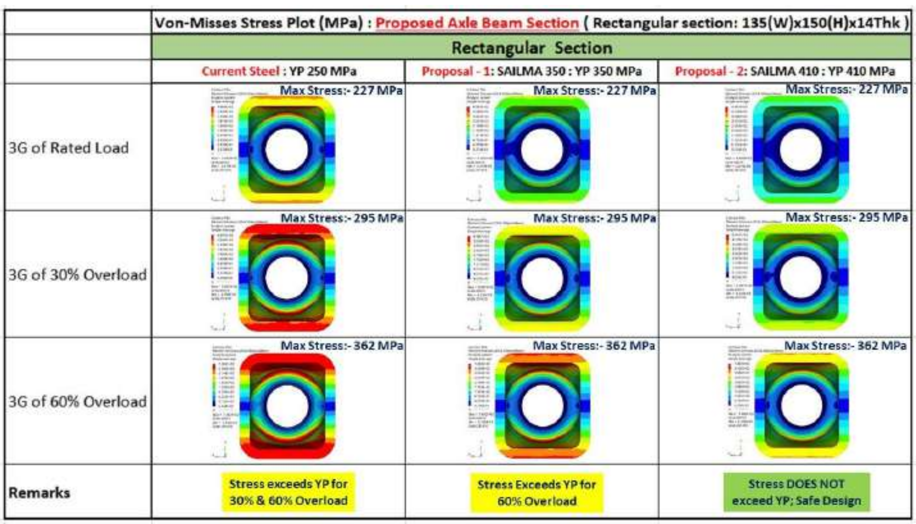


Table 2 Linear static analysis result summary

Type	*Geometry*	*Failed*	*Proposed 1* (*Proposal 2*)
Axle beam sections	Circular section	135Ø × 112Thk	135Ø × 14Thk
	Rectangular section	135(W) × 140(H) × 12Thk	135(W) × 150(H) × 14Thk
Steel	Grade	E250	SAILMA 410
	YP (MPa)	250	410

4.2 Modal analysis

The modal analysis was performed for both axle beams (failed and proposed). Figure 13 shows the numerical values of the five modes. The left model is the failed non-drive rear axle beam, while the right is the proposed non-drive rear axle beam. The frequency for the 5 modes has been tabulated in the following Table 3 as well.

Figure 13 Modal analysis CAE plot for non-drive rear axle beam (see online version for colours)

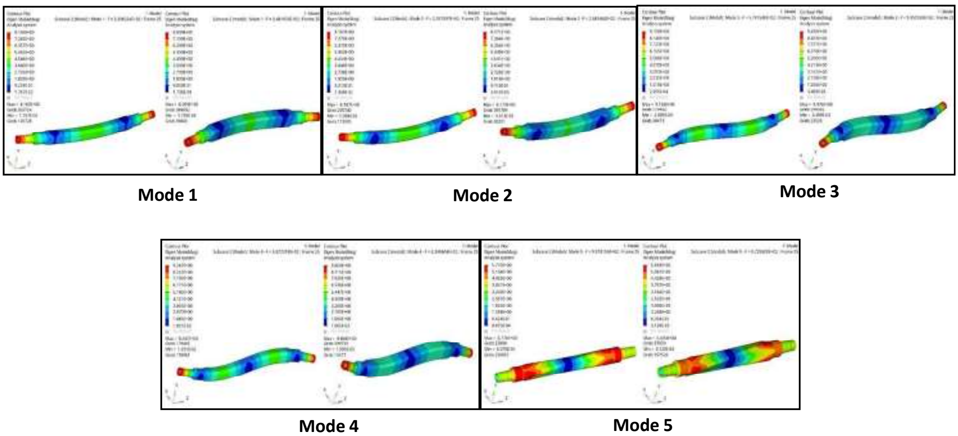
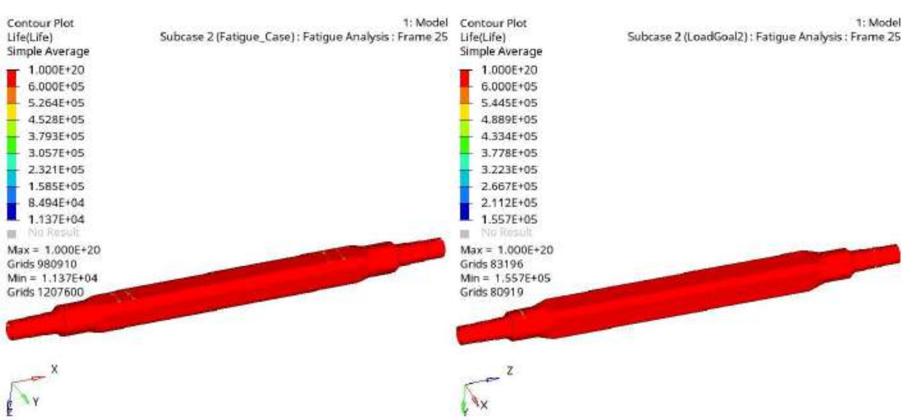


Table 3 Natural frequencies of both proposed and failed axle beams

S. no	*Mode number*	*Natural frequency (FEA) in Hz*	
		Failed rear axle beam	*Proposed rear axle beam*
1	1	229.622	248.105
2	2	235.759	268.346
3	3	574.154	595.059
4	4	587.232	634.560
5	5	957.816	972.551

Figure 14 Fatigue analysis CAE plot for non-drive rear axle beam (see online version for colours)



4.3 Fatigue analysis

For non-drive automotive rear axles of heavy vehicles, the desired fatigue life is 6×10^5 cycles per industry standards. Figure 14 depicts the fatigue life cycles of the failed axle beam on the left and the proposed axle beam on the right. Both the axle beams pass in the fatigue analysis test as it has a fatigue life cycle greater than 6×10^5 cycles.

5 Conclusion

The bending failure of an axle beam critically impacts the vehicle's performance and hampers the maintenance costs as well. As a result, the Linear Static Analysis for the axle beam was performed, which helped in highlighting the causes of failure, by taking into account the loading condition during vehicle operation and also overloading done by the customer. Accordingly, a safe axle beam design is proposed with an increase in section and higher YP material. The Modal Analysis of the failed and proposed axle beam design was also carried out to understand each mode's modal shapes and frequency, and it turned out to be within safe limits. From the Fatigue Analysis, it was also concluded that the failure and the proposed axle beam design have a design life of 6×10^5 life cycles.

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Conflicts of interest

The authors declare that they have no conflict of interest.

References

Avikal, S., Bisht, A., Sharma, D., Hindwan, H., Yadav, S., Kumar, K.C.N. and Thakur, P. (2020) 'Design and fatigue analysis of front axle beam of a heavy duty truck using ansys', *Materials Today: Proceedings, 10th International Conference of Materials Processing and Characterization*, Vol. 26, pp.3211–3215 [Online], doi: 10.1016/j. matpr.2020.02.901.

Chaudhary, S.K., Rajak, A.K. and Ashish, K. (2021) 'Failure analysis of rear axle shaft of a heavy vehicle', *Materials Today: Proceedings, International Conference and Exposition on Mechanical, Material and Manufacturing Technology (ICE3MT)*, Vol. 38, pp.2235–2240 [Online], doi: 10.1016/j. matpr.2020.06.312.

Çiçek, B.C., Acar, B.S.K. and Lder, N.A. (2021) 'Dynamic analysis and design optimisation of a heavy military vehicle', *International Journal of Heavy Vehicle Systems*, Vol. 28, No. 3, p.309 [Online], doi: 10.1504/IJHVS.2021.117502.

Firat, M. (2011) 'A computer simulation of four-point bending fatigue of a rear axle assembly', *Engineering Failure Analysis*, Vol. 18, No. 8, pp.2137–2148 [Online], doi: 10.1016/j. engfailanal.2011.07.005.

Gonzalo, T. (2013) *Reliability Analysis in Rear Axles for Truck*, 2013-36–0256 [Online], doi: 10.4271/2013-36-0256 (Accessed 22 April, 2021).

Kepka, M. and Kepka, M. (2018) 'Deterministic and probabilistic fatigue life calculations of a damaged welded joint in the construction of the trolleybus rear axle', *Engineering Failure Analysis*, Vol. 93, pp.257–267 [Online], doi: 10.1016/j. engfailanal.2018.07.015.

Nataraj, M. and Thillikkani, S. (2020) 'Failure analysis of leaf spring suspension system for heavy load truck vehicle', *International Journal of Heavy Vehicle Systems*, Vol. 27, Nos. 1–2, p.1 [Online], doi: 10.1504/IJHVS.2020.104413.

Panachev, I.A. and Kuznetsov, I.V. (2015) 'Management procedure for life cycle of rear axle metalworks of heavy haulers', *Journal of Mining Science*, Vol. 51, No. 2, pp.267–273 [Online], doi: 10.1134/S1062739115020088.

Perumal, V., Palanivelu, S., Mookherjee, S.P. and Jindal, A.K. (2011) 'Influence of forging process on fatigue properties of AISI 4140 steel axle component', *Journal of Engineering Materials and Technology*, Vol. 134, No. 010909 [Online], doi: 10.1115/1.4005405 (Accessed 22 April, 2021).

Sharma, R., Kim, T., Storch, R.L., Hopman, H. (J.J.) and Erikstad, S.O. (2012) 'Challenges in computer applications for ship and floating structure design and analysis', *Computer-Aided Design, Applications in Ship and Floating Structure Design and Analysis*, Vol. 44, No. 3, pp.166–185 [Online], doi: 10.1016/j. cad.2011.10.001.

Sun, Y., Luo, J., Mi, G.F. and Lin, X. (2011) 'Numerical simulation and defect elimination in the casting of truck rear axle using a nodular cast iron', *Materials and Design*, Vol. 32, No. 3, pp.1623–1629 [Online], doi: 10.1016/j. matdes.2010.11.009.

Suresh Kumar, G. and Kumaraswamidhas, L.A. (2021) 'Design optimization focused on failures during developmental testing of the fabricated rear-axle housing', *Engineering Failure Analysis*, Vol. 120, p.104999 [Online], doi: 10.1016/j. engfailanal.2020.104999.

Thangapazham, P., Kumaraswamidhas, L.A., Muruganandam, D. and Dharanivendhan, T. (2020) 'CAE analysis and road load data acquisition experimentation on bogie bracket of heavy duty commercial vehicle', *International Journal of Heavy Vehicle Systems*, Vol. 27, No. 3, p.258 [Online], doi: 10.1504/IJHVS.2020.108735.

Topaç, M.M., Günal, H. and Kuralay, N.S. (2009) 'Fatigue failure prediction of a rear axle housing prototype by using finite element analysis', *Engineering Failure Analysis*, Vol. 16, No. 5, pp.1474–1482 [Online], doi: 10.1016/j. engfailanal.2008.09.016.

Verma, R.P., Singh, M. and Lila, M.K. (2021) 'Failure prediction of rear axle of a three wheeler vehicle by dynamic analysis: computational approach', *Materials Today: Proceedings* [Online], doi: 10.1016/j. matpr.2021.02.002 (Accessed 22 April, 2021).

Walton, D., Prayoonrat, S. and Taylor, S. (1986) 'Computer-aided fatigue analysis', *Computer-Aided Design*, Vol. 18, No. 5, pp.263–274 [Online], doi: 10.1016/0010-4485(86)90296-4.

Wang, X., Xu, W., Huang, Y., Zhong, M. and Fan, H. (2012) 'Simulation of the vertical bending fatigue test of a five-link rear axle housing', *International Journal of Automotive Technology*, Vol. 13, No. 6, pp.923–932 [Online], doi: 10.1007/s12239-012-0093-5.

Wu, H., Liu, C., Zhao, Z., Zhao, Y., Zhu, S., Liu, Y. and Bhole, S. (2006) 'Design of air-cooled bainitic microalloyed steel for a heavy truck front axle beam', *Materials and Design*, Vol. 27, No. 8, pp.651–656 [Online], doi: 10.1016/j. matdes.2004.12.014.

Zhang, M., Ji, X. and Li, L. (2016) 'A research on fatigue life of front axle beam for heavy-duty truck', *Advances in Engineering Software*, Vol. 91, pp.63–68 [Online], doi: 10.1016/j.advengsoft.2015.10.006.

Zhao, L.H., Zheng, S.L., Feng, J.Z., Zhou, H.F. and Xing, Y.F. (2014) 'Fatigue assessment of rear axle under service loading histories considering the strengthening and damaging effects of loads below fatigue limit', *International Journal of Automotive Technology*, Vol. 15, No. 5, pp.843–852 [Online], doi: 10.1007/s12239-014-0088-5.