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Correlation of Simulation, Test Bench and Rough Road Testing in terms of Strength and Fatigue Life of a Leaf Spring

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Abstract

There are three major methods to verify the durability characteristics of a new designed leaf spring. These are simulation, test bench and rough road testing.

Simulation is a rapid approach to find out the very first results for the assessment of the design. Test bench uses a pre-defined load program to estimate the lifetime of the leaf spring. It takes more time than simulation and is more costly. Rough road testing covers a complete endurance run for the whole heavy duty truck structure which is very costly and takes a very long time to accomplish.

The aim of this paper is to reduce the time and the cost of the development procedure of a new designed leaf spring. The most efficient way to reach this goal is to correlate the results of the testing and simulation, so that, it would be possible to release new designs mostly depending on the simulation which is the fastest and the reasonable way to reach a final evaluation.

A new designed leaf spring, with two leaves, is simulated in finite element analysis with the loads from multi body simulations in order to reach a fatigue life assessment; is tested in the test bench with the pre-defined loads from the rough road; is mounted to a complete truck structure to run a full rough road truck program to reach the final evaluation.

In this paper, these three durability assessment techniques are compared and correlated with each other as a main scope. Additionally, the simulation methodology, the structure of the test bench and the procedure of the rough road testing are given in details.

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Keywords: Leaf Spring, Test Bench, Virtual Test Rig, Load Spectrum Determination, Test Spectrum, Fatigue, Finite Element Method, Multi Body Simulation

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1. Introduction

Correlation of simulation is a profitable method to help the designers to achieve their goals in a more reasonable way. Because of high competition aspect in the market, cost and weight optimized designs are noteworthy nowadays within the vehicle engineering development activities. Therefore, strength and fatigue life simulation of leaf springs is going to be explained and correlated within this paper including examples.

Nomenclature

FE	finite element	P_o	probability of occurrence
FEM	finite element modelling	σ	stress for constant amplitude loading
MBS	multi body simulation	$\overline{\sigma}$	stress for variable amplitude loading
D	damage sum	σ_k	knee point of the S-N curve
L_s	sequence length	a	amplitude
L_{Test}	test spectrum length	f	frequency
L_{Design}	designed service length	k	slope of the S-N curve
N	number of cycles for constant amplitude loading	k’	slope of the prolongation
$\overline{N}$	number of cycles for variable amplitude loading	n	number of tests, number of cycles
N_k	fatigue life at knee point	t	time
P_s	probability of survival		

Multiaxial loads are acting on the leaf spring assembly in a truck structure and therefore they have great influence on the drivability of the truck. Vertical, lateral and longitudinal forces, with high moments during start, braking and torsion are acting on the leaf spring and should be investigated in detail for an accurate correlation of the simulation.

Sonsino [1] stated that variable amplitude loading tests are performed because none of the cumulative damage hypotheses can predict the fatigue life for these loadings. Hence such tests are required to have real damage sums with Wohler- and Gassner-lines, see Fig. 1.

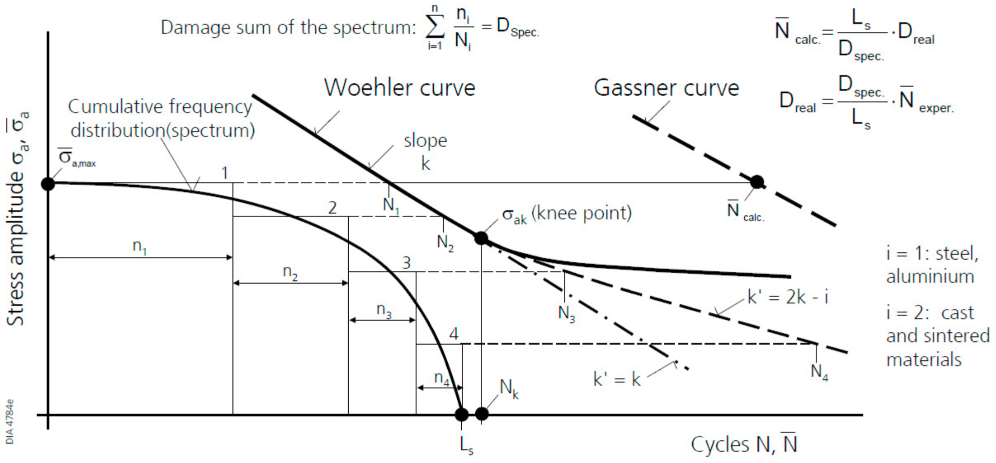

Fig. 1. Modification of S-N curve and calculation of fatigue life [2]

Based on the Palmgren-Miner-Rule modified by Haibach [3], the damage of a spectrum with size L_s can be calculated:

$$\sum \left(\frac{n}{N}\right)_i = D_{spec} \tag{1}$$

and the real sum is determined from this value by using experimental results:

$$D_{real} = \frac{D_{spec}}{L_s} \cdot N_{exp} \tag{2}$$

There are three major steps to be completed for the correlation study:

- Getting the measurement data of the leaf spring from the rough road testing
- Implementing the measurement data and the self-defined program of the leaf spring into the test bench
- Strength and fatigue life analysis of the leaf spring depending on the provided input data

By accomplishing all these steps, correlation of the simulation can be performed. The correlation study, including these steps, is going to be clarified through the following chapters.

2. Strength and fatigue life of a leaf spring

2.1. Rough road testing

The measurements were done on the rough road located in the Daimler Truck Testing Center in Wörth, Germany. This rough road simulates the desired fatigue life time for the vehicle durability and consists of 14 test tracks that differ from each other by indicating different damage results depending on different manoeuvers. For every type of truck such as; on-road, off-road, tractor, tipper, platform etc. there is a pre-defined test program including different types of tracks with a certain number of loops. The testing vehicle should complete its own testing program without a failure in order to reach the desired fatigue lifetime.

Strain gauges are applied on the upper side of the leaf spring to track the strain data (see Fig. 2). This strain data is going to be used for the creation of the load spectra for the test bench and also for the strain correlation progress.

For the correlation study of the leaf spring at front axle, the most critical tracks are picked and investigated. The reason for this issue is, most of the fatigue damage acting on the leaves is occurring on the tracks which have mostly vertical impacts and braking moments. Therefore, track a (as the vertical track) and track b (as the braking track) is selected and analyzed for this study.

Rough road data consists of forces and moments obtained from wheel force transducers (see Fig. 2). This data is used both for the test bench measurements and also in a MBS model in order to obtain the cutting forces acting on the middle of the leaf spring. Fatigue life analysis is performed depending on these cutting forces and moments [4].

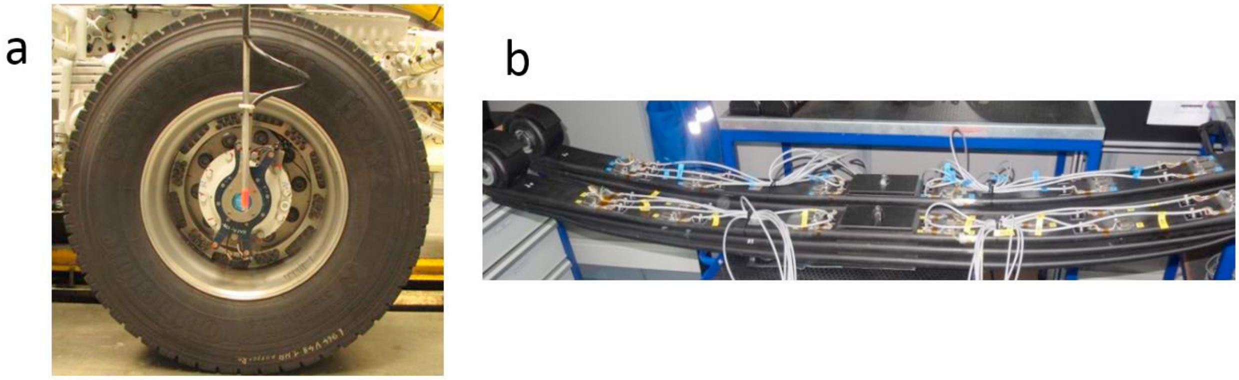

Fig. 2. (a) Wheel force transducer; (b) Strain gages on the leaf spring.

2.2. Test bench

The measurement data from the rough road testing is used as an input for the test bench loading program. This input data is filtered and aligned for the test bench accuracy. The loading program or the input data is also validated by measuring the damage values in this test bench. Several statistical methods are worked with LMS Tecware [5] in order to determine the damage level and realize frequency calculations. With this software, it is possible to calculate the total damage value at each strain gage point by utilizing the damage in the each track. These strain and damage values are compared with the rough road data in order to assure that the test bench is working in parallel with the rough road testing. The test program and the validation of the test bench is performed depending on the input from the rough road testing with the help of additional software such as Diadem and LMS software package [6].

The test unit consists of 5-cylinder, so that the signal of test spectra can be applied in 5 directions, see Fig. 3. In this test bench, two springs (left and right) can be examined simultaneously. Two 250 kN cylinders, two 100 kN cylinders and a 100 kN cylinder were placed such that they simulate the vertical forces, forces in the driving direction and lateral forces respectively. Thus, low frequency oscillations acting from the frame of the loaded vehicle, high frequency vertical loads arising from the road, lateral and longitudinal forces acting on the vehicle and also moments during braking and starting can be simulated. The two leaf springs were connected to the axle with the original attached parts (torsion bar arm, brackets, etc…). In this way, all of the attached parts will be also proved [4].

Fig. 3. Test bench

2.3. Simulation

For a correlation study, a deeper investigation is necessary for the strength and fatigue life analysis of the leaf spring. In the current simulation process of a leaf spring, various calculation methodologies are applied in order to accomplish a comprehensive calculation process. These methodologies are illustrated in Fig. 4.

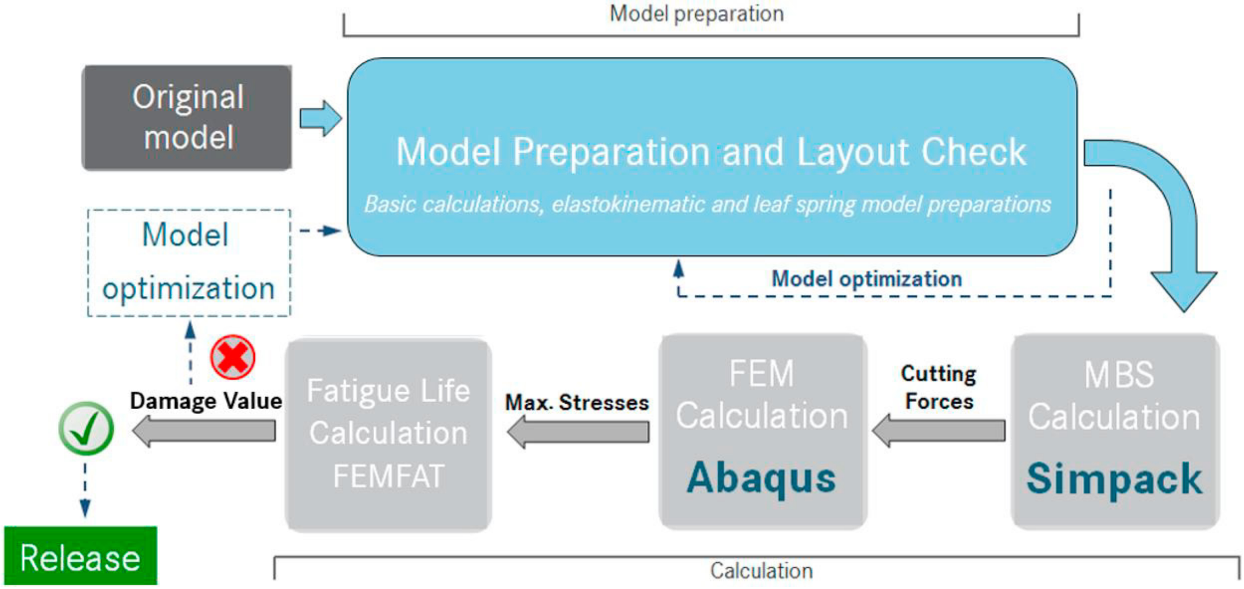

Fig. 4. Flow of the simulation steps

2.3.1. Model Preparation and Layout Check

The aim of this step is to check the stiffness value with a simplified finite element model. More importantly another purpose of this step is to prepare a leaf spring model which is to be used in the subsequent multi body simulations (MBS).

BLAFES [7] is a FORTRAN based in-house developed software for dimensioning and calculation of leaf springs based on mathematical calculations. The main aim of this software is to have a rapid calculation of the stiffness of the leaf spring and to have an overview of thickness profile under vertical loading.

Using the loaded geometry data of the leaf spring, the finite element model is created with a number of bar elements in Medina [8] along the length of the leaves (see Fig. 5). The characteristics of each leaf are defined in MakSim which is an in-house software to create Abaqus input files to define section properties according to section dimensions of leaf spring. This final model is calculated with Abaqus [9] in which a vertical loading is applied. The stiffness value is once more checked in this point.

After the result of the elastokinematic model is verified, the model is converted into a data which can also be imported and used in MBS. As a final step of the elastokinematic part, the model is delivered to the MBS.

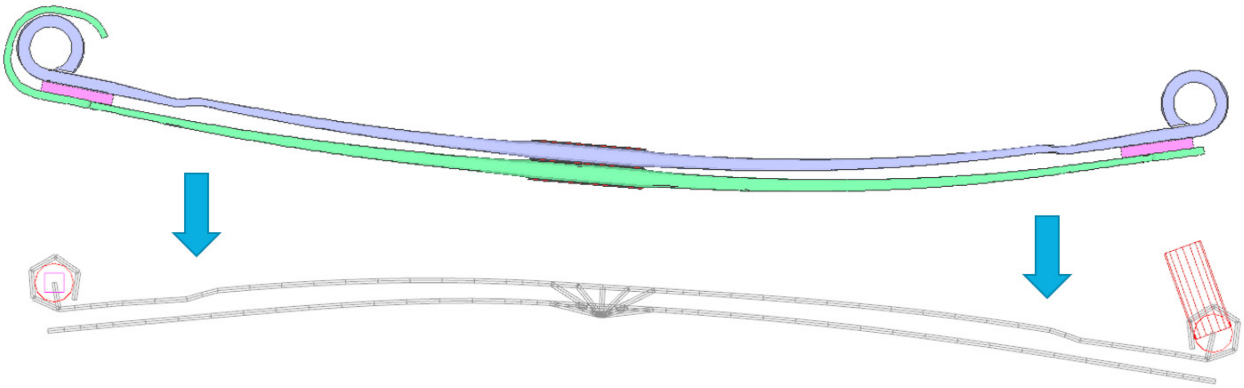

Fig. 5. Overview of an elastokinematic model

2.3.2. Multi Body Simulations (MBS)

MBS is performed to prepare the loading input for the finite element analysis (FEM). The multibody simulation model of the suspension system is prepared depending on the cad geometry of axle, leaf spring and other components. For this study, only the suspension system model of front axle is modeled as the focus is the leaf springs in the front axle system which can be seen in the figure 6.

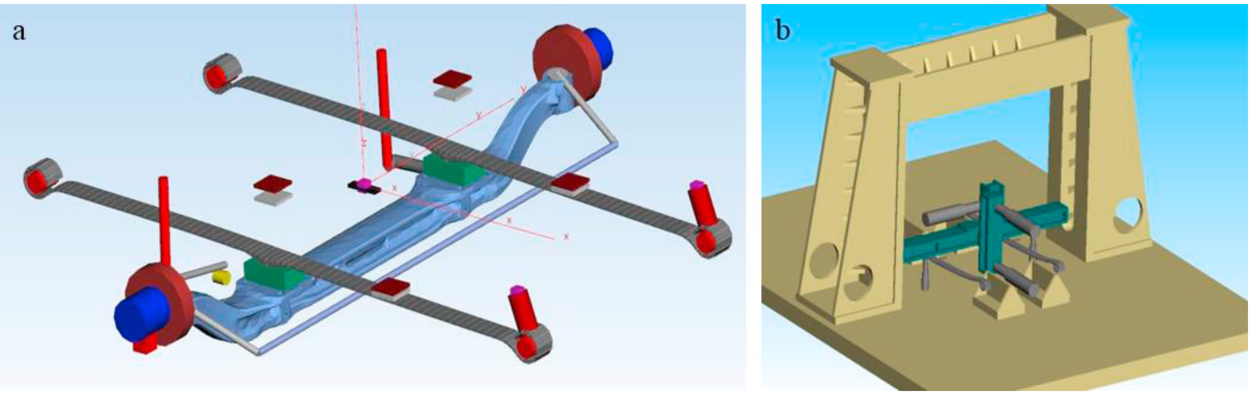

Fig. 6. (a) Front axle multi body simulation model; (b) Virtual test rig

One other methodology for MBS model build up is to build a virtual test rig in figure 6. MBS model of the fatigue test bench (virtual test rig) is also generated to evaluate time dependent forces and moments acting on the leaf spring. Thereby, damage calculations based on accelerated fatigue test signals could be realized. In the virtual test rig, the cylinders are excited with displacement values taken from testing. In order to validate, the reaction forces of each cylinder in MBS model are compared with the forces applied in the test bench.

The validation of the MBS model is also shown as measurements and calculation results in figure 7. The MBS model; which is excited with the wheel force collected from the test, is validated by comparing the displacement and acceleration outputs with the data collected from the same test. As it can be observed from the figure 7, very close results are achieved from the measured and calculated deflections.

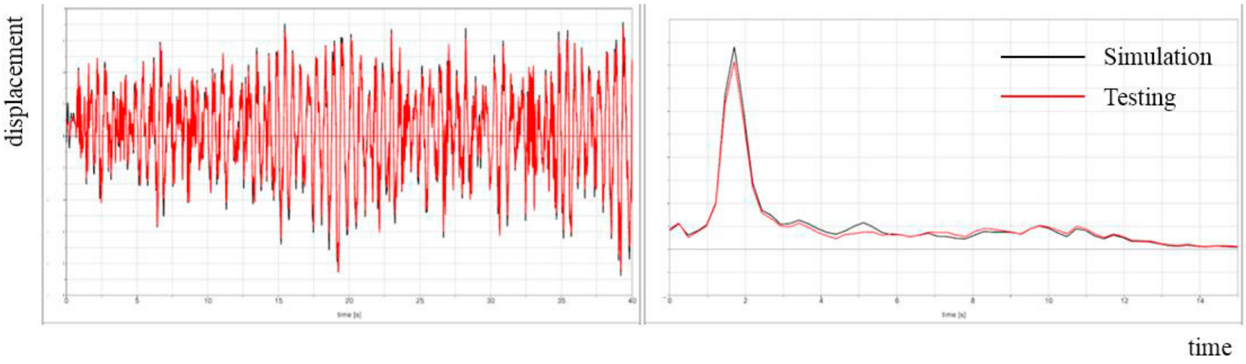

Fig. 7. Correlation of the MBS model

After the validation of the multibody simulation model, the forces and moments on the wheel hub from the rough road testing is applied to take out the forces and moments directly acting on the leaf spring. These forces and moments on the leaf spring are applied as the input data in the finite element simulations. Furthermore, the history of load spectra is coupled with the FEM results in order to perform a fatigue life analysis.

2.3.3. Finite Element Simulations

Leaf spring is modelled with solid elements in Medina (see Fig. 8). Unloaded spring geometry is used for the FEM analyses. The loads from the MBS are applied to the model and the stress results are evaluated. First comparisons are made with the stress results. Mostly, the time point in which the max vertical deformation occurs, is the comparison loading case.

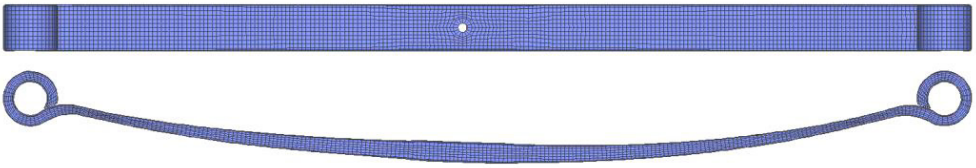

Figure 8. Unloaded leaf spring finite element model

After the stress comparison, FEM analysis are also used as an input for fatigue life calculations. Maximum forces and moments of time histories in each direction should be applied as unit load to have necessary input data for channel-max FEMFAT [10] calculations.

2.3.4. Fatigue life analysis

Stress results are not always enough to make a decision that confirms the sufficient durability characteristics of the new design. As the final step of the analysis, fatigue life calculation is performed on both leaf springs (the original and the new design). From the modeling side, same models which are used for FE-Analysis are also used for FEMFAT calculations.

Channel-max calculation type is selected in FEMFAT for multi-channel fatigue life calculation based on static superposition approach [11]. Clamping areas including the bolting holes are excluded from the fatigue life calculation evaluations. Six channels (see Fig. 9) are defined as inputs. Force-time histories, which are calculated in the preceding MBS calculations, are used as input values in each corresponding channel together with the stress results for the maximum values of the forces or moments in the time history [11].

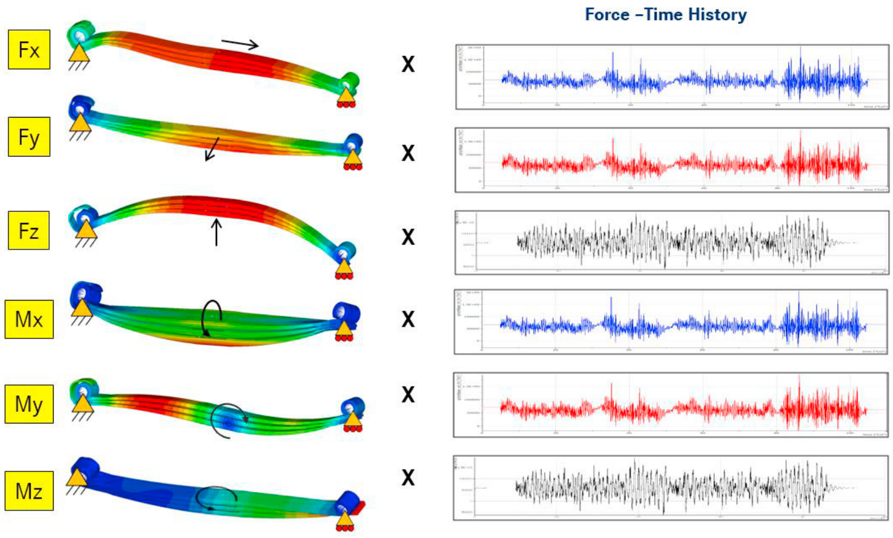

Fig. 9. Six sample channels for multi-channel fatigue life calculation

Six force-time history tables are taken from MBS. Each force-time history input is coupled and superposed with the corresponding stress results so that the stress time histories are calculated. Using these stress time histories, a fatigue life analysis with static superposition is then performed by calculating the cumulative fatigue damage according to the relative Palmgren-Miner rule (modified by Haibach) [1, 2, and 3]. That means, for each force and moment directions, 6 separate load cases with unit loads should be analysed in the previous finite element calculations. These results should be used as input in each corresponding channel separately in channel-max calculations (superposition of the individual stress components at every point in time) [11].

3. Correlation of a sample leaf spring

As a first step of the correlation study, this leaf spring is mounted to a vehicle which will run the rough road testing track for the concerning measurements. For this case, the forces and moments are collected from the wheel force transducers. In this way, the load spectra is created to run on the test bench depending on these rough road measurements.

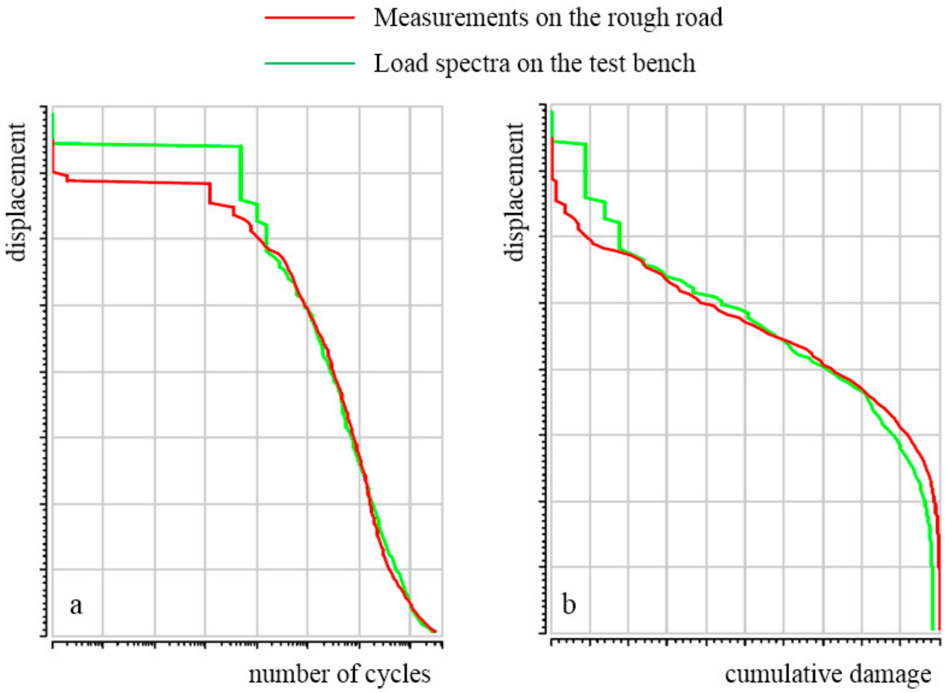

Fig. 10. (a) Cycle count of the strain gauges; (b) Damage comparison

As it can be seen in the figure 10, load spectra is applied in the test bench depending on the measurements on the rough road. Track a, which has mostly vertical loading through it, has the greatest effect on damage values. Track b, which has mostly braking moments through it, is also kept in the correlation study because it causes high stress values on the leaf spring.

Fatigue life analysis is performed with both loading conditions. First case is; signal from track a is applied to the MBS front axle model and the load spectra is reached. With this load spectra, FE-analyses are performed to find out the stress values. Damage values are calculated on the leaf spring depending on these stress values and time histories from MBS. In the second case, signal from track a is applied to the MBS virtual test rig and the load spectra is reached. With this load spectra, FE-analyses are performed to find out the stress values. Damage values are calculated on the leaf spring depending on these stress values and time histories form MBS.

FE-simulations are performed depending on the inputs from MBS. First validation is done by comparing the strain results from the testing and simulation. As explained in the rough road testing and test bench section, the strain values are measured with strain gauges. In this way, it is possible to compare the stress and strain values between the test and simulations like in figure 11 which is mostly matching each other.

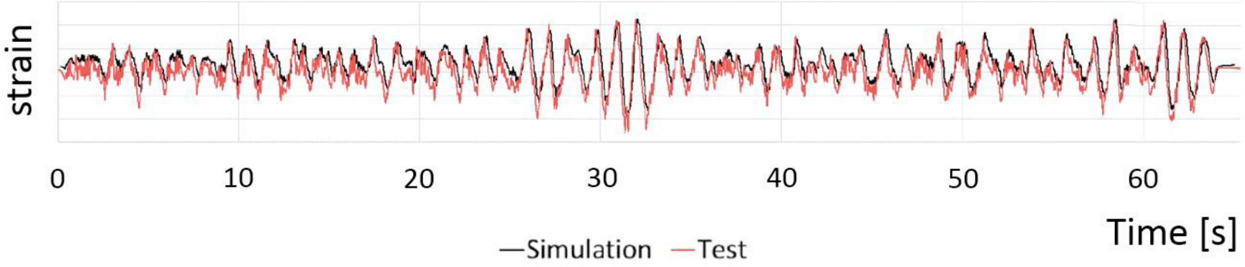

Fig. 11. Stress/Strain comparison between simulation and testing (sample point)

As a result of these simulation and test process, damage results are compared, which can also be seen in figure 12. Maximum damage locations and distribution of the damage through the leaf spring are matching in both simulations. This phenomenon clarifies that the accelerated test bench program depending on the rough road measurements, which has been created to run the test bench, is correlating with the measurements and the load spectra of the rough road testing.

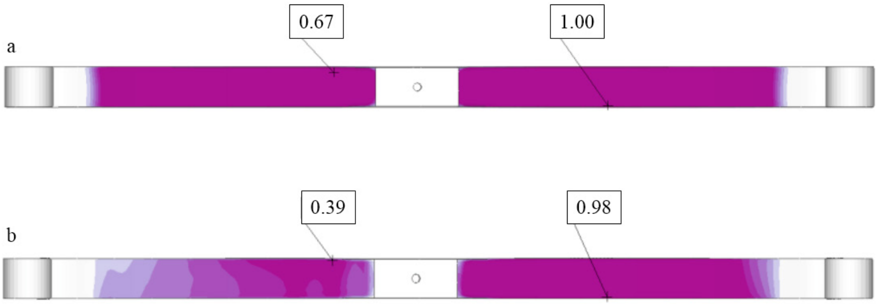

Fig. 12. Damage comparison in the simulation; (a) Rough road input; (b) Test bench input

4. Conclusion

The aim of this study is to explain how the correlation between the following three methodologies is done; simulation, test bench and rough road testing in terms of strength and fatigue life of a leaf spring. The paper also includes the process of validation and the explanation of each discipline in detail. The following statements can be concluded from this study:

- Rough road testing of the vehicle is performed, in order to measure the forces and moments acting on the wheel hub. This step is also necessary to obtain the load spectra of the leaf spring in the vehicle testing for test bench.
- Test bench measurements are executed with accelerated load spectra, in order to measure the strain values from the strain gauges which are mounted on the leaf spring.
- MBS models are prepared. These include both axle and test rig models which are both used for the load spectra evaluation for the FE-analyses.
- FE-analysis is performed, in order to get the stress results on the spring and also to prepare the unit load results for fatigue life calculations.
- Fatigue life analysis is executed, in order to reach the damage values depending on the FE-analysis which are performed with the MBS input.

- By comparing all these disciplines, the correlation of simulation, test bench and rough road testing can be accomplished.

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References

[1] Sonsino, C.M., ”Fatigue Testing Under Variable Loading”, Int. Journal of Fatigue 29, 1080-1089, 2007

[2] Sonsino, C.M., “Principles of Variable Amplitude Fatigue Design and Testing”, In: Fatigue Testing and Analysis under Variable Amplitude Loading Conditions, ASTM STP 1439, 3-23, 2005, doi: 10.1520/STP11294S

[3] Haibach, E., “Betriebsfestigkeit: Verfahren und Daten zur Bauteilberechnung“, 3. Edition Springer Verlag Berlin Heidelberg New York, 2006

[4] Oezmen, B, Altiok, B, Guzel, A, Kocyigit, I, Atamer, S “A novel methodology with testing and simulation for the durability of leaf springs based on measured load collectives” doi: 10.1016/j.proeng.2015.02.044

[5] LMS TecWare, User’s Manual, LMS International, Belgium,

[6] DIAdem, User’s Manual, National Instruments, USA, 2012

[7] BLAFES, Version 1.6, User’s Manual, Jurgen Fischer - Technische Beratung,

[8] Medina, Version 8.3.2, User’s Manual, T-Systems, Germany, 2013

[9] Abaqus, Version 6.14, User’s Manual, Dassault Systémes Simulia Corp., Providence, RI.

[10] FEMFAT, Version 5.1, User’s Manual, Engineering Center Steyr, Austria, 2014

[11] Bakir, M., Siktas, M., and Atamer, S., "Comprehensive Durability Assessment of Leaf Springs with CAE Methods," SAE Technical Paper 2014-01-2297, 2014, doi: 10.4271/2014-01-2297.