

Risk Assessment and Reliability Management of Tractor Front Axles Using Experimental and Numerical Analysis



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Abstract

The front axle is one of the most significant structural parts in an agricultural tractor that supports the vehicle load, provides a cushion effect when driving on uneven ground and ensures steering stability during different conditions of operation. As the front axle experiences repetitive loading, impact loads and tough weather conditions, it is prone to causing fatigue damage and structural failure. It is crucial to understand the reasons behind these failures to enhance reliability, longevity, and safety in tractor parts. This study is a complete failure analysis of a cracked front axle of a tractor that failed prematurely in the field. The investigation started with a comprehensive visual inspection and was found that there was a large crack starting at the area where the wheel is attached, and there was severe corrosion and surface deterioration. Metallurgical characterization, hardness, fractographic analysis, and finite element analysis (FEA) were used for the investigation of the root cause of failure. A numerical model was created to investigate the stresses and stress concentrations in critical areas for typical loading configurations. Next, the experimental observations were compared with the simulation results to determine the failure mechanism. Experiment results show that the crack started at the high stress concentration area and grew as cycles were repeated. Corrosion products were observed on the fracture surface, indicating that the environment degradation played a part in the crack growth, which eventually led to the loss of load carrying capacity in the axle. The maximum stresses were then seen to be concentrated near the crack initiation site so the FEA results corroborated the experimental results. The study also shows how material quality, geometric discontinuities and service loading impact the fatigue performance of the component. The results give an insight into the structural behavior and failure modes of tractor front axles and highlight and underline the need for hybrid investigations of experiments and simulations for accurate elucidation of the failure mode. The suggestions in this study, such as design optimization, material selection, and condition monitoring to be performed periodically, can greatly improve the fatigue life and reliability of any agricultural tractor's front axle. The research results will help for the design of agricultural equipment, component design, maintenance, failure prevention, and safe design of agricultural machinery which are more durable and safe.

Keywords: Failure analysis, Tractor front axle, Fatigue failure, Finite element analysis, Stress concentration, Fractography, Metallurgical analysis, Corrosion, Structural durability.

Introduction

The automotive, agricultural and industrial sectors rely heavily on the excellent strength, rigidity, wear resistance and ability for the manufacture of complex shapes that cast metal components exhibit. Of these, cast iron and cast steel housings are common in engine blocks, gearboxes, axle housings and support structures where they are subject to significant mechanical stresses and loads during operation. All

these components, although widely used, are subject to cyclic loading, vibration, impact forces, thermal changes and corrosive environment during their lifetime. These conditions may cause a progressive

deterioration of the material, with cracks initiating and developing to the point of failure.

Cast component failures are significant problems in

engineering applications as they cause machine down time, maintenance costs and safety issues. In many instances, cracks develop at areas where stress is amplified, like at mounting bosses, bolt holes, fillets, or casting discontinuities. After initiation these cracks grow gradually with continued loading until the remaining cross section has lost the capacity to withstand the applied load and the failure occurs suddenly. Crack growth by corrosion-assisted fatigue

can also dramatically affect the useful life of the component when environmental conditions like moisture, oxidation, and corrosive media are present. To enhance the reliability of components in the future and to design optimum components, it is necessary to understand what has caused the failures. Failure analysis is the process of visually investigating, characterizing the material, metallurgically examining, hardness testing, and using numerical simulation to determine the cause of failure. These investigations can provide valuable insights for engineers to suggest the corrective actions that can be taken, such as design changes, material selection, manufacturing improvements, and preventive maintenance strategies. The present study aims to perform failure analysis of a cast housing with a crack that was removed from service after being subjected to structural damage. The first visual inspection found a major crack that was formed at one of the mounting areas, in addition to a large amount of corrosion and deterioration of the surface. The crack location and morphology indicate that the component was exposed to long duration cyclic loading and in bad environment resulting in the loss of structural integrity. A systematic investigation which included visual inspection, fractographic analysis, metallurgical characterization, hardness testing and finite element analysis (FEA) was then conducted to determine the exact cause of failure. The stress distribution around the cracked region was evaluated and critical stress concentration zones were identified and failure pattern was made to be validated. The result of the present work are relevant to the failure mechanism of cast structural components and practical suggestions for its improvement of durability, reliability and service life are offered, which will be helpful for similar engineering components in the fields of automotive and industrial applications.

Literature Review

The agricultural tractor is used for various field tasks like ploughing, tillage, hauling, transport etc. and is subjected to highly variable loading condition. The front axle is one of the most important load carrying elements of the various structural components because it carries the weight of vehicles, transmits steering forces, and suffers from dynamic impact load from uneven terrain. Accordingly, the fatigue failure and the structural damage of tractor front axles are been important research topics for the last few years. Modern investigations focus on the synergy of

experimental testing, finite element analysis (FEA), digital twin technology and fatigue life prediction for enhancing reliability and durability of agricultural machinery.

Gao et al. (2026) recently showed that the use of machine learning methods can greatly enhance the prediction of fatigue life of cast iron structural components by providing accurate estimation of stress-life relationship under variable loading. They demonstrated that their models, based on the data, can supplement the traditional fatigue life analysis of engineering components and help to predict their remaining service life. In a related study, Mourujärvi et al. (2026) examined the fatigue characteristics of heavy section ductile iron castings made for automotive and agricultural purposes. They reported that casting quality, micro_structural homogeneity and defect distribution are significant factors affecting fatigue strength and fatigue crack initiation. According to these studies, the type of materials used is a significant factor in the durability of cast axle housings and structural supports.

Kinser et al. (2026) gave a detailed overview of the crack initiation and propagation in cast steel components. The authors concluded that casting defects like shrinkage cavities, inclusions, and pores are preferred sites for the initiation of fatigue cracks, especially under cyclic loading. They stressed the need to integrate metallurgical characterization and fractographic analysis in order to properly characterize failure mechanisms. Similarly, Gróza and Nadot (2026) verified the defect stress-gradient approach for nodular cast iron components through experimental testing and showed that the presence of local stress concentration around the casting defect plays a crucial role in fatigue crack propagation. The findings are useful for the theoretical assessment of crack initiation in heavily loaded components in the tractor axle.

The finite element analysis technique has proven to be an essential method to analyze the stress distribution and structural integrity of tractor front axles. Sharma and Kumar (2023) conducted structural optimization of tractor front axle using finite element analysis and concluded that optimum geometric modifications of tractor front axle helped to reduce the stress concentration with minimum impact on the structural stiffness of the front axle. In a similar way, Liu et al. (2024) studied structural durability of heavy vehicle axle systems under dynamic loads and found finite element simulation has the ability to find the critical stress areas of the system that can cause fatigue failures. Such studies have shown that numerical simulation has a great potential to shorten prototype development time and boosts component reliability.

The accuracy of computational models is also equally important and must be ensured by experimental validation. Li et al. (2024) carried out field tests for the dynamic loads of the front axles of agricultural tractors under various operating conditions. They reported that load spectra under off-road operating

conditions are highly fluctuating and that merely static load assumptions cannot be used to represent one. Thus, by inputting actual field load data in the fatigue assessment, the fatigue life prediction can therefore be enhanced. Similarly, recently, fatigue load spectrum editing for accelerated durability testing of the front axles of tractors was investigated, and approaches have been proposed based on power-density.

The use of digital technologies has further improved the SHM of agricultural machines. Singh et al. (2024) built an IoT-based data acquisition system for real-time monitoring of agricultural vehicle performance, which helps in the continuous acquisition of load, vibration, and operating parameters. A more recent development is the use of the digital twin for fatigue life prediction of the front axle housing of a tractor. The proposed framework combines real-time sensor data with finite element analysis to provide a more accurate estimation of cumulative fatigue damage and prediction of remaining useful life, which can then be used for implementing predictive maintenance and minimize unexpected failure.

Failure analysis studies remain a handy tool for learning about real-world engineering failures. Yavuz (2023) examined the failure of a tractor front axle in a study that involved metallographic analysis, hardness testing, chemical composition analysis, and finite element simulation. The study was able to conclude that the region of high stress concentration was the source of the fracture, and cyclic loading helped to initiate and propagate fatigue cracks until catastrophic failure occurred. The author suggested the geometric design and manufacturing quality of the axle were improved to minimize the stress concentration and improve the fatigue strength of the axle.

Corrosion has also become an important factor in the service life of a structural components under fatigue. An overview of localized corrosion initiation by non-metallic inclusions and how corrosion pits may affect to increase crack nucleation under cyclic loading were provided by Liu et al. (2022). Likewise, Awe (2022) showed that material inclusions and metallurgical defects were significant causes of premature failure of automotive brake disc. These investigations highlight the need to consider manufacturing defect and degradation of the environment in the design of safety-critical automotive and agricultural components. Recent advances in electric agricultural tractors have further led to studies on lightweight structure design and virtual fatigue evaluation. Kim et al. (2025) investigated fatigue life of electric tractor frames using virtual iteration methods with the measured axle loads. Their findings also showed that hybrid approach with field measurement and numerical simulation can be used to achieve more accurate fatigue life estimation and to realize lightweight design with maintaining the safety of the structure.

Problem Description

Cast metal housings are widely used in vehicles' power transmission system for its high strength, dimensional stability, and allowing geometries. Operating, however, these components are continuously subjected to cyclic mechanical loading, vibration, impact forces and varying environment. These service conditions can cause stress concentrations at local areas, such as around mounting bosses, bolt holes, fillet areas and cause crack initiation and propagation. These cracks can also result in reduced safety, higher maintenance expenses and system failure if not detected. The failed component that was the subject of this study had a significant crack that was suspected to have started from the mounting boss and propagated towards the main body of the casting. The fracture surface and adjacent areas were heavily covered with corrosion products, and the overall extent of corrosion products suggesting long crack growth under service conditions prior to final failure was discovered by visual examination. High cyclic stresses in conjunction with corrosion-assisted degradation of the component suggest the location of the fracture, which was at a location where the load carrying capability of the component was greatly diminished. The resulting damage has affected the structural integrity of the housing and it can no longer be used for service.

Methodology:

A systematic sequence of experimental investigations and numerical simulations was adopted to identify the root cause of failure of the cracked cast housing as the methodology. The entire process is demonstrated below.

Step 1: Component Inspection

The defective cast housing, removed from operation, was visually examined in detail. High resolution photographs were used to document the location, orientation and extent of the crack. Surface conditions including discoloration, corrosion, casting flaws and distortion were carefully inspected for potential crack initiation locations.

Step 2: CAD Model Development

According to the actual size of the cast housing, a three-dimensional CAD model of the cast was created by using commercial CAD software. Every important geometry such as mounting bosses, bearing seats, ribs, fillets and holes were modeled in the appropriate manner to make them accurate for the actual component. The whole of the CAD model was used for Finite element analysis.

Step 3: Material Characterization

The spectroscopic analysis of the casting material and its comparison with the standard specification, were carried out to detect the chemical composition of the casting material. Metallographic specimens were sectioned, mounted, ground and polished and then etched. Microstructure has been observed using OM to determine the graphite morphology, matrix structure, inclusions, porosity and other metallurgical defects

that may be considered significant for failure.

Step 4: Hardness Evaluation

Brinnell hardness test was performed on various zones such as crack area and unaffected areas. Hardness values obtained were compared to assess if any materials degradation occurred or if there was localized hardening which may have led to crack initiation.

Step 5: Fractographic Examination

The fracture surface was carefully inspected visually and by scanning electron microscopy (SEM). The fracture morphology was analyzed to determine the crack initiation site, crack propagation area and the final fracture zone. Fractographic characteristics like fatigue striations, Cleavage facets, Dimples, oxidation and brittle/ductile fracture characteristics were recorded to determine the predominant failure mode.

Step 6: Finite element analysis

CAD model was imported to ANSYS Workbench to perform structural analysis. The material properties were suitably assigned according to the cast material and a high-quality finite element mesh was developed. Realistic boundary conditions and loading conditions were applied. To find the stress distribution, deformation and stress concentration regions, static structural analysis has been carried out. Experimental measurement of the position of the cracks was obtained and the results compared with the numerical results.

Step 7: Failure Assessment

The results of visual inspection, metallurgical analysis, hardness testing, fractographic examination and finite element analysis were combined to determine the root cause of failure. Significant factors such as geometric discontinuities, casting defects, material properties, cyclic loading and operating conditions affecting crack initiation and crack propagation are critically studied.

Step 8: Design Recommendations

Appropriate recommendations based on the investigation results were suggested to improve the cast housing structure and its service life. The recommendations involve changing the design of the structure to minimizing the concentration of stress, optimizing fillet radii and wall thickness in the structure, increasing the quality of the cast by controlling defects, improving the material or heat treatment process of the structure, and preventive maintenance.

Failure Analysis for Front Axle Supports.

The failed front axle support in the figure has a major structural crack in the mounting boss area, progressing from the circular bearing seat towards the inclined rib. The origin of the fracture seems to have been at the interface of the bearing housing and the supporting rib which is an area that is subject to high stress concentration under the service loading. It continued to grow through the wall thickness until it caused the mounting portion to separate from the main housing, rendering it inoperable.

Visual examination also reveals a significant amount of surface corrosion, dirt collection, and degradation, suggesting that the component may have operated for a long time under harsh conditions and conditions. The fracture surface itself is relatively rough in nature, typical of a progressive crack propagation, finally followed by overload failure. The abrupt change in cross-section, the mounting bosses, and the fillet regions in the housing geometry also may have played a role in enhancing local stresses and in accelerating initiation of cracks. Failure probably occurs because of the repeated cyclic loading to which the front axle support is exposed during tractor operation as a result of the vertical, longitudinal and lateral loading forces applied during operation, such as operation on hilly terrain, braking, steering and dynamic impact loading. Other casting defects such as porosity, shrinkage cavities, or inclusions in the crack initiation area may also have contributed by providing stress raisers in the cast and consequently fatigue strength of the component would be diminished. In order to identify the exact root cause of failure, the following testing and investigations of the damaged component should be performed: visual inspection, metallographic examination, hardness testing, fractographic analysis by Scanning Electron Microscope (SEM), and Finite Element Analysis (FEA). When correlated with the experimental observations, these numerical stress analyses can lead to the identification of the most critical failure mechanism and to the appropriate design modifications, namely, increases in fillet radii, optimization of wall thickness, improvement in the quality of casting and use of different materials with a higher level of fatigue resistance. These measures will contribute to the increased durability, strength and longevity of the front axle support in heavy duty agricultural use.

CAD Modelling

In order to accurately represent the geometry of actual front axle support, the front axle support's CAD model was developed by using a three-dimensional parametric CAD software package as shown in fig.1. The base profile was created as the starting point for the modelling process and extruded to build the main housing structure. The following features were then added such as internal cavities, mounting bosses, bearing seats, support ribs, and side flanges, using the standard modeling features such as cut-extrusion, revolve, and rib features. Precise dimensions have been used to create all mounting holes, bearing bores and alignment holes, ensuring that proper assembly with mating parts can be made. To simulate the manufacturing requirements and to reduce stress concentration, fillets and chamfers were added to the sharp edges and corner area. The use of symmetry and pattern tools was made wherever possible, to increase the modelling efficiency and for maintaining dimensional consistency. The finished model is a close match to the real front axle support and has all necessary functional and structural elements for

assembly and load transfer.

Check for manufacturability, dimensional and geometric accuracy of the last CAD model by assigning the properties of materials. It was then exported in STEP and IGES formats and analysed in the finite

element analysis (FEA) software ANSYS for structural performance and test. The model developed is used for stress analysis, deformation analysis, fatigue analysis and design optimization of the front axle support for different loadings.

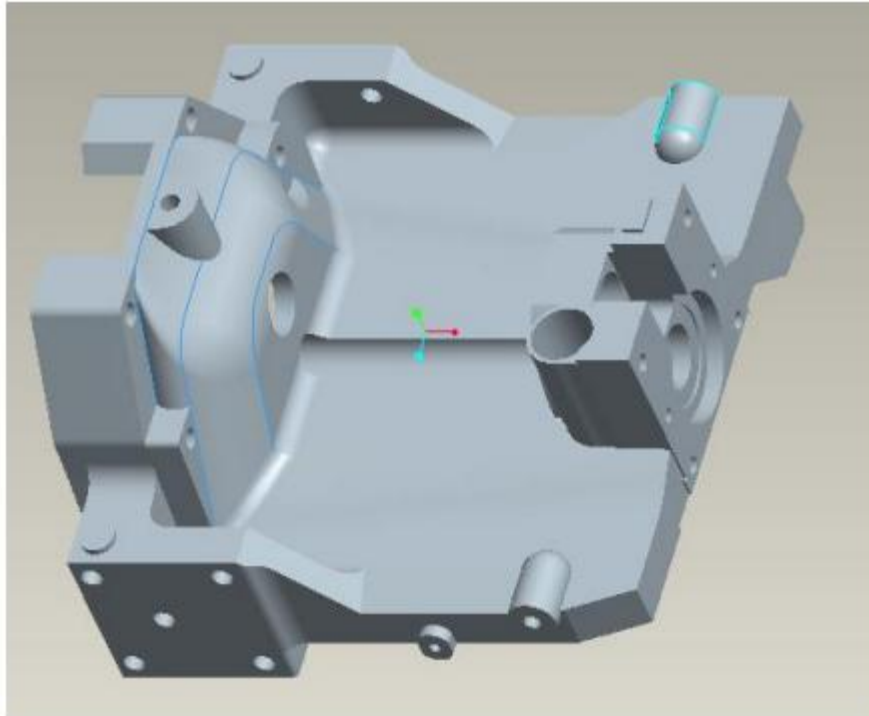


Fig.1.Front axle support

Results and Discussion

The structural analysis of the tractor front axle support was carried out by considering both the conventional loading conditions and the additional contact loading generated when the front axle reaches its maximum rotational limit of 12° during fatigue loading. Unlike conventional designs, which primarily consider the 3g fatigue loading as the worst-case

scenario, the present investigation incorporated the contact force developed between the front axle and the axle support due to axle rotation. This approach provided a more realistic representation of the operating conditions experienced by the front axle support during severe field operations and the analysis as shown in fig.2.

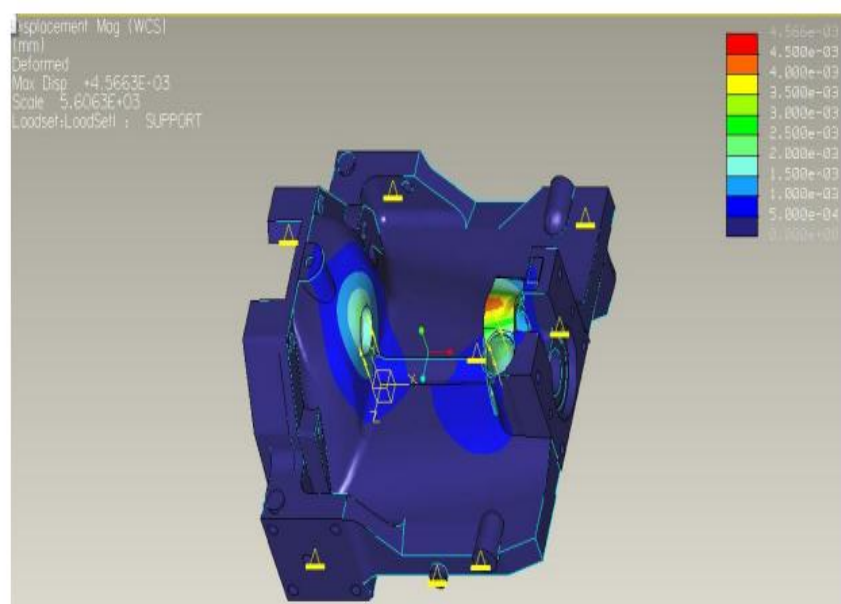


Fig.2.Front axle structural analysis

Table 1. Load case of 1g with angular variation of 1 to 12 degrees

Load Case = 1g, Wheel Force = 9810N, $\alpha = 1-12^\circ$						
A	F_g (N)	F_c (N)	R_y (N)	R_z (N)	F_{HR} (N)	F_{HL} (N)
1	9810	28500	497.39	18686	9342.9	9342.9
2	9810	28513	995.09	18686	9342.9	9342.9
3	9810	28535	1493.4	18686	9342.9	9342.9
4	9810	28565	1992.6	18686	9342.9	9342.9
5	9810	28605	2493.1	18686	9342.9	9342.9
6	9810	28653	2995	18686	9342.9	9342.9
7	9810	28710	3498.8	18686	9342.9	9342.9
8	9810	28776	4004.8	18686	9342.9	9342.9
9	9810	28851	4513.3	18686	9342.9	9342.9
10	9810	28935	5024.6	18686	9342.9	9342.9
11	9810	29029	5539	18686	9342.9	9342.9
12	9810	29132	6057	18686	9342.9	9342.9

Table 1 gives Load case of 1g with angular variation of 1 to 12 degrees. To find the reaction forces at the pivot shaft and the contact interface, a modified free body diagram was created. The contact force (F_c) and resulting reaction forces of 36 loading cases were then determined based on this model by varying the position of the front axle support with respect to angle. It was found that the contact force amplitude and directionality had great influence on the angular position of the support and considerably affected the stress distribution in the component. FEA results indicated that the stresses in this condition (1g, normal static loading condition) were well below the material yield stress, indicating the existing design would be strong enough for normal loading during tractor operation. But, for the 3g fatigue loading condition, significantly higher stresses were seen in the vicinity of the pivot shaft and in the contact area. Stresses were also raised further by the extrapolation of contact loading that resulted in stress concentrations significantly greater than those for conventional loading assumptions.

The highest von Mises stress was found to be invariably around pivot shaft holes and axle-support contact interface. These are the areas of sudden changes of geometry or load transfer and are therefore very prone to the initiation of fatigue cracks. The results show that repeated rolling-in of the front axle on the support during maximum axle articulation may prematurely allow fatigue damage, especially under dynamic loading in the field where impact loading occurs very often. Stress contours also indicated that the greater the contact force, the more

localization of deformation at the contact surface. The total displacement of the support was within the design allowable limits, but multiple deformations may result in degradation of materials and crack propagation during long-term service. The crack initiation sites obtained from the simulations were compared with the experimental failure sites post visual inspection of the damaged part, the conclusions were that crack initiation sites predicted by the simulated model were in good agreement to the experimental ones, thus confirming the validity of the numerical model. Selected loading cases were tested in total during the analysis of the 36 cases and several showed a distinctly lower stress concentration, indicating that the orientation of the front axle support plays an important role on the performance of the structure. It may therefore be possible to reduce the peak stresses and increase the fatigue life by optimising the geometry of the support and the point of contact, without increasing the weight of the component.

Results showed that contact loading needs to be taken into account as a design criterion apart from the classical static and fatigue loading. Traditional 3g loading condition may not be reflective of actual axle loading in severe operating conditions, which can result in earlier than expected front axle support failures. Design and analysis with realistic contact interactions allows for a better assessment of the structural behavior and design of more robust and safe tractor front axle assemblies.

Conclusion:

This study investigated the static and fatigue failure as well as contact loading of a tractor front axle support with a detailed structural and failure analysis. The present investigation was based on the fact that, in the conventional design procedures only the 3g fatigue loading is considered to be the worst case scenario whereas the additional contact force generated while the front axle is in the maximum rotation limit of 12° is also considered. To arrive at a more realistic representation of the actual field operating conditions, a slightly modified free body diagram was developed to arrive at an accurate determination of the contact and reaction forces acting on the axle support. FEA resulted in a significant difference in the magnitude of the stress concentration at the pivot shaft holes and the contact area supporting the axle with contact loading. These areas were recognized as being the most important regions in which fatigue crack initiation could occur because of repeated fatigue loads and local deformations. The expected failure pattern was in agreement with the numerical predictions, which showed that the rupture of the structure is mainly caused by the combined influence of the contact interaction and the fatigue loading sequence. The 36 different loading cases, evaluated in addition, also indicated that the angular position of the front axle support has a significant effect on the stress distribution. Peak stresses can be effectively reduced, and fatigue performance of the component can be enhanced due to optimization of support geometry and contact location without compromising the structural strength. As a whole the study has shown that contact loading must be considered as a part of the design and durability evaluation of the support system for front axles of tractors. The methodology of analytical calculations coupled with finite element simulation proposed in the article is an effective method for predicting critical stress areas and also increasing the reliability of the components. The results provide useful information for tractor manufacturers to design a stronger front axle support to minimize pre-mature axle failure, maintenance costs and improve operational safety and service life of the agricultural tractor.

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