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Investigation of the Effect of Loading on Fatigue Life by Comparing Strain Gauge Measurements and Finite Element Analysis Under Gradually Increasing Load in An Axle Housing

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ABSTRACT

In this study, the stress values obtained from commercial finite element analysis software ANSYS® and stress values measured by strain gauges applied on an axle housing in test environment were compared. The axle housing is a test sample from heavy duty commercial vehicles. Besides from stress values comparison, fatigue behavior of the housing was observed under gradually increased loading conditions via hydraulic loaded test benches. Load conditions, configuration change steps, test parameters and fatigue life results will be explained in detail. It was observed that the results of FEA and strain gauge are coherent to each other and as the load was increased, the fatigue life decreased. The stress values in specified points of housing increase linearly with the load increment. However, as predicted, the relationship between load change and fatigue life is not linear. For instance, fifty percent increase in load reduces life by about seventy-five percent. The aim of the study is firstly correlate the FEA results by comparing with the test measurements and then try to observe the effect of load increase on the fatigue life which will be a beneficial source for estimation of the life of the axle housing under diverse loadings in the further studies.

Keywords: Axle housing, strain gauge application, stress and fatigue life comparison, finite element analysis

Bir Diferansiyel Kovanında Kademeli Artan Yükleme Koşulları Altında Gerinim Ölçer Ölçümleri ve Sonlu Elemanlar Analizi Kıyaslanarak Yüklemenin Yorulma Ömrüne Etkisinin İncelenmesi

ÖZ

Bu çalışmada, sonlu elemanlar analiz programı ANSYS®' den elde edilen gerilme değerleri ile test ortamında diferansiyel kovanına bağlanan gerinim ölçerler ile ölçülen gerilme değerleri kıyaslanmıştır. Çalışmada kullanılan parça ağır ticari araçlarda kullanılan bir diferansiyel kovanıdır. Çalışmada gerilme değerleri karşılaştırmasının yanı sıra, hidrolik yüklemeli test tezgâhları ile kademeli artan yükleme koşullarında kovanın yorulma davranışı gözlemlenmiştir. Yük koşulları, test konfigürasyonları ve yorulma ömür sonuçları makalede detaylıca anlatılmıştır. Sonlu elemanlar analizi ve gerinim ölçer sonuçlarının birbiri ile uyumlu olduğu ve yük arttıkça yorulma ömrünün azaldığı gözlemlenmiştir. Gövdenin belirlenen noktalarında gerilim değerleri, yük artışı ile lineer olarak artmıştır. Ancak yük değişimi ile yorulma ömrü arasındaki ilişki doğrusal değildir. Yükteki yüzde elli artış, yorulma ömrünü yaklaşık yüzde yetmiş beş azaltmıştır. Çalışmanın amacı, öncelikle sonlu elemanlar çalışmalarının güvenilirliğinden testler ile karşılaştırma yaparak emin olmak, ilerleyen çalışmalar ile birlikte diferansiyel kovanının ömür tahmininde faydalı bir kaynak olacak şekilde ve daha fazla yük ile daha az çevrimde test gerçekleştirerek ürünün güvenilirliğinden emin olunabilecek alt yapıyı hazırlamaktır.

Anahtar Kelimeler: Diferansiyel kovanı, gerinim ölçer uygulaması, gerilme ve yorulma ömrü kıyaslaması, sonlu elemanlar analizi

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1. INTRODUCTION

Axle housing is a safety component located under vehicles whose objective is to house differential gear systems (see Figure 1), carry the gross axle weight ratings (GAWR) and endure for a life time of the vehicle. GAWR is the most distributed weight the axle of a vehicle can support. Especially, rear axle housing of a heavy duty vehicle [1] withstand great proportion of the load which is not only static but also dynamic

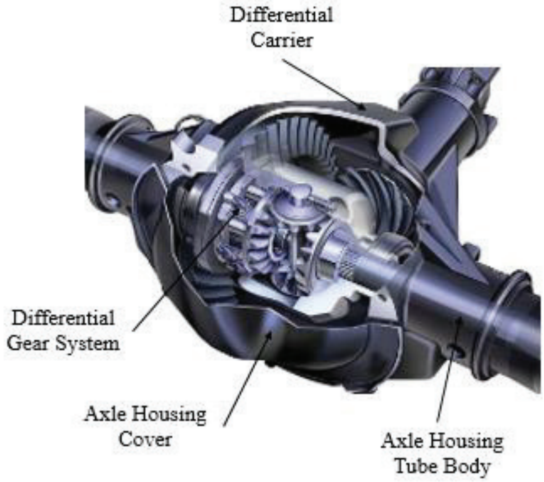


Figure 1. Differential Gear System Covered by an Axle Housing

Figure 2. Sample Axle Housing of a Heavy Duty Commercial Vehicle

generated by the rough road conditions. The below figure (Figure 2) is viewing from rear side of a rear axle housing of a heavy duty commercial vehicle.

Rear axle housing has;

- two brake flanges for connection with brake systems,
- two spindles for connection with wheel hubs
- a differential system inside connection with axle mil for transmitting rotation movement to the wheels
- a cover for protection of the differential from outside surroundings and prevention of oil leakage
- a ring for connection with differential carrier

See below figure (Figure 3) for marked view of components on axle housing.

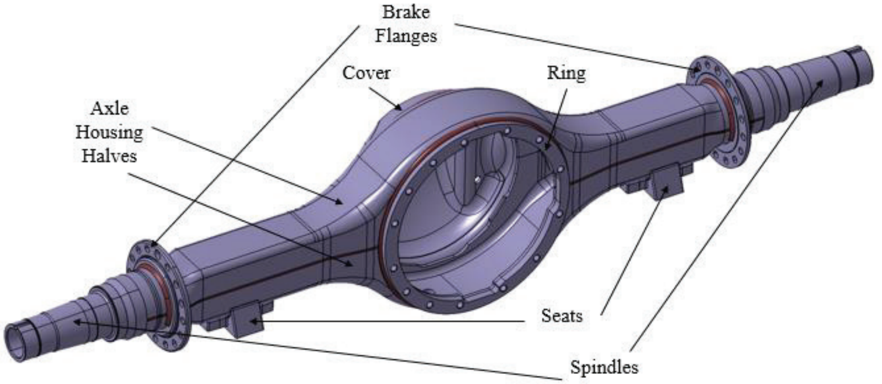


Figure 3. Rear Axle Housing Components

The static and dynamic strength of the axle housing is essential for the vehicle safety. Axle housing should operate till the end of service life of the vehicle which means it should not be replaced during the designated distance of usage. That's why, to ensure the stability of the housing, static and fatigue simulations are performed in design stage and validation bench tests after manufacturing.

The components of the housing are assembled by arc and friction stir welding to each other. Welding is the most common used method for joining two metals. It provides good adhesion on the product by fusion of the components and the weld. Besides the advantages, the welding weakens the material strength because high heat increase during the process both in the components and welding itself. Moreover, the hardness and surface roughness of the weld affect the strength of the structure under static and/or dynamic loading. That's why, the connection areas are the most critical and sensible regions for the failure of the housing.

To investigate and predict the effect of the welding on the product before manufacturing it, some simulation tools can be used. However, these tools are very expensive. The simulations usually are performed without taking into account of the welding process which is cheaper and weld effect is ignored. To see the welding effect, bench tests are conducted to the products as validation. The real life under vehicle conditions are set for the fatigue bench tests. This test process should cover the life of the product under the failure occurs. That's why the tests take relatively long time to accomplish.

Along with this study, the time of testing is objected to be decreased. Considering the validation sample amounts and the elapsed time for getting results, any decrease of the test time would have great influence on money and time saving. Among other methods [2], one of the ways of decreasing this time is to increase the load of the product under fatigue bench testing.

2. FEA SIMULATION

In the study, the effect of the change in loading conditions to the stress concentrated areas and fatigue life of the axle housing was investigated and experimentally examined by effectively using simulation (FEA), validation (test bench) and data acquisition (DAQ) tools. To define these high stress concentrations on the axle housing, simulation process was conducted.

- The product modeled with 3D CAD program CATIA® (V5 R18 version) [3] was imported into a finite element analysis (FEA) software program, ANSYS® Mechanical Workbench (2021 R2 version) [4].
- The model is meshed to finite number of elements; fined around the stress concentrated regions, critical components and load application areas. Other component

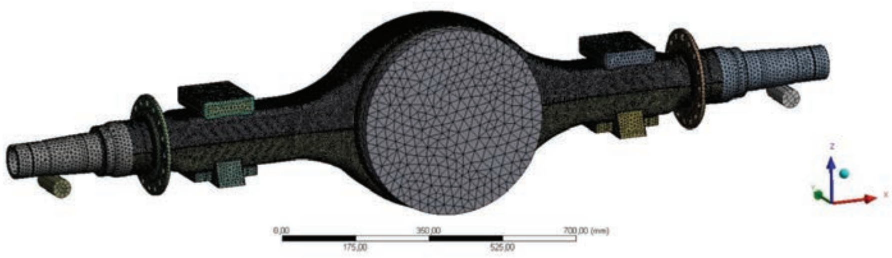


Figure 4. FEA Model Mesh Density

were meshed relatively coarse to decrease solving time. The model (see Figure 4) was meshed with;

  - ○ Tetrahedron (tet10) type of elements having which are 778.257 elements in total with 1.277.635 nodes
  - ○ Element sizes of; axle housing halves: 4.75mm, welds: 3mm, ring: 10mm, spindle: 10mm, cover: 10mm, brake flanges: 10mm, seats: 8mm, differential cover: 24mm

- The load application and support conditions were set to simulate vehicle riding conditions (Figure 5);

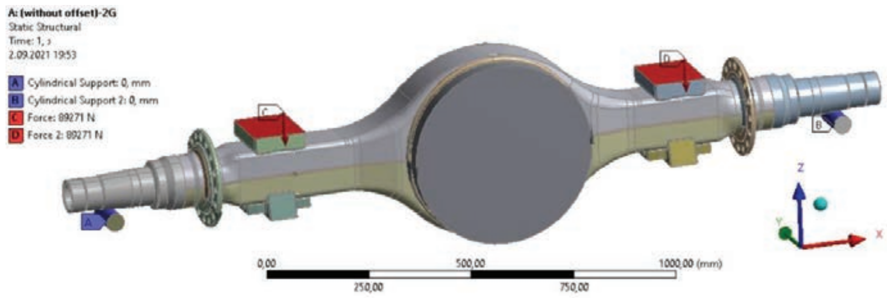


Figure 5. Load Application and FBD of FEA Model

  - Cylindrical supports were added at the track widths to allow the axle housing is free at tangential direction but fixed in axial and radial directions.
  - The loads were applied at the axle seats downwards (-z) starting with GAWR and increased gradually.

- According to the results of structural analysis (Figure 6), the high stress zones

Figure 6. FEA Stress Results Display and Defined Strain Gauge Locations

were defined and geometrically suitable nearest points were selected to apply strain gauges for measuring the critical actual stress during the test loading. One of the critical regions was at banjo area of the housing and selected for SG1, the other was at the ring weld area and selected for SG2.

3. VALIDATION TEST AND DAQ

Testing axle housing was integrated into the test rig with combinations of setup parameters. In, all the conditions the housings were placed at cylindrical supports at the track width, which are the same positions of the wheels touch the ground at riding condition. And, the housings were mounted to the pistons at the spring seats where the vehicle loads were transferred through. For the offset included tests, the pistons were moved apart having 80mm total distance in between. The set up dimensions used in the tests are listed as below and can be seen in Figure 7 and Figure 8:

- Track Width: 1869.4 mm
- Spring Distance: 1028.7 mm
- Load Offset Value: 40mm

- After the housing was placed in the rig, the strain gauges were bonded on the axle housing (Figure 9) defined locations by following the instructions of strain gauge application process [5]. In the meanwhile, the data acquisition system was set up and the gauges were connected to the data logger. The loading was initiated to the pistons and the test has begun. The gauges were rosette type which means each of them can collect from all 3 directions of strains. The strain values coming from 6 channels were recorded all along the test. Then, they were converted to stress data to compare with the FEA stress results.

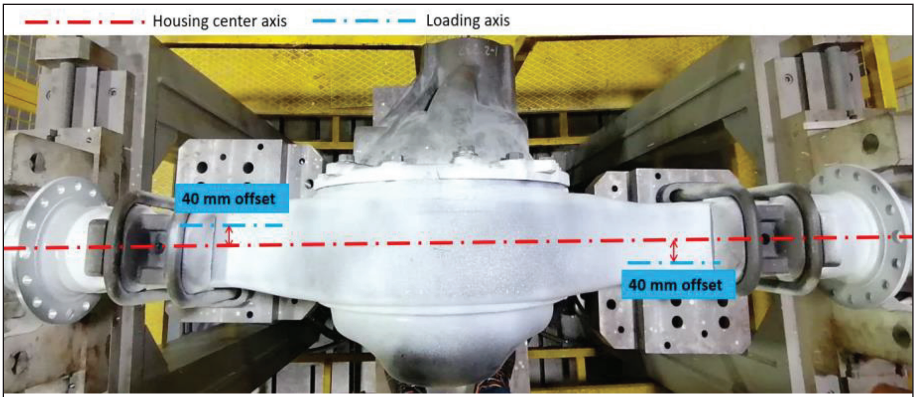


Figure 7. Test Set-up View from top showing the Load Offset

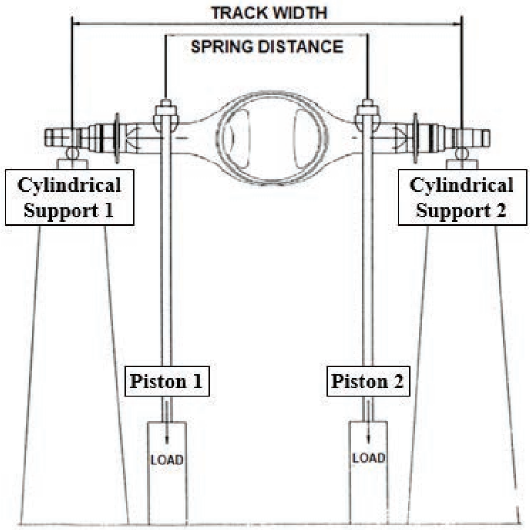


Figure 8. Test Set-up View from front showing the Load Application and Support Locations representing the Road Conditions

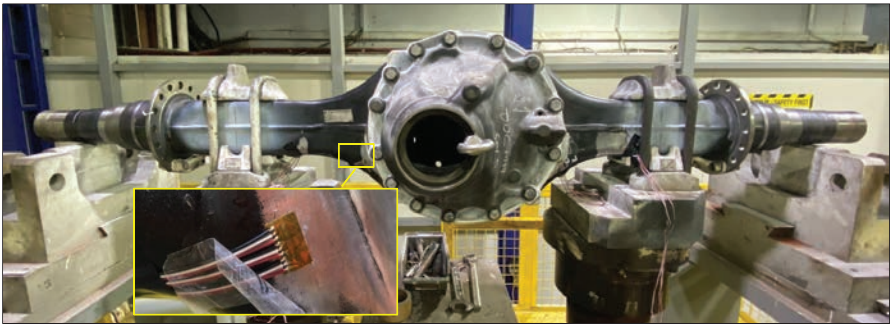


Figure 9. A Close View of Rosette type Strain Gauge bonded on the Axle Housing

- The test was carried out in 4 stages. The loadings were determined according to the load carrying capacity of the housing and the riding conditions [5]. Moreover, during the test stages, the configuration of the axle housing parts, and the loading offsets were changed to investigate their effect on the stresses.
- In the first 3 stages; the load was started starting with 9100 kg and increased with 455kg in each 500 cycles up to reach 13650 kg by in total 16500 cycles. In every stages the configuration of the housing or the load offset was changed. These repeated 11 steps are tabled below (Table 1).

Stage 1: With differential carrier, without offset (0-5500 cycles) 9100 kg to 13650 kg

Stage 2: With differential carrier, with offset (5500-11000 cycles) 9100 kg to 13650 kg

Stage 3: Without differential carrier, with offset (11000-16500 cycles) 9100 kg to 13650 kg

- In the final stage, at stage 4, the test continued with a load of 13650 kg until a crack initiate on the product.

Stage 4: With differential carrier, 13650 kg loading with offset, until the product cracks (16500-168000 cycles)

Table 1. Loading Steps for the first 3 Stages

Step	Cycle	Load [kg/piston]	Preload [kg/piston]
1	0-500	9100	182
2	500-1000	9555	194
3	1000-1500	10010	200
4	1500-2000	10465	209
5	2000-2500	10920	218
6	2500-3000	11375	227
7	3000-3500	11830	236
8	3500-4000	12285	245
9	4000-4500	12740	254
10	4500-5000	13195	263
11	5000-5500	13650	273

4. ASSUMPTIONS IN SIMULATION, VALIDATION AND DAQ

- The actual differential carrier geometry is very complex to model. In favor of model simplicity, the FEA analysis was performed with a representative dummy sheet plate cover. This plate provides integrity to the housing as connected to the ring area. Even if with the sheet plate, covering this area gives the required stiffness to the housing.

- All sub-parts (especially the welds) were modeled in ideal way, for example, neither surface roughness nor shape discontinuity was modelled in the CAD program. Then the FEA was performed directly on this model [7]. This may cause differences in FEA and strain gauge stress results. As the housing may have some geometrical differences as in manufacturing limits, it may result in stress concentration in some areas.
- Since the areas on the housing where the strain gauges were attached did not directly correspond to the mesh points on FEA, the stress values corresponding to the SG location were read and averaged in order to get closest stress value to represent the stress extracted area. [8] A sample averaging in FEA shown in below Figure 10:

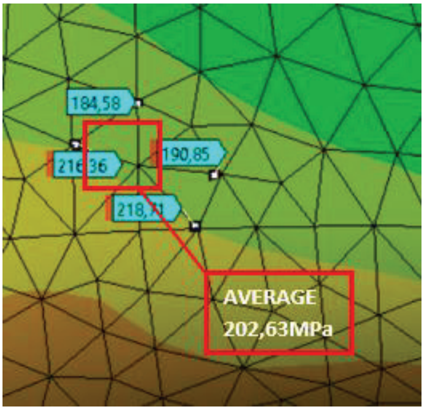


Figure 10. Sample of Averaging the FEA Stress Values representing the SG bonded Location Stress

- It is normal to have difficulty to place strain gauges exactly in the highest stress areas due to geometrical inconsistency like curvature or discontinuity in thickness. In this study, the gauges are tried to be placed as nearest point as could.
- Strain gauges are sensitive equipment; in some gauges, the stress could not be read after a while test had been started. In some gauges, fluctuations were observed in the stresses due to environmental and bonding factors such as temperature, contact quality, the slightest incompatibility in bonding. Also, the deterioration of some rosettes as observed during the test. In this article, 2 reliable strain gauges (SG1 and SG2) will be focused out of 4 sticked gauges.
- It was aimed to adhere the strain gauges in parallel with the x-axis (seam welding of the housing halves), but there were small differences in angles between x axis.

For this reason, the values of the “ϕ” angle were measured after the bonding process for each strain gauge by taking the x-axis as a reference, as shown in Figure 11. The transformation calculations were made by using these angles and below Equation 1 [9].

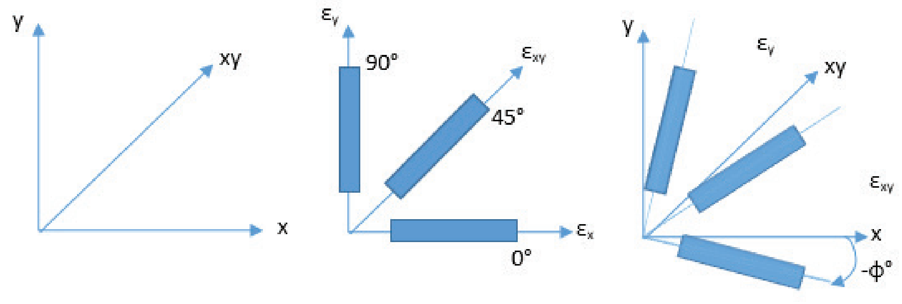


Figure 11. Strain Gauge Axis Difference with Reference Global Coordinate

Then the transformed strain values were obtained in global coordinate system of the housing.

$$\boldsymbol{\mathring{a}}_1 = \varepsilon_x \times \cos^2\phi_1 + \varepsilon_y \times \sin^2\phi_1 + \gamma_{xy} \times \sin\phi_1 \times \cos\phi_1$$

$$\boldsymbol{\mathring{a}}_2 = \varepsilon_x \times \cos^2\phi_2 + \varepsilon_y \times \sin^2\phi_2 + \gamma_{xy} \times \sin\phi_2 \times \cos\phi_2$$

$$\boldsymbol{\mathring{a}}_3 = \varepsilon_x \times \cos^2\phi_3 + \varepsilon_y \times \sin^2\phi_3 + \gamma_{xy} \times \sin\phi_3 \times \cos\phi_3$$

Equation 1: Angle Transformation Equations for Strains in all 3 Directions

5. RESULTS

5.1 Stage-1 Test Results and FEA Comparison

In this stage, the axle

- with differential carrier
- between 0-5500 cycles
- with gradual and cyclic loading starting from 9100kg to 13650kg
- without offset was tested

The measured (SG) and calculated (FEA) stress values for SG locations were graphed below as Figure 12 and Figure 13:

As seen in the above graphs, for both SG locations (especially for SG2):

- the FEA and SG stresses are parallel and close

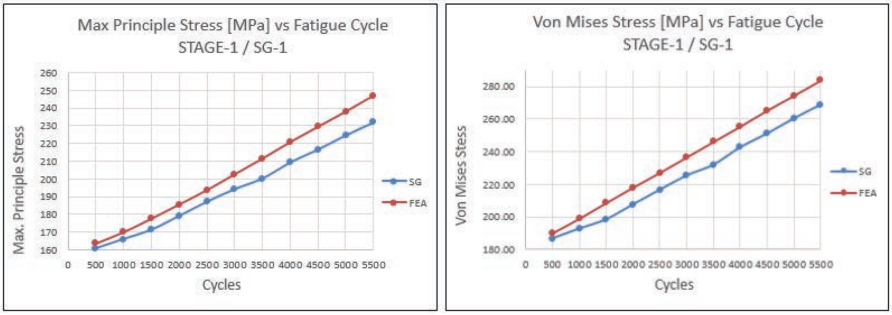


Figure 12. MP, VM Stress Results at Stage 1 / SG 1 and Comparison with FEA

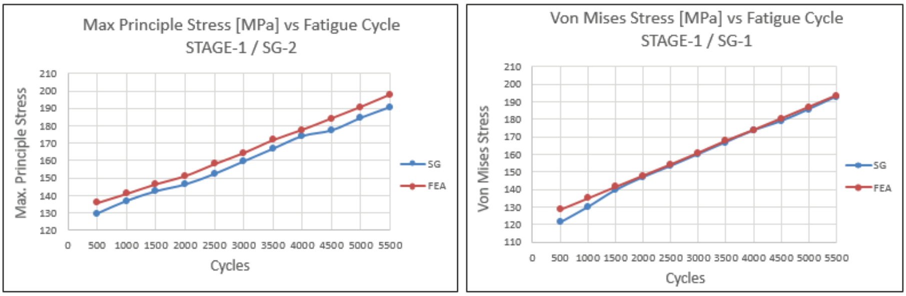


Figure 13. MP, VM Stress Results at Stage 1 / SG 2 and Comparison with FEA

- one can say, FEA and test are confirming each other
- moreover, it is observed that the stresses are increased as the load increased
- another observation is that the FEA stresses are slightly bigger than the measured ones. That is good and beneficial since the simulation will give conservative prediction for the non-tested situations [10]

5.2 Stage-2 Test Results and FEA Comparison

In this stage, the axle:

- with differential carrier
- between 5500-11000 cycles
- with gradual and cyclic loading starting from 9100kg to 13650kg
- with offset was tested

The measured (SG) and calculated (FEA) stress values for SG locations were graphed below as Figure 14 and Figure 15:

As seen in the above graphs, offset given FEA and test results are closer to each other than without offset condition.

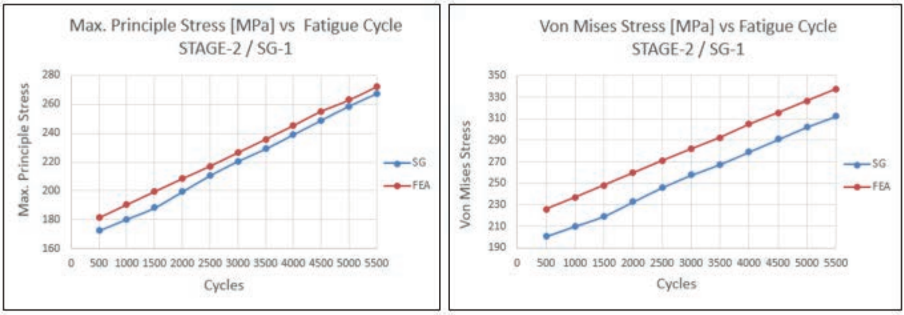


Figure 14. MP, VM Stress Results at Stage 2 / SG 1 and Comparison with FEA

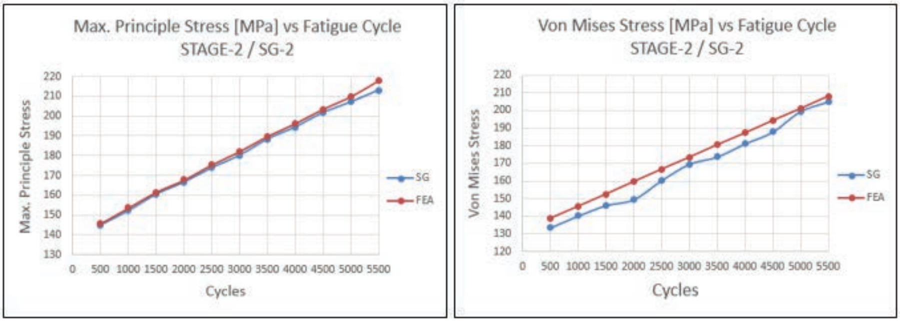


Figure 15. MP, VM Stress Results at Stage 2 / SG 2 and Comparison with FEA

- Similar comments of stage 1 can be done for the stage 2 as well
- Moreover, it was observed that the stresses increased around 10% compared to without offset condition.

5.3 Stage-3 Test Results and FEA Comparison

In this stage, the axle:

- without differential carrier
- between 11000-16500 cycles
- with gradual and cyclic loading starting from 9100kg to 13650kg
- with offset was tested

The measured (SG) and calculated (FEA) stress values for SG-1 location were graphed below as Figure 16;

As seen in the above graphs;

- Removing the cover from the housing during the test, caused an increase of approximately 22% in the maximum principal stress values and an increase of approximately 23% in the equivalent stress values in the strain gauge test results. [11]

- However, in the analysis performed by suppressing the cover on the FEA, the maximum stress value was found below the stress value compared to the with cover condition. This is an unexpected and unrealistic situation. In the face of this decrease in the maximum principal stress, the equivalent stress remained almost constant. The reason is thought to be due to the fact that the cover used in the model made on FEA does not reflect the real conditions exactly. The dummy cover is used in the model which is not as heavy as the real carrier and no load is given to the cover to compensate this difference.
- In addition, it was observed after the experiment that the SG2 did not give reasonable values due to the failure of the SG2-2 channel during the test. For this reason, the values read from the SG1 without cover state and the stress values in the with cover state SG1 were compared in below Figure 17.

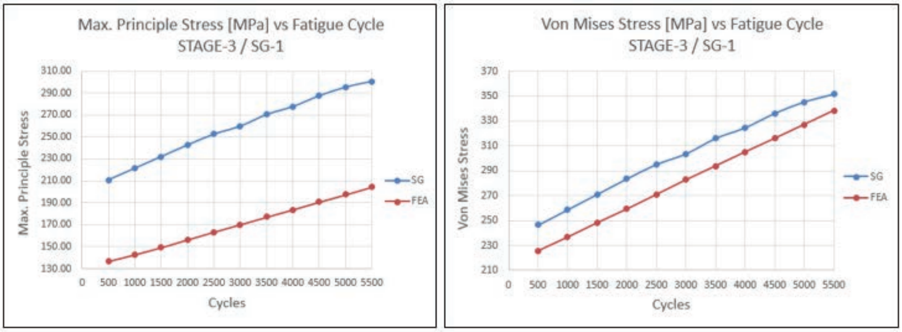


Figure 16. MP, VM Stress Results at Stage 3 / SG 1 and Comparison with FEA

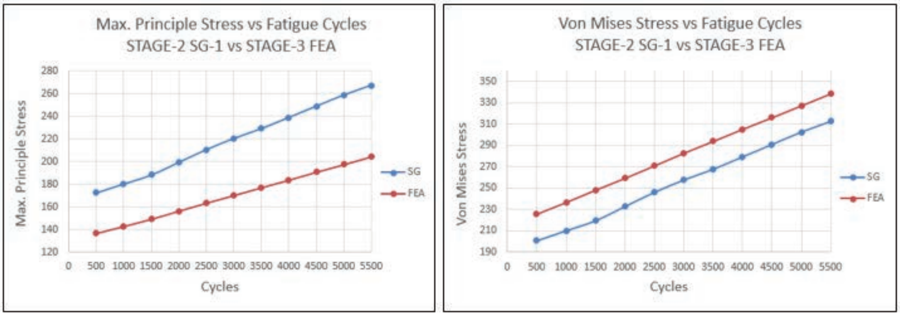


Figure 17. MP, VM Stress Results Comparison of Stage 2 SG 1 with Stage 3 FEA

5.4 Stage-4 Test Results

In this stage, the axle:

- with differential carrier
- between 16500-168102 cycles
- with constant cyclic loading of 13650kg
- with offset was tested

In the last stage of the experiment, the housing having differential carrier was left to fatigue test [12] at 13650 kg loading with offset. The test pistons are programmed to stop at a certain deflection difference in case of any crack initiation or propagation. By the help of this setup, the system stopped at cycle 168102 by a large deflection detection. The housing was examined and 80 mm crack were determined in the ring welding zone as picture in Figure 18. Although, the crack initiation cycle could not be captured, with foresight of prior experiences, it is predicted that the crack had initiated in the weld and propagate through the housing half at banjo region. Although the area where the crack is expected to occur is the ring welding area [13] and the crack occurred in this region as a result of the test, the stresses in the cracked region could not be observed because the geometry of the relevant region is not suitable for bonding the strain gauge.

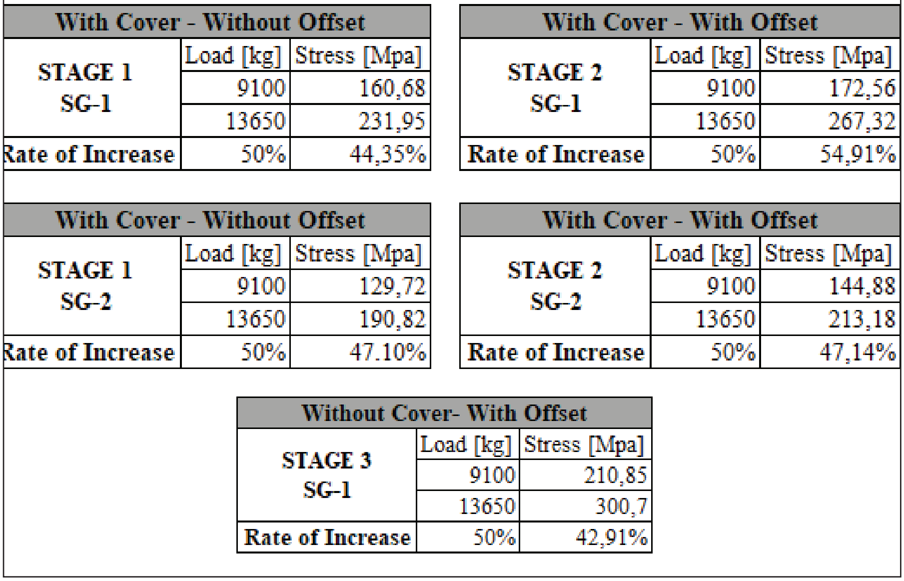
6. CONCLUSIONS

Through this study, some observations were performed about the behavior of the housing in defined stages. A comparison can be done on the correlations between the applied load and obtained stress. The comparisons are shown in the below Table 2 and similarly in Figure 19 for the stages that loads gathered from SGs.

According to the results;

Figure 18. Fatigue Crack at the end of Stage -4

Table 2. Load Increase and Stress Relation



With Cover - Without Offset		
STAGE 1 SG-1	Load [kg]	Stress [Mpa]
	9100	160,68
	13650	231,95
Rate of Increase	50%	44,35%

With Cover - With Offset		
STAGE 2 SG-1	Load [kg]	Stress [Mpa]
	9100	172,56
	13650	267,32
Rate of Increase	50%	54,91%

With Cover - Without Offset		
STAGE 1 SG-2	Load [kg]	Stress [Mpa]
	9100	129,72
	13650	190,82
Rate of Increase	50%	47.10%

With Cover - With Offset		
STAGE 2 SG-2	Load [kg]	Stress [Mpa]
	9100	144,88
	13650	213,18
Rate of Increase	50%	47,14%

Without Cover- With Offset		
STAGE 3 SG-1	Load [kg]	Stress [Mpa]
	9100	210,85
	13650	300,7
Rate of Increase	50%	42,91%

- When the housing is loaded with offset (offset amount is also effective, 40mm offset is given in this study), the stresses increased by 10% compared to the without offset condition.
- When the housing is loaded without cover, the stresses increase by 20% for the SG1 region.
- When the loading of the housing is increased by 50%, the stresses also increase linearly by 50% with this increase.
- It is observed that the increase is linear when the increase in housing loading from 9100 kg to 13650 kg at intervals of 455 kg.

Also, the test in this study was terminated at cycle 168,102. Considering its 153.102 cycles with 13650kg loading, result is like below:

- First objective of the study is to correlate FEA and test results in order to use FEA for the non-tested welded products confidently.
- After accomplishing that, secondly, observe the effect of load increase on the fatigue life which will be a beneficial source for estimation of the life of the axle housing under diverse loadings in the further studies. If the estimation can be achieved than by increasing the load, the testing time can be reduced. Consequently, there will be a major reduction in testing time and money spent on validation of the products.

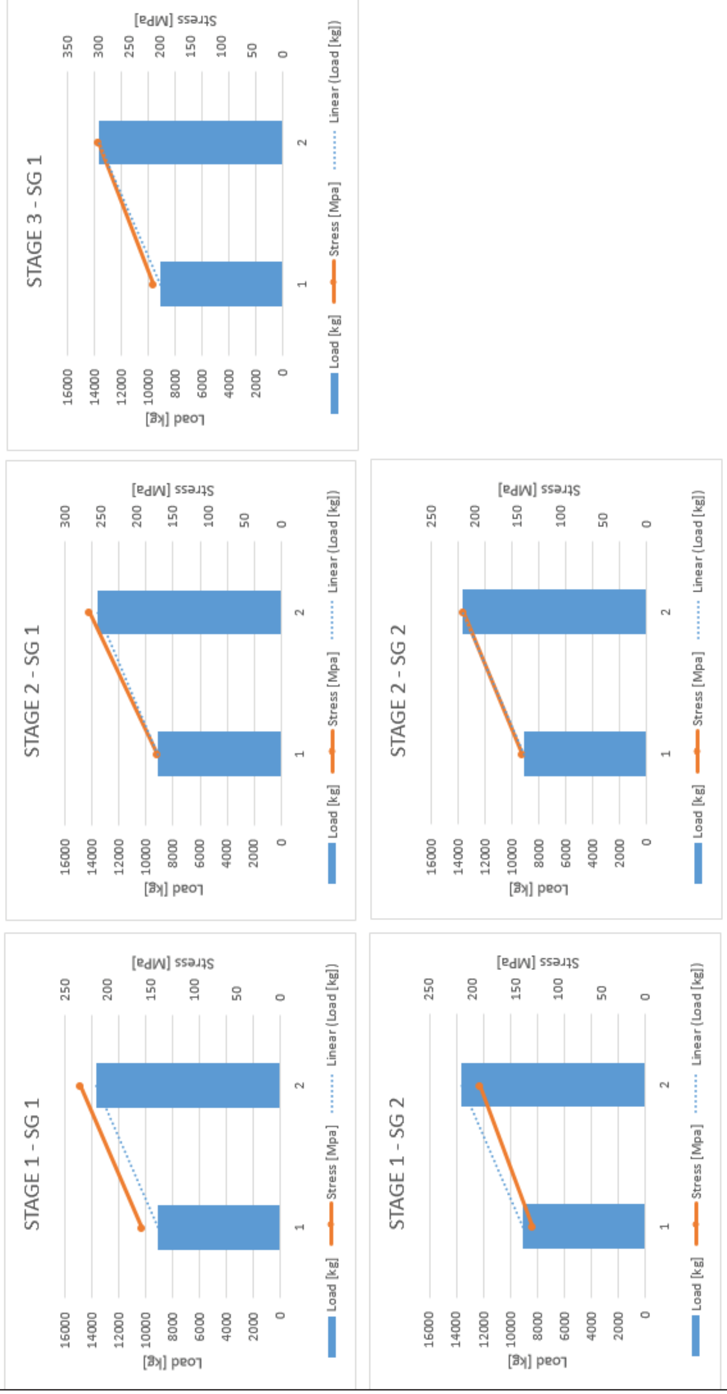


Figure 19. Load Increase and Stress Relation in Graphics

Compared to the nominal tests carried out at up to now with GAWR in the Ege Endüstri Test Center, based on prior experience of testing periods, it is observed that by this study, 50% increase in load caused a 76.72% decrease in life. That means, fatigue acceptance criteria of the product can be redefined to a profitable value by proceeding this study until getting a confidence level. This study will lead to upcoming ones.

7. SYMBOLS

ε: epsilon, strain value

γ: gamma, shear strain value

ϕ: phi, representing the angle difference between SG x direction and global x direction

8. ACKNOWLEDGEMENTS

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REFERENCES

1. **Topaç, M. M., Günal, H., Kuralay, N. S.** 2008; "Fatigue Failure Prediction of a Rear Axle Housing Prototype by Using Finite Element Analysis", Eng Fail Anal (2008), DOI:10.1016/j.engfailanal.2008.09.016

2. Hongwei Zhang, Liangjin Gui, Zijie Fan, "A New Method to Accelerate Road Test Simulation on Multi-Axial Test Rig", SAE Technical Paper Series, vol.1, 2017

3. CATIA V5 R18 Designers Guideline, CADEM, Assembly Design, 2007

4. ANSYS Mechanical APDL Theory Reference 2021 R2. ANSYS Inc, Canonsburg; s.5-26, s.779-781

5. IMC Veri Toplama Sistemi ile Strain Gage Uygulama ve Teori Eğitimi (2021), BİAS Mühendislik Ltd. Şti, İstanbul.

6. **Reimpell J., Stoll H., Betzler J.W.** 2001; "The Automotive Chassis: Engineering Principles" 2nd Edition, ISBN 0-7680-06570 Butterworth-Heinemann, Oxford; s.318-325

7. **Budynas, R. G., Nisbett, J. K.** 2011; "Shigley's Mechanical Engineering Design" 9th Edition, ISBN 978–0–07–352928–8, McGraw-Hill, New York; s.358, s.954-972

8. **Topaç, M. M., Günal, H., Kuralay, N. S.** 2009; "Ağır Ticari Taşıt Arka Aks Gövdesinin

Tekrarlı Düşey Yük Altında Yorulma Ömrünün Sonlu Elemanlar Analizi yardımıyla İyileştirilmesi", Mühendis ve Makine, Cilt: 51, Sayı: 601, s.10-20

9. **Lee Y. L., Pan J., Hataway R., Barkey M.** 2005; "Fatigue Testing and Analysis" 1st Edition, ISBN 0-7506-7719-8, Elsevier Butterworth-Heinemann, Burlington; s.1-57

10. Xian Zhong Yu, Gang Jie, Ping Hui Huang, Si Cheng Tang, "Fatigue Life Prediction of Driving Axle Housing Assemble Based on FEA", Advanced Materials Research, vol.179-180, pp.1217, 2011.

11. **Kuralay N. S.** 2008; "Motorlu Taşıtlar; Temel ve Tasarım Esasları, Yapı Elemanları, Cilt 1; Tahrik ve Sürüş Sistemleri", ISBN 978-9944-89-610-8, TMMOB Makina Mühendisleri Odası, İzmir; s.124-137

12. **Topaç, M. M., Günal, H., Kuralay, N. S.** 2008; "Kamyon Arka Aks Gövdesinde Oluşan Yorulma Hasarının Sonlu Elemanlar Yöntemiyle İncelenmesi", Mühendis ve Makine, Cilt: 49, Sayı: 583, s.3-10.

13. **Schijve J.** 2009; "Fatigue of Structures and Materials" 2nd Edition, ISBN-13: 978-1-4020-6807-2, Springer Science Business Media B.V, Berlin/Heidelberg; s.535-557