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ESTABLISHMENT OF NEW DURABILITY PROCEDURE FOR OFF-HIGHWAY FRONT AXLE SYSTEM

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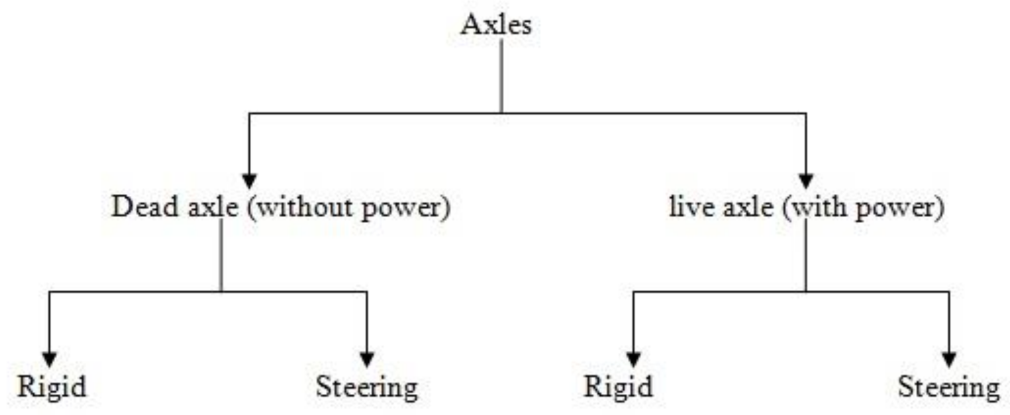
***Abstract*—Axle is a structural part of tractor which supports the structural load of the tractor. Front axle system consist of trumpet, central body, trunion support, brake housing, wheel-hub, steering system i.e., steering cylinder, tie rod and swivel housing etc. will be the major components of axle assembly. Primary function of the axle is to support the weight of the tractor, to transmit the power to the wheels, and to steer the wheels.**
Most common practice only stress results to validate the axle design, which leads to overdesign of the structure. So to optimize the model as per requirement, durability calculation is introduced. So now the scope of the project is to develop/establish new durability procedure with standard load cases, which can use as a standard procedure for future axle calculations.

***Index Terms*—FEA, Front Axle, Off-highway, Durability, Experimental validation**

I. INTRODUCTION TO OFF-HIGHWAY AXLES

Axle is a structural part of tractor which supports the structural load of the tractor. Front axle system consist of trumpet, central body, trunion support, brake housing, wheel-hub, steering system i.e., steering cylinder, tie rod and swivel housing etc. will be the major components of axle assembly. Primary function of the axle is to support the weight of the tractor, to transmit the power to the wheels, and to steer the wheels. Axles are broadly classified as follow,



Dead axle: Dead axle is not part of the drive train. It only serves the purpose to support for part of the vehicle while mounting for the wheel assembly. The rear axle of front wheel drive vehicle can be considered as dead axle.

Live axle: Live axle is used to transmit the power to the wheels. The shaft in a live axle assembly may or may not actually support part of the weight of a vehicle, but it does drive the wheels connected to it.

Rigid axle: Rigid axle is a live axle but without steering. Hence it does not steer the wheels. Rigid axle transmits the power.

Steering axle: Primary function of the steering axle is to achieve angular motion of the front wheels to negotiate turn and to provide directional stability. The steering axle is component of vehicle which contributes its ability to direct towards the desired route. These axles must be structurally strong because they are responsible to withstand the load of the vehicle as well as extra load on the vehicle.

II. INTRODUCTION TO FATIGUE

In materials science, fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading (material is stressed repeatedly).

1. Fatigue may occur when a member is subjected to repeated cyclic loadings.
2. The fatigue phenomenon shows itself in the form of cracks developing at particular locations in the structure.

3. Cracks can appear in diverse types of structures such as: planes, boats, bridges, frames, cranes, overhead cranes, machines parts, turbines, reactors vessels, canal lock doors, offshore platforms, transmission towers, pylons, masts and chimneys.
4. Structures subjected to repeated cyclic loadings can undergo progressive damage which shows itself by the propagation of cracks. This damage is called fatigue and is represented by a loss of resistance with time.

Fracture mechanics can be divided into three stages:

A. Crack nucleation
B. Crack-growth
C. Ultimate ductile failure

III. MAIN PARAMETERS INFLUENCING FATIGUE LIFE

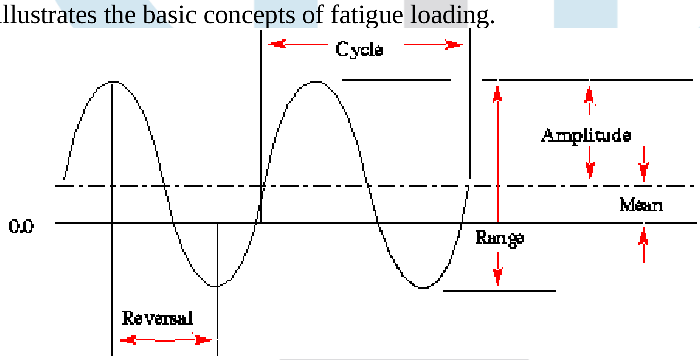
The fatigue life of a member or of a structural detail subjected to repeated cyclic loadings is defined as the number of stress cycles it can stand before failure. Depending upon the member or structural detail geometry, its fabrication or the material used, four main parameters can influence the fatigue strength

1. Stress difference, or as most often called stress range.
2. Structural detail geometry.
3. Material characteristics.
4. Environment.

Structural durability analysis is a tool for evaluating a design's structural worthiness, or its durability, under the cumulative effect of simple or complex loading conditions. Strength analysis evaluates if the model can structurally instantaneously withstand the maximum static or transient stresses applied to it. This static strength evaluation serves to determine if a fatigue evaluation is required. For example, if peak stresses exceed the material ultimate strength a fatigue evaluation is required. The strength evaluation also serves to determine which stress or strain life criterion should be used in the fatigue evaluation. See Understanding the strength evaluation for more information. Generally speaking, fatigue life can be defined as the number of cycles to failure due to repeated load involving the initiation and propagation of a crack or cracks to final fracture. Results of a fatigue analysis are displayed as contour plots that show the number of fatigue cycles the structure can undergo before crack initiation occurs.
Fatigue analysis uses the cumulative damage approach to estimate fatigue life from stress or strain time histories. Estimation is accomplished by reducing data to a peak/valley sequence, counting the cycles, and calculating fatigue life is customary. This measurement and others are deliberate, using specifications that anticipate this paper as one part of the entire proceedings, and not as an independent document. Please do not revise any of the current designations.

IV. BASIC CONCEPT OF FATIGUE ANALYSIS

The following figure illustrates the basic concepts of fatigue loading.



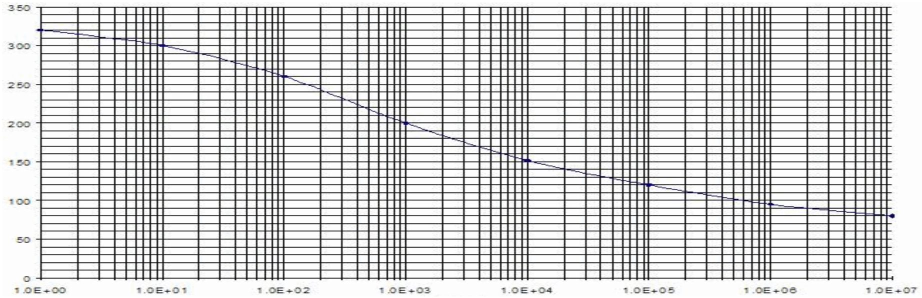
The process of estimating fatigue life for experimentally obtained data can be separated into three steps:

1. Peak/valley reduction
2. Cycle counting
3. Damage estimation

The fatigue life criteria equations define S-N or E-N curves using durability material properties.

V. S-N AND E-N CURVES

1. S is the amplitude or the range of a stress cycle.
2. E is the amplitude or the range of a strain cycle.
3. N is the number of cycles or the number of reversals of stress or strain to failure.



S-N curve for brittle aluminum with an ultimate tensile stress of 320 MPa: stress in MPa vs life cycles

The S-N and E-N curves may also include the effect of mean stress of the loading cycle. Using the rainflow counting, the durability solver identifies the stress or strain amplitude and the mean stress of each cycle in the stress or strain time history of a transient event. The damage of each cycle is then evaluated using the S-N or E-N curve of the selected life criterion.
High cycle fatigue requires more than 105 cycles to failure and is generally used for applications with low loads and relatively long lives. If the strength evaluation shows large margins of safety or safety factors, then high cycle fatigue is the likely failure mechanism.
Low cycle fatigue requires a range of 10 – 105 cycles to failure and is generally used for applications with large loads and relatively short lives. If your strength evaluation shows small strength margins of safety or safety factors, the structure may not tolerate many cycles until failure, and low cycle fatigue is the likely failure mechanism.

VI. STRAIN LIFE

strain life criterion is typically used for low cycle fatigue. The stress level may be higher and the number of cycles to failure may be lower. The durability solver can calculate the fatigue life using the following strain life approaches,
The maximum principal strain amplitude approach
The maximum shear strain amplitude approach

Maximum principal strain amplitude approach

The maximum principal strain amplitude life equation uses the modified Morrow equation as follows:

$$\frac{\Delta\epsilon_1}{2} = \frac{\sigma'_f - \sigma_m}{E}\left(2N_f\right)^b + \epsilon'_f\left(2N_f\right)^c$$

where:

$\frac{\Delta\epsilon_1}{2}$ is the maximum principal strain amplitude.

σm is the mean stress of the cycle along the principal axis.

2Nf is the number of reversals to failure.

σ'f is the fatigue strength coefficient material property.

b is the fatigue strength exponent material property.

ε'f is the fatigue ductility coefficient material property.

c is the fatigue ductility exponent material property.

If you choose not to include the mean stress effects in the fatigue evaluation, the mean stress σm is zero.

Maximum shear strain amplitude

The maximum shear strain amplitude approach is based on the assumption that the notch shearing strain amplitude will correlate life with the shear strain amplitude in uniaxial test specimens. It uses the shear strain amplitudes on the maximum shear plane in the strain life equation as follows:

$$\frac{\Delta\gamma_m}{2} = \left(1+\nu_e\right)\frac{\sigma'_f}{E}\left(2N_f\right)^b + \left(1+\nu_p\right)\epsilon'_f\left(2N_f\right)^c$$

where:

$\frac{\Delta\gamma_m}{2}$ = Shear strain amplitude on maximum shear plane.

νe = Poisson's ratio.

νp = 0.5

This equation does not take into account the mean stress effects.

The maximum principal strain amplitude life equation is used when you select Strain Life Maximum Shear from the Fatigue Life Criterion list in the event dialog box.

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Field of application
Whenever a structure is subjected to time varying loads, fatigue must be taken into account. Typical structures subjected to time varying loads are for example:
Rotating machinery (pumps, turbines, fans, shafts).
Pressure vessel equipment (vessels, pipes, valves).
Land based vehicles, ships, air and space crafts.
Bridges, lifting equipment, offshore structures.

VII. PROBLEM DEFINITION
Due to introduction of new fatigue software, there is a need to develop the durability procedure for front axle system of tractor for Vertical test and Traction test- forward (TRC-FWD), Traction test- reverse (TRC-REV) to these two test load conditions considering the effect of as cast surface vs machined surface fatigue life.

VIII. MAIN OBJECTIVE
- Perform finite element analysis to the front axle system of tractor for Vertical test and Traction test- forward (TRC-FWD), Traction test- reverse (TRC-REV) to these two test load conditions.
- Correlate FEM results with lab test results.
- Develop/Established new durability simulation method for axle.
- Perform fatigue life calculation.
- Evaluate the effect of as cast surface and machined surface on fatigue life of axle by comparing lab test failures.
- Validation with the experimental results.

IX. FINITE ELEMENT ANALYSIS OF FRONT AXLE SYSTEM
Based on the literature review, it has been reviewed that the high stresses are likely to be occurred in the axle beam hence it is selected as the important/significant part to analysis. In this analysis the front axle is analyzed by the two test load condition as follows:
Vertical test (VT)
Traction test- forward (TRC-FWD)
Traction test- reverse (TRC-REV)

X. SCOPE
Scope of the project:
Previously using only stress results to validate the axle design, which leads to overdesign of the structure. So to optimize the model as per requirement, durability calculation is introduced. So now the scope of the project is to develop new durability procedure for company standard load cases, which company can use as a standard procedure for future axle calculations.

XI. INPUT DATA
Input data for the Finite Element Analysis of Front Axle System is as follows:

Input Data	Value
Load	52240 N
Torque at Wheel	18000 Nm
Reference Track	1214 mm
Wheel Radius	558 mm

Load: This is the load on the axle that is equivalent to the division of the vehicle's weight in accordance with the various work configurations. This load allows the vehicle to travel up to this maximum speed.
Reference Track: This is the track or distance to which the load bearing capacity is applied.

Traction test: Traction test is carried out by fixing the tyres of the axle and the load is applied.
Two loads will be considered here vertical and horizontal. The load is converted in to dynamic load by using 2 factor of acceleration for TRC load case. It is checked for 20000 cycles.

Vertical action due to contact wheel ground and calculated by
TRC_FWD = (52240 ×2)/2 = 52240 N

Horizontal load: for horizontal load we need

T= F × r ....where

T = torque / r = wheel radius

Torque and wheel radius we know as input data from that force will be calculated and that force will be used for this load test.

TRC_FWD = (18000 / 0.558)/2 = 16129 N

TRC_REV is same in the magnitude as in TRC_FWD but in the opposite direction to forward load case.

TRC_REV = (18000 / 0.558)/2 = -16129 N

Vertical test (VT):

In this case maximum load is given in the pulsating form and it is checked for 15000 cycles. The input load is converted in to maximum dynamic load by considering 2.5 as acceleration factor and is calculated as,

VERTICAL TEST = (52240 × 2.5)/2 = 65300 N

XII. MATERIAL DETAILS

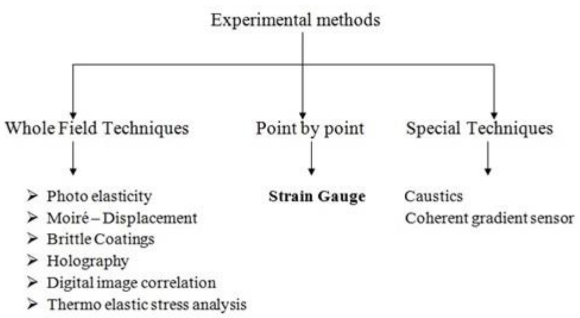
Parts	Material	Young's modulus (MPa)	Poisson's ratio	Density (tonne/mm3)	Tensile Strength(MPa)
Trumpet, Brake housing	EN-GJS 400 Spheroidal C.I	169000	0.28	7.2 e-09	400
Central body	EN-GJS 500	165000	0.28	7.2 e-09	500

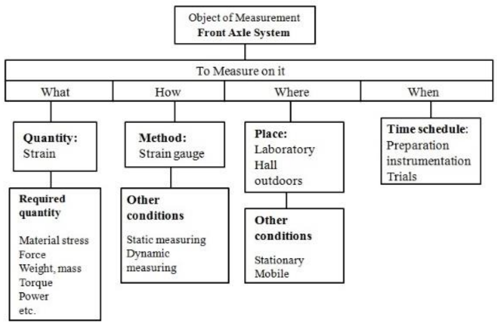
Mechanical properties used for the different components for the analysis.

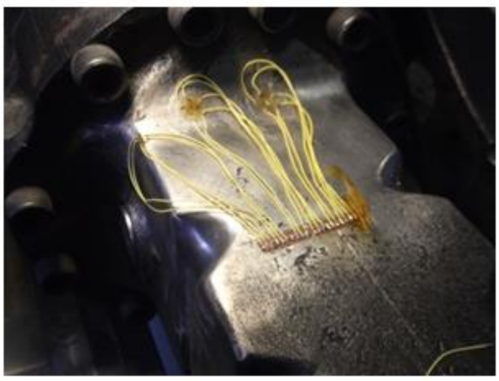
XIII. RESULTS AND DISCUSSION PART - I

XIV. EXPERIMENTAL VALIDATION

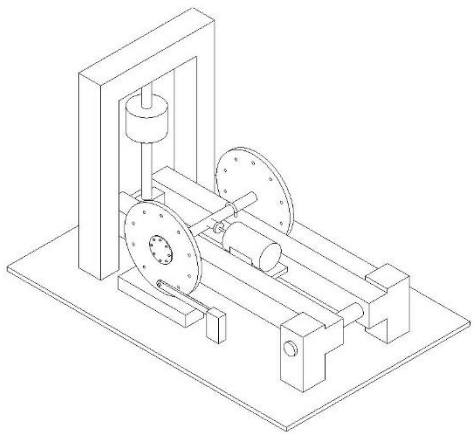
It had been carried out finite element analysis for the front axle system and collected FEA results. But to propose new simulation method validation is important. Hence, Front axle system is tested experimentally. The results were correlated with the FEA results within 10%. The experimental testing is carried out by strain gauging. There are various techniques of experimentation they classified as follows,







Experimental set-up of strain gauging



Test bench setup

Structural test carried out on the Test bench consisting of a vertically oscillating platform; the axle is fitted to the bottom part of the platform, while the ballasts are fixed to the top part. Tires are fixed to the axle wheel hubs that support the required dynamic load. The lifting and release operations are carried out by hydraulic cylinders supplied by a control unit.

COMPARISON OF RESULT ACHIEVED BY NUMERICALLY AND EXPERIMENTALLY

	VT (MPa)	TRC (MPa)	
Numerical results	355	185	189
Experimental results	348	172	175

Resulted shows that results of maximum stress in the trumpet measured by numerically and experimentally. The results of finite element method were verified by experimental methods. The results obtained were correlated with FEA results to validate the proposed new simulation method and they are within acceptable range.

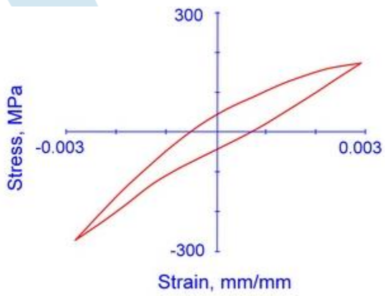
XV. DURABILTY ANALYSIS

Cast Iron Material Fatigue Study: As most of the structural components of axle are made of cast iron, it is required to study the fatigue behavior of cast iron material.

A. Fatigue Prediction Method for Cast Iron

1. Elastic-plastic behavior in stress concentrations control fatigue life.
2. Rainflow counting is used to determine damaging events corresponding to closed elastic-plastic hysteresis loops.
3. Mean stresses are tracked according to input loading sequences.
4. Smith-Watson-Topper parameter accounts for mean stress
5. Neuber' Rule is used to determine notch root stress and strains.

Cast irons such as gray and nodular iron are really composite materials composed of a steel matrix and distributed particles of graphite of different sizes and shapes. In nodular iron, the graphite particles are roughly spherical and fairly consistent in size. In gray iron, crack-like graphite flakes are distributed in clusters throughout the steel matrix. The presence of the graphite makes cast iron more prone to surface cracking and stiffer in compression than in tension. Gray iron exhibits these behaviors more markedly than nodular iron. For these reasons, the monotonic and cyclic stress-strain behavior of cast iron, specifically gray cast iron, is very different and special models are needed to account for these differences.



B. Stress/Strain Response

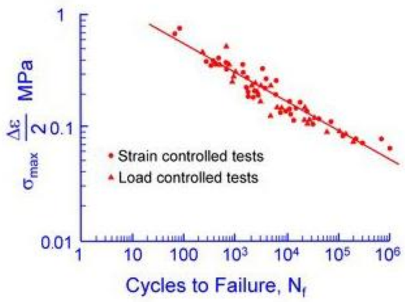
The stress/strain response in cast iron is controlled by the properties of the steel matrix and, more importantly, the details of the graphite morphology. Quantity, distribution, and shape of the free graphite all affect the degree to which the steel matrix is weakened. Other researchers have reported that, for gray iron under tensile loading, properly oriented graphite flakes crack and debond from the matrix. Detailed early studies by Gilbert of the microstructure of gray iron under tensile load indicated that graphite debonding occurs only near the free surface. He made the following observations:

- Curvature in the tensile stress/strain curve is not only associated with elastic and plastic deformation of the matrix, but is also due to volume increase in the spaces occupied by the graphite.
- This volume increase is most pronounced on the specimen surface where graphite flakes, oriented perpendicularly to the load can actually crack or debond from the matrix.
- Gray iron is stiffer in compression than tension because the spaces occupied by the graphite do not see corresponding decreases in volume.

Nodular iron has similar matrix structure to gray iron, but free graphite is in the form of roughly spherical nodules rather than interconnected graphite flakes. Because the internal notch effect of spherical graphite is less severe than for graphite flakes, nodular iron behaves elastically over a considerable stress range in tension and compression. The elastic limit in compression is, however, slightly higher than in tension. This phenomenon is attributed to a greater local stress concentration effect in tension, resulting in plastic deformation at a lower average stress. At tensile stresses above the elastic limit, the volume of spaces occupied by graphite increased due to voids formed in the direction of loading. Contrary to the behavior of gray iron, however, little overall increase in volume occurred under compressive stress.

B. Fatigue Analysis Parameter

The relationship between loading parameters and cycles to failure for cast irons should, in some way, account for the surface crack phenomenon. Smith, Watson and Topper suggested a parameter, the product of the maximum stress and stain amplitude in a hysteresis loop, to include the effects of mean stress and early crack growth for fatigue in metals. The following figure shows this parameter plotted against cycles to failure for pearlitic gray iron under a variety of testing conditions. Peak stress and strain amplitude can be measured initially or at the half life with equally good correlation.



This parameter not only accounts for mean stress, but also provides a single relationship for both load-control and strain-control data. Unlike wrought materials, a single straight line fits the data reasonably well with two material constants for the slope and intercept.

$$\sigma_{\max} \frac{\Delta\varepsilon}{2} = I_{SWT} \left(N_f\right)^{S_{SWT}}$$

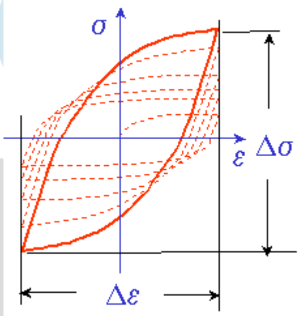
Loading parameter Vs cycles to failure

Where, σmax is maximum tensile stress and Δε/2 is the strain amplitude.

D. Constant Amplitude Strain Life Technical Background

The strain life method had its major development during the 1960's. It is based on the premise that the local stresses and strains around a stress concentration control the fatigue life. Although most structures and machine components have nominal stresses that remain elastic, occasional high loads and stress concentrations cause plastic deformation around notches. Fatigue damage is dependent on the local plastic strains around stress concentrators.

The local plastic strains are controlled by the elastic deformation of the surrounding elastic material. Even though external loads are applied, the local region is strain or deformation controlled. The strain resistance of the material is a better measure of the fatigue performance than the stress resistance.



E. Material Properties

Strain controlled tests are always conducted in axial loading. Deflections are controlled and converted into strain. The resulting forces are measured to compute the applied stress. Metals undergo transient behavior when they are first cycled. In this example the material becomes stronger with each loading cycle into the plastic range. Other materials loose strength when they are repeatedly plastically deformed. After the initial transient behavior most materials have steady state behavior described by the hysteresis loop. During the fatigue test the strain range, Δε, is controlled and the resulting stabilized stress range, Δσ, is recorded along with the cycles to failure. In strain life testing cycles to failure is converted to reversals to failure. One cycle has two reversals and a symbol 2Nf is used.

Before plotting the strain vs. fatigue life, the total strain that was controlled during the test is Strain controlled test

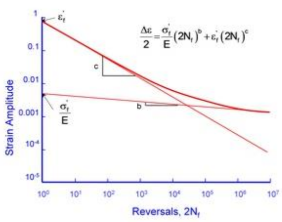
divided into the elastic and plastic part. The elastic strain is computed as the stress range divided by the elastic modulus. Plastic strain is obtained by subtracting the elastic strain from the total strain. Test data is then fit to a simple power function to obtain the material constants; fatigue ductility coefficient, ε'f , fatigue ductility exponent, c , fatigue strength coefficient, σ'f , and fatigue strength exponent, b.

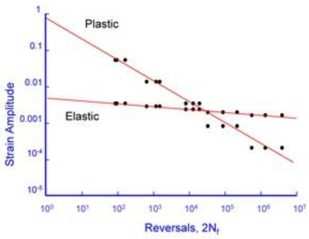
The total strain is then obtained by adding the elastic and plastic portions of the strain to obtain a relationship between the applied strain and the fatigue life.

Strain Vs. Fatigue life

for elastic and plastic

$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c$$



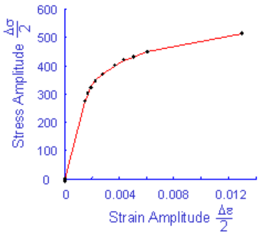


The materials deformation during a fatigue test is measured in the form of a hysteresis loop. After the initial transient behavior, the material stabilizes and the same hysteresis loop is obtained for every loading cycle. Each strain range tested will have a corresponding stress range that is measured. The cyclic stress strain curve is a plot of all of this data.

Total Strain Vs Fatigue life

The cyclic stress strain curve describes the behavior of the material after it has been plastically deformed in service a few times. You can think of the traditional stress strain curve as describing the behavior of the material as it was manufactured. A simple power function is fit to this curve to obtain three material properties; cyclic strength coefficient, K' , cyclic strain hardening exponent, n' , and elastic modulus, E.

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{\frac{1}{n'}}$$



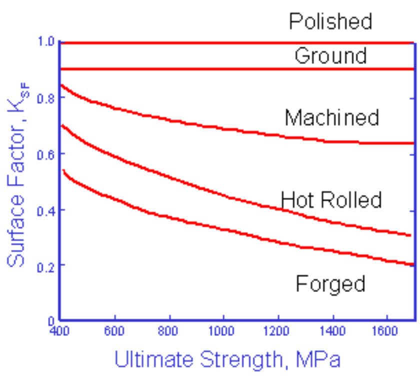
Cyclic stress strain curve

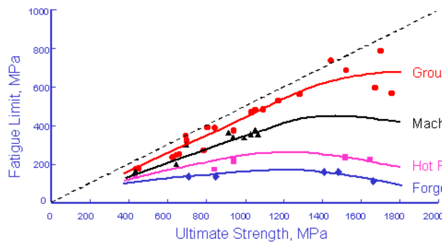
G. Surface Finish Effects

Materials, as they are tested, are always in a different surface condition than the materials as they are actually used. Test specimens are polished to eliminate the effects of surface finish. Fatigue cracks usually nucleate on the surface so that the condition of the surface plays a major role in the fatigue resistance of a component, but only at long lives. At short lives cyclic plasticity dominates the behavior of the material and surface finish is less important. The degree of surface damage depends not only on the processing but also on the strength of the material. Higher strength materials are more susceptible to surface damage. An important part of the analysis is to "correct" the basic materials data to obtain an estimate of the fatigue life of the material in the component or structure of interest. To account for this in the analysis the material fatigue limit is reduced by a surface finish factor, kSF.

The original data for constructing this curve is shown below. The factors tend to provide conservative estimates for fatigue lives. These data are fit to a simple power function to obtain an estimate of the surface factor for any hardness steel.

$$k_{SF} = \alpha S_u{}^{\beta}$$





Fatigue limit Vs UTS

Parameter for surface factor calculation

	α	β
Ground	1.58	-0.085
Machined	4.51	-0.265
Hot Rolled	57.7	-0.718
Forged	272	-0.995

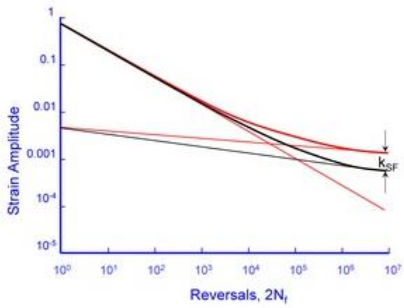
The effect of surface finish is reduced for higher strain levels where cyclic plasticity controls the behavior. Surface finish won't have any effect on the static strength of the material.

Surface finish effects are included in the analysis by altering the slope of the elastic portion of the strain-life curve. The surface finish corrected slope is given by

$$b_{SF} = b - \frac{\log\left(\frac{1}{k_{SF}}\right)}{\log(2N_{FL})}$$

It is important to note that this correction should be done after the cyclic strength properties are determined.

Corrected strain life curve wrt surface finish factor

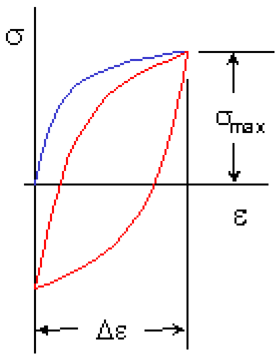


H. Mean stresses

Tensile mean stresses are known to reduce the fatigue strength of a component. Compressive mean stresses increase the performance and are frequently used to increase the fatigue strength of a manufactured part. The Smith-Watson-Topper (SWT) parameter is used to account for the effect of mean stresses in the strain approach. The major variables are the maximum stress, σmax, and strain range, Δε, of the stable hysteresis loop.The strain range provides the driving force for growing small micro cracks and the higher the maximum stress the easier it is for these micro cracks to grow. They proposed a simple damage parameter, PSWT, of

$$P_{SWT} = \sigma_{max}\frac{\Delta\varepsilon}{2}$$

Stable hysteresis loop

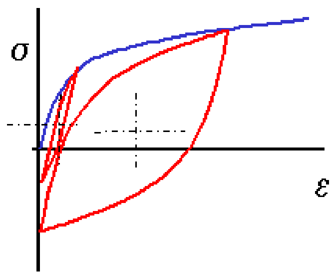


Any combination maximum stress and strain range of that has the same PSWT will have the same fatigue damage. A loading cycle with high maximum stress and small cycles strain ranges can do as much damage as a cycle with low maximum stresses and high cyclic strains. The SWT damage parameter can be related to the constant amplitude material properties generated without a mean stress. In a materials test the maximum stress is equal to the stress amplitude for the zero mean stress strain range.

$$P_{SWT} = \sigma_{max}\frac{\Delta\varepsilon}{2} = \left(\frac{\Delta\sigma}{2}\right)_{R=-1}\left(\frac{\sigma_f'}{E}(2N_f)^b + \varepsilon_f'(2N_f)^c\right)$$

This expression requires an iterative solution because the stress range, Δσ, is a complex function of 2Nf.
Fatigue damage is dependent on the local stresses and plastic strains around stress concentrators. Local mean stresses can be larger or smaller than the nominal mean stress depending on how much plastic deformation occurs around the stress concentration. Local stress strain response for nominal zero to tension loading is shown below. The maximum stress in the hysteresis loop will always be on the materials cyclic stress strain curve shown by the blue line in the figure.

The local strain range increases with an increase in the nominal stress range as shown by the two hysteresis loops in the drawing. Compressive stresses are formed around the stress concentration upon unloading even though the external nominal stresses were all in tension. Local mean stresses do not increase because the maximum stress is on the flat portion of the cyclic stress strain curve.

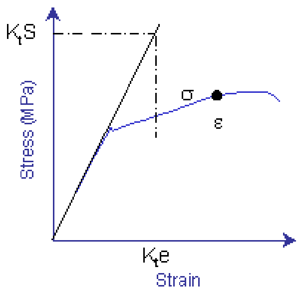


Material cyclic stress strain curve

I. Neuber's Rule

Neuber's rule is used to convert an elastically computed stress or stain into the real stress or strain when plastic deformation occurs. For example, we may compute a stress with elastic assumptions at a notch to be KtS and this stress exceeds the strength of the material. The real stress will be somewhere on the materials stress-strain curve at some point σ.

Neuber's rule states, with some mathematical proof, that the product of the elastic solution is equal to the product of the real elastic plastic solution. Mathematically this is expressed as
KtS·Kte=σ·ε.



Elastoplastic behavior curve

J. Fatigue Procedure

Considering all the parameter mentioned above in the technical study, fatigue procedure is developed for this axle. As the particular application is come under the high stress level and low number of cycle so strain life approach is advisable for this kind of application. To perform strain life fatigue approach, material data is received from the tested cast iron sample. The same material is used to made actual castings of this axle components. To convert the non-zero mean strain, Smith, Watson Topper (SWT) criteria is used.

- **Load cycle for VT:** As in this test vertical load is applied on the wheel in the pulsating mode so the fatigue load path is mentioned as 0 to max to zero again.

- **Load cycle for TRC:** TRC, continuous vertical load and traction is applied in forward and reverse direction so complete reversal cycle (R= -1) applied as a load path.
- **Material Curve for Fatigue Analysis: S**tudied in technical background, major material properties required for strain life approach are fatigue ductility coefficient, fatigue ductility exponent, fatigue strength coefficient, fatigue strength exponent, cyclic strength coefficient and cyclic strain hardening exponent. these properties are obtained from testing the same casting sample which is used.

K. Results and Discussions Part-2

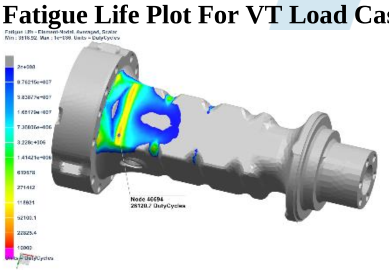
The first iteration surface finish effect is not considered in the fatigue results and compared the results of analysis with lab test results of failure cycles. During the actual testing the same axle is run for 50000 cycles of TRC,10000 cycle of VT at 2.5g and 3692 cycles of VT at 3.5g until failure. so to conclude the comparison whatever difference observed in the testing and durability results is because of not considering the surface finish factor in durability procedure. As per literature survey it is observed that the only material properties change with surface finish factor is fatigue strength exponent. The fatigue strength exponent for particular surface finish is calculated by below formula,

$$b_{SF} = b - \frac{\log\left(\frac{1}{k_{SF}}\right)}{\log(2N_{FL})}$$

Where,
bSF = Fatigue strength exponent for particular surface finish
b = Fatigue strength exponent for machined surface finish (at KSF=1)
KSF = Surface finish factor
2NFL = Number of reversal.

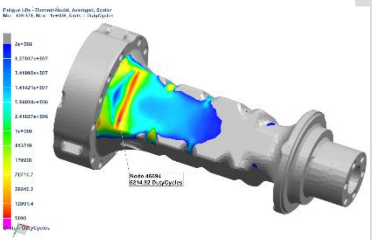
By using the above formula, different bSF values are calculated as per particular surface finish factor and putting that value in Fatigue procedure, results are checked against lab test results.

Fatigue Life Plot For VT Load Case At 2.5g With 0.5 Surface Finish Factor.



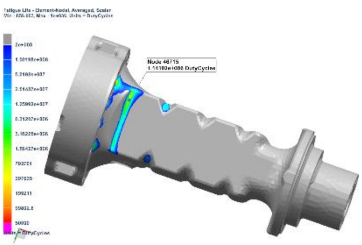
As shown in figure results of fatigue life plot for trumpet for VT load case with 2.5g load. Surface finish factor considered is 0.5 Stresses are highlighted in the area where actual trumpet is failed during lab test.

Fatigue Life Plot For VT Load Case At 3.5g With 0.5 Surface Finish Factor.



As shown in figure results fatigue life plot for trumpet for VT load case with 3.5g load. Surface finish factor considered is 0.5 Stresses are highlighted in the area where actual trumpet is failed during lab test.

Fatigue Life Plot For TRC Load Case With 0.5 Surface Finish Factor.



As shown in figure results fatigue life plot for trumpet for combine TRC load case. Surface finish factor considered is 0.5 Stresses are highlighted in the area where actual trumpet is failed during lab test

L. EXPERIMENTAL INVESTIGATION:

Testing results are used to check the difference between lab test results to actual results considering the missing effect of surface finish factor.

4) TRC Test cycle requested and carried out

Wheels torque FWD / REV (Nm)	Pinion torque FWD / REV (Nm)	Axle load (N) required / effective	Track (mm) required / effective	Cycle type (impulses)	Duration (cycles no.)
18000	1453	104480 / 104480	1214 / 1214	1 FWD / 1 REV	50000

5) VT Test cycle requested and carried out

Track (mm) required / effective	Deceleration to wheels (g)	Duration(cycles no.) required / effective	Axle load (N) required / effective	Tyres Type
1214/1214	2.5	10000 / 10000	52240 / 52240	15.00 R24
1214/1214	3.5	Breakage/3692	52240 / 52240	15.00 R24

CONCLUSION:

Combine Damage Calculation

As the VT and TRC test was perform on the same axle model upto failure so durability results can match with lab test results by using Miners rule cumulative damage is calculated. To match the results that damage should be equal to 1.

Damage calculation conclusion for various Ksf values.

Ksf	TRC	VT 2.5	VT 3.5	Total Damage
	50000	**10000**	**3692**	
1Ksf	7.14E+09	5.25E+06	2.70E+05	0.02
0.9Ksf	9.31E+08	1.48E+06	1.10E+05	0.04
0.8Ksf	1.37E+08	4.68E+05	50145	0.10
0.7Ksf	2.23E+07	1.67E+05	25310	0.21
0.6Ksf	3.96E+06	55733	10897	0.53
0.5Ksf	**1.14E+06**	**26120**	**6214**	**1.02**

As seen in above table, 0.5 value of surface finish factor gives the matching results with lab test results. So the designed **fatigue procedure is approved** as per this surface finish factor.

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