Strength and Fatigue Life Analysis of Leaf Springs used in Heavy Duty Trucks

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Abstract: *A noticeable number of weight and cost reduction projects are performed with the help of highly improved computer aided engineering (CAE) tools within the vehicle engineering development activities. In this paper, a complete optimization study is applied to a leaf spring with 5 leaves used in the rear axle suspension systems of 6x4 heavy duty trucks by reducing the number of leaves down to 4 together with weight and cost reductions.*

A brief overview of the project is as follows; the stiffness of the leaf spring is calculated with in-house software based on mathematical calculations using the thickness profile of the leaves. Then the results of these calculations are compared with non-linear elastic leaf spring calculations which are conducted with Abaqus. This elastic leaf spring finite element (FE) model is transferred into multi body simulation (MBS) model, which is established with Simpack, in order to determine the forces acting on the leaf spring. Using the results of the MBS calculations, which are time histories of the internal forces and moments on the leaf spring, the FE simulations are performed with Abaqus. Stress results are not always enough to conclude that the leaf spring will preserve its integrity until the desired lifetime although they may give a rough estimation. Concurrently, without fatigue life analysis it is not correct to make a final decision. Therefore, as the final step of the project, a multi-channel fatigue life calculation process is performed to assess the durability characteristics of the new design, showing that the weight and cost reduction is achievable without worsening the fatigue life of the leaf spring.

Keywords: *Damage, Dynamics, Elasticity, Fatigue Life Analysis, Finite Element Analysis, Multi-Body Dynamics, Optimization, Suspension.*

1. Introduction

Multiaxial loads are acting on the leaf spring assembly in a truck structure and therefore it has great influence on the drivability of the truck. Because of this reason, the new design with reduced number of leaves (Figure 1) should withstand all forces like the current design assuring same strength and fatigue characteristics. In other words, it should be lower in cost and weight but at the same time the new leaf spring assembly should, however, meet durability requirements. This fact brings great responsibility to the development process of the new designed leaf springs. Hence, a complete optimization process [11] is applied for the entire design cycle, the results of which are described in this paper.

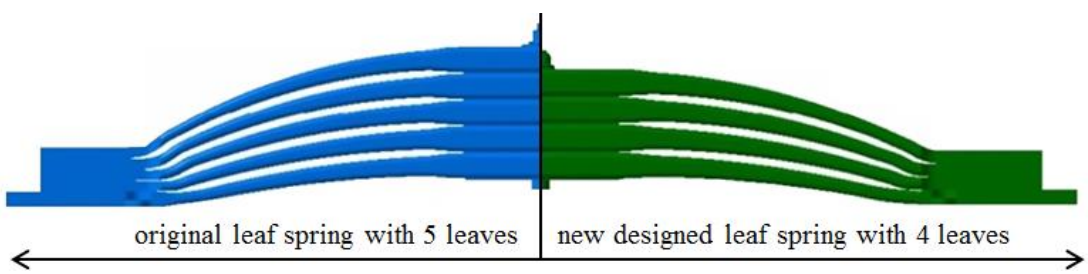

Figure 1. General overview of both leaf springs

2. Calculation Steps

Rather than a typical calculation process based on static finite element analysis, this study has a distinctive point of view on the durability assessment of a leaf spring because various calculation methodologies are applied for a comprehensive calculation process. All steps in Figure 2 are necessary for the optimization process of the leaf spring. They are to be explained within the following sections.

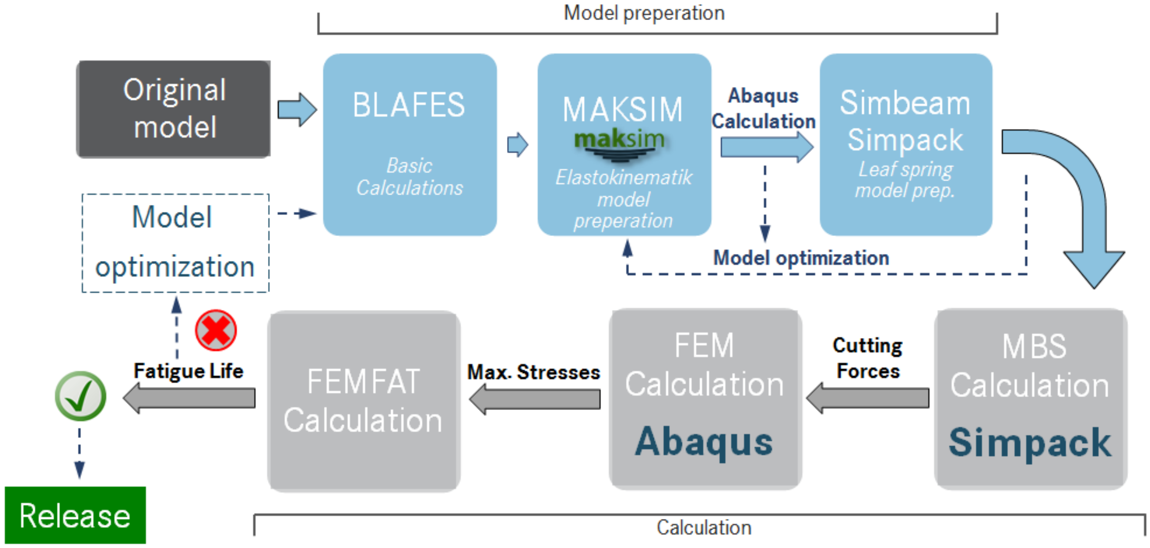

Figure 2. Flow of the Calculation Steps

2.1. Basic Checks with BLAFES

BLAFES [1] 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 under vertical loading. Additionally a general overview of the stress results is also achieved. Having the stiffness values and the general overview of the stress results available in hand at the first step, is very important to make the first assessment within the design phase. This prevents time loss from the beginning. Therefore, this significant first step is helpful in order to reach a feasible design to implement within the following steps of the calculation flow. The new design should have expected stiffness values like the currently used original leaf spring. Hence, a similar or a predictable safety, comfort and dynamic vehicle behaviors are accomplished.

The reference stiffness value of the original leaf spring, which is the one from the producer, is 3636.3 [N/mm]. The stiffness value calculated by BLAFES is shown in Figure 3 and found as 3595.7 [N/mm] (Equation 1). The results indicate that the stiffness values from the producer and from the simulation of the leaf spring are matching each other. The comparison here is done in order to see how much difference there is between the simulation value and the producer's value. After the comparison, it is found that there is only 1 % difference between the stiffness values, which indicates that the model verification is fulfilled. Having the basic stiffness check accomplished, it is decided to continue with further steps through the calculation flow shown in Figure 2.

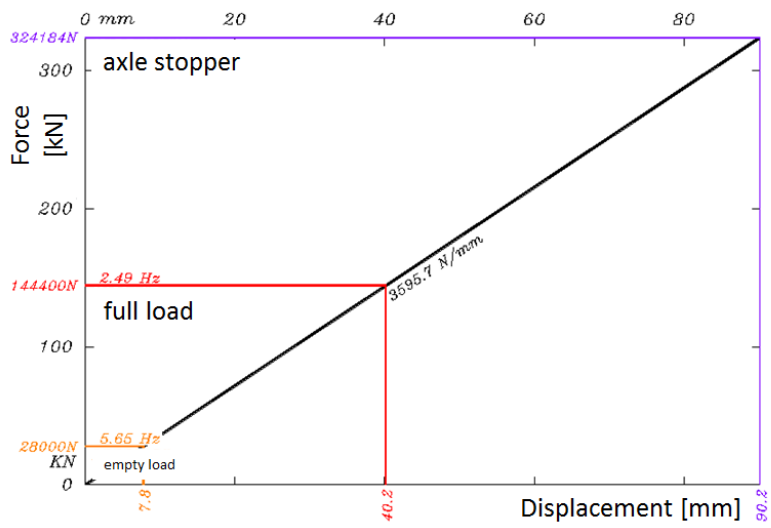

Figure 3. Stiffness results of the original leaf spring

$$k_{original} = \frac{144400[N]}{40.16[mm]} \cong 3595.7\left[\frac{N}{mm}\right] \quad (1)$$

The stiffness value of the new designed leaf spring calculated with BLAFES is shown in Figure 4 and found as 3882.4 [N/mm] (Equation 2). In comparison to the one of the original leaf spring, it can be observed that there is approximately 8 % increase in the stiffness value which is already expected and considered to be within the required tolerances. A similar stiffness comparison method is also done both in elastokinematic and FE-calculations in the next steps.

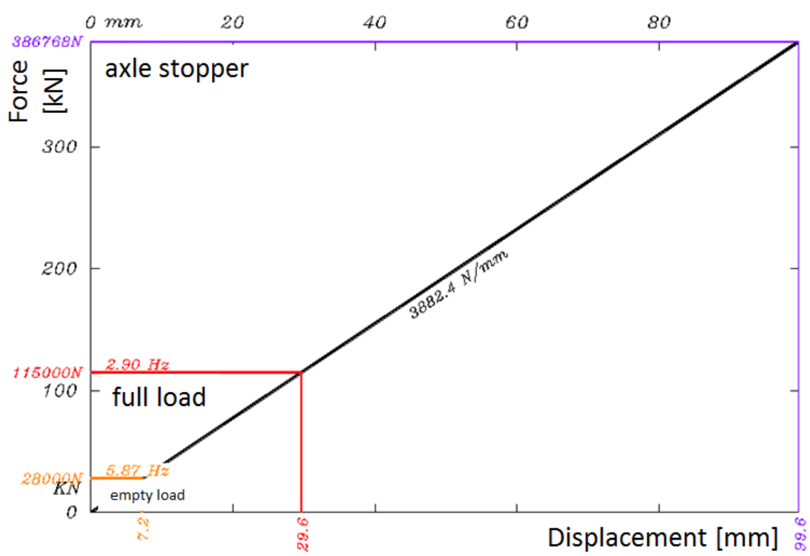

Figure 4. Stiffness results of the new designed leaf spring

$$k_{new\_designed} = \frac{115000[N]}{29.62[mm]} \cong 3882.4\left[\frac{N}{mm}\right] \quad (2)$$

2.2. Elastokinematic Calculations

The aim of this step is to make another check of 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).

Using the unloaded geometry data of the leaf spring, the finite element model is created with a number of bar elements in Medina [2] along the length of the leaves. The characteristics of each leaf are defined in MakSim (patent applied for) which is an in-house software to create Abaqus input files to define section properties according to section dimensions of leaf spring.

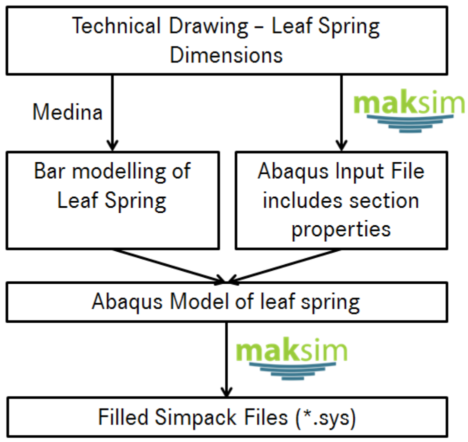

Figure 5. MakSim's tasks during simulation process

This final model is calculated with Abaqus [4] in which a vertical loading is applied. The stiffness value is once more checked in this point. There is nearly 8 % of stiffness increase of the new designed leaf spring in compare to the original one according to elastokinematic calculation results which is very close to the comparison based on BLAFES results.

After the result of the elastokinematic model (Figure 6) 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.

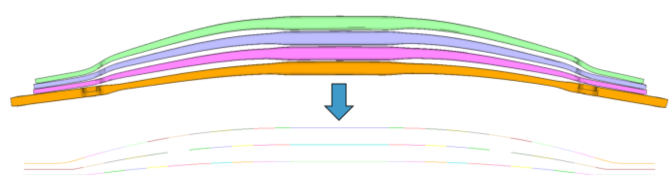

Figure 6. Overview of an elastokinematic model

2.3. MBS Calculations

The aim of this calculation step is to build up an accurate multi body simulation model and to calculate the load collective on the leaf spring.

First, wheel forces are measured from a test vehicle at the torture track using wheel force transducers (Figure 7). Torture tracks are circuits of various sizes, skid pans, bad road surfaces etc. The advantage of torture track testing is to shorten the total durability testing time. There is also digitalized road data which is the measured road profile of these tracks. With a torture track calculation, this road data is applied to the full vehicle simulation model and a dynamic simulation of the ride of the vehicle on this track is performed.

For each wheel 6 channels are measured (Forces in x, y, z directions and moments in x, y, z directions). Spring deflections and accelerations are also measured from the vehicle in order to compare the MBS model. The measured forces and the moments are applied to MBS model as input values.

Figure 7. Wheel force measurements

Secondly, the multibody simulation model is prepared. At this part, only the rear axle model is modeled as the focus is the leaf springs in the rear axle system. Axles, suspensions, leaf springs, longitudinal control arms, triangular control arms, anti-roll bar are modelled including all non-linear characteristics of these elements within the MBS model of the rear axle in SIMPACK [3] (Figure 8).

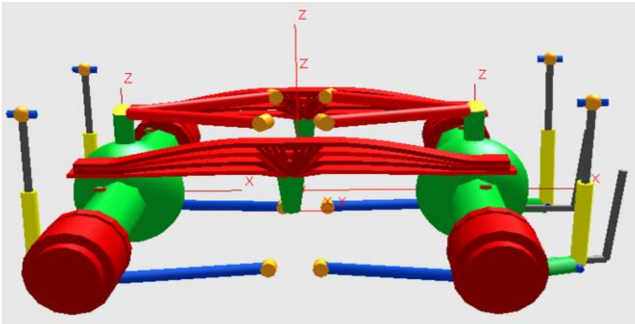

Figure 8. Rear axle multi body simulation model

The comparison of the MBS model is also shown as measurements and calculation results (Figure 9). Spring deflection and acceleration data, which are also measured during wheel force measurements, are used to compare the calculated spring deflection and accelerations. As it can be observed from the Figure 9, very close results are achieved from the measured and calculated spring deflections.

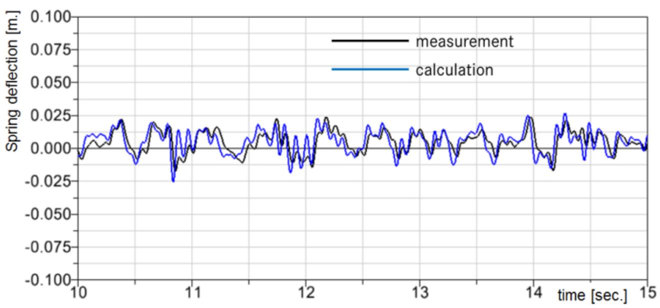

Figure 9. Comparison between measured and calculated spring deflections

After the MBS model comparison, the measured wheel forces are applied to MBS model and torture track calculation is performed. Two separate MBS models are built, one of which contains the original design of the leaf spring with 5 leaves whereas the other one includes the new design with 4 leaves. Calculations with both MBS models are performed in which the load collectives on the leaf springs are calculated as time histories of the internal forces (cutting forces) and moments acting on the leaf springs. In addition, level crossing and range pair counting evaluations of the calculated forces are conducted.

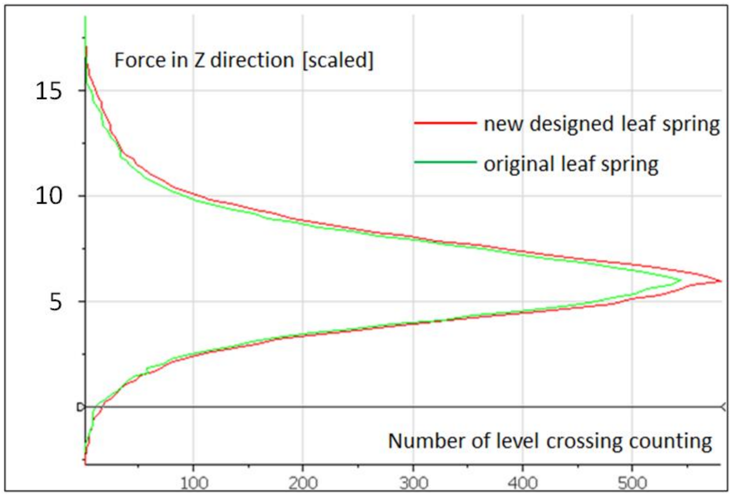

Figure 10. Level crossing counting of two leaf springs (Force in Z direction)

Figure 10 shows the results of level crossing counting of the forces acting on the front connection point of each spring in vertical direction. The results indicate that the forces acting of the new designed leaf spring has a more intensive level crossing distribution than the forces acting on the original one.

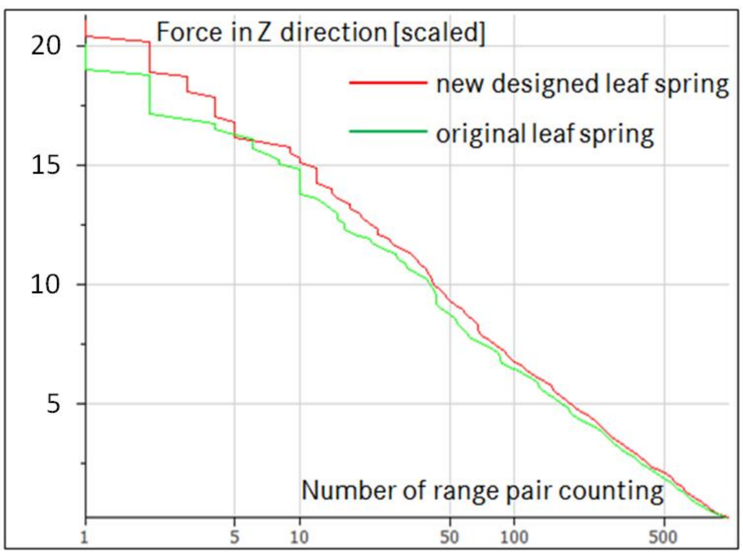

Figure 11. Range-pair counting of two leaf springs (Force in Z direction)

Figure 11 shows the range pair counting of the forces acting on the front connection point of each spring in vertical direction. The results here also indicate that the forces acting of the new designed leaf spring has a more intensive range pair distribution than the forces acting on the original one, which shows clearly that the new designed leaf spring undergoes a heavier loading. The calculated time histories of the internal forces and moments on the leaf springs are used within the further analysis steps the calculation process.

2.4. FEM Calculations

Unloaded leaf spring geometry is used for finite element modeling in Medina. Clamping plate and the U-bolts are also modeled and mounted on the leaf spring model in order to reach more accurate results. HEXA elements are used to model the leaves of the spring and for the sandwich plates between the leaves. TETRA elements are used to model the clamping plate and the U-bolts. The original leaf spring model with 5 leaves has 170731 nodes and 121647 elements and the new designed leaf spring with 4 leaves has 134899 nodes and 93623 elements. Same material is used for both leaf springs and that means the differences are purely geometric. Figure 12 shows a general view of the calculation model. The calculations are performed with Abaqus approximately in 2 hours with 8 processors at 2.93 GHz.

Figure 12. Unloaded original leaf spring finite element model

Contacts between the leaves are defined and boundary conditions are also applied in the model. The definition of the contacts and boundary conditions is essential to have a base model to work on; however, applying the load cases has also a great importance to reach accurate results. One other reason for the importance of the load cases is that the same finite element model is also used for the subsequent fatigue life calculation step with FEMFAT [5] using the stress results which are calculated in Abaqus and the internal forces and moments coming from MBS. A deformed shape of the leaf spring assembly, at one of the critical time points with high vertical loading, can be seen in Figure 13.

Figure 13. Deformed shape of the leaf spring assembly

As a first step of the analysis, pre-tension forces are applied to each U-bolt for clamping. After assuring that the pre-tension works correctly in the simulation, next step is to apply the forces and moments acting on the leaf spring. For the calculations and comparison based on stress values, the applied forces and moments are selected from the complete time histories from MBS. For this purpose, the values of the forces and moments at the time point, at which the maximum vertical force is observed, are used. The forces are applied on both fixing sides of the spring. Simulations are performed by Abaqus. Pre- and post- processing is done with Medina. One outcome from the FE-simulations is stiffness results. There is roughly 7 % stiffness increase of the new designed leaf spring in compare to the original one matching very well with the previous BLAFES and elastokinematic calculations results. Another outcome is the stress results. Therefore, principal stress results (first and the last leaf in detail) are shown in Figure 14. The stress and the damage values within the figures throughout the paper are scaled to the maximum value in the corresponding figure showing the maximum as 1.00 and the others scaled in percentage (%) values in relation to the maximum.

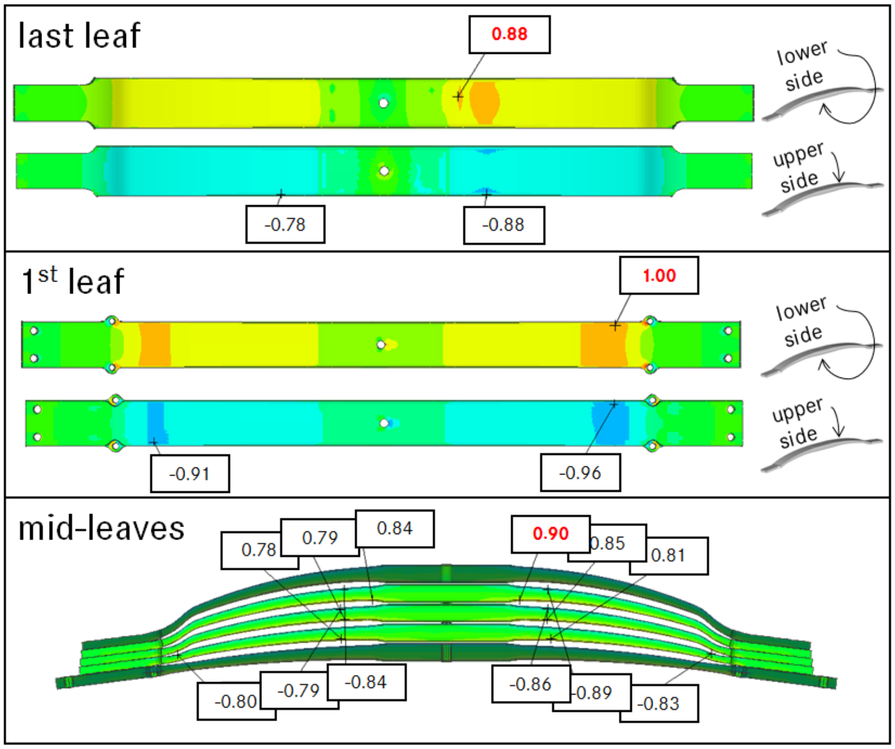

Figure 14. Principal stresses on the original leaf spring

In Figure 15, a comparison of the original and the new designed leaf spring is shown. It can easily be observed that, although there is an increase in forces and moments coming from MBS for the new designed leaf spring, the stresses are decreasing in all leaves of the new design. This is a result of the optimized design with higher thickness distribution; however, a fatigue life calculation step should be performed to have an accurate conclusion regarding the durability characteristics of the new designed leaf spring.

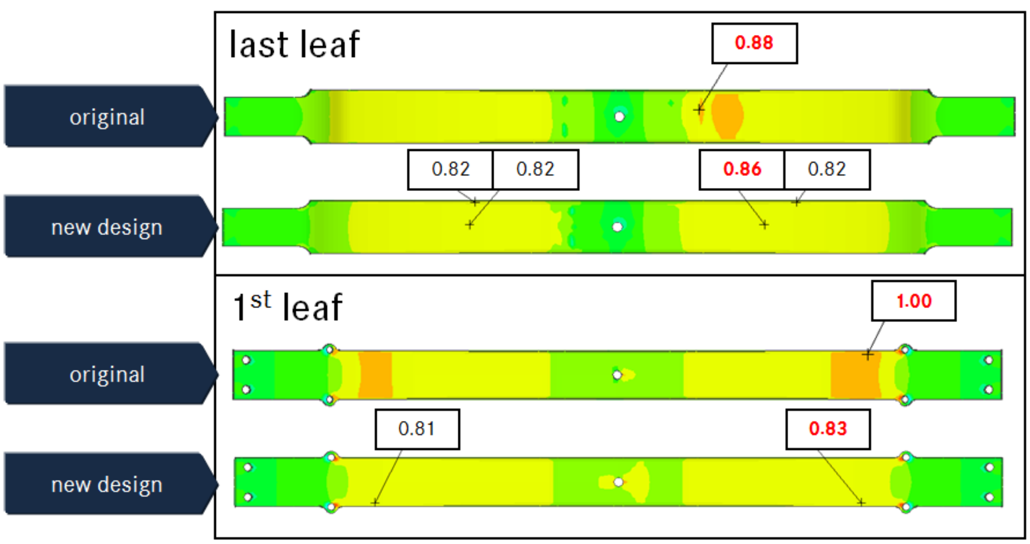

Figure 15. Comparison of the principal stresses of the leaf springs

Preparation for fatigue life calculation is also done within the FE-calculation step. In order to obtain a comparison of the maximum stresses, the time step with maximum forces and moments in vertical direction is applied to the model and the results are shown Figure 15. However for the fatigue life calculations, maximum forces and moments of time histories in each direction should be applied to have necessary input data for channel-max FEMFAT calculations.

2.5. FEMFAT Calculations

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 [5, 6, 7]. Clamping areas including the bolting holes are excluded from the fatigue life calculation evaluations. 12 channels (Figure 16) 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.

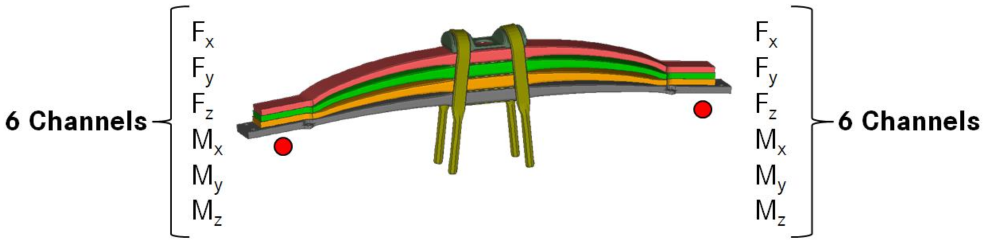

Figure 16. FEMFAT channel-max model

12 force-time history tables are taken from MBS. One example is shown in Figure 17. 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) [8, 9, 10]. That means, for each force and moment directions, 12 separate load cases with unit loads should be analyzed 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) [4].

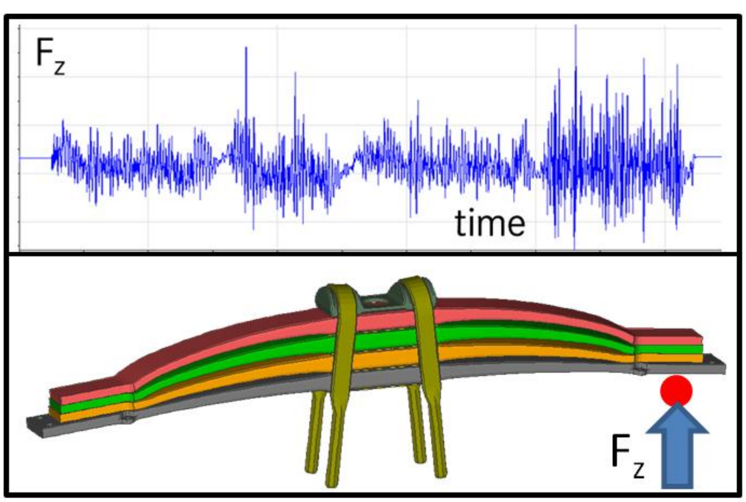

Figure 17. Sample of a force-time history in Fz

As it is already explained within the previous sections of this paper, the main reason which makes the results of this particular fatigue life calculation important is; although the stresses on the new design is lower than the original spring, the range pair calculations show that higher forces are acting on the new design (Figure 11). Therefore, the comparison of the damage values plays an incredibly essential role on the accurate assessment of the durability characteristics of the spring. Hence, the results for each leaf of both original and new leaf spring are illustrated in a comparison which has both stress and damage values in Figure 18 and 19.

In case of the original design, both the spots and the order of the maximum stress and damage values are similar, and the most critical point is observed on the 1st (first or the lowest) leaf (Figure 18).

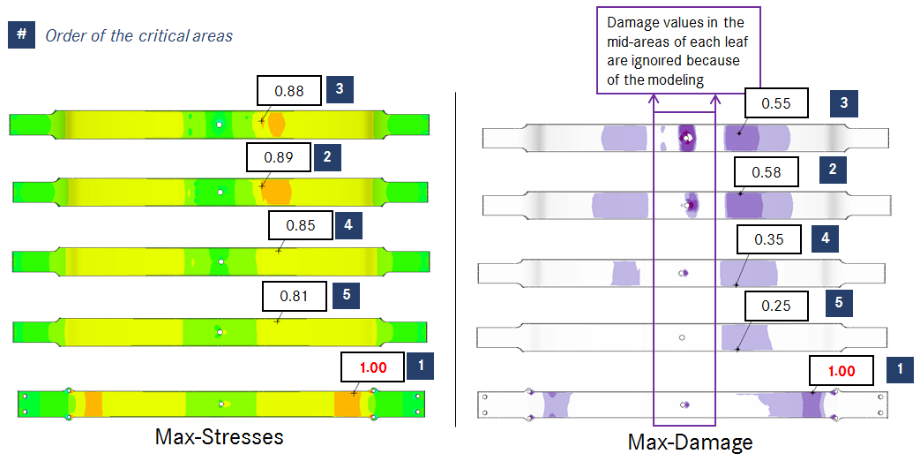

Figure 18. Comparison – original design

The spots with the maximum stress values and maximum damage values are matching each other in general for the new designed leaf spring (Figure 19). However, the order of the maximum stress values and maximum damage values are different (Figure 19). It can be seen that, based on the stress results the most critical point by far is observed on the 3rd leaf (counting from bottom upwards), whereas the damage results indicate that the maximum damage value is reached on the last (4th or the uppermost) leaf. A comparison based on the maximum stress values of the original and new designed leaf spring would lead to an outcome indicating the new design is superior as the maximum stress value on the new design is significantly lower than the one on the original design. Without a fatigue life calculation, such a reduction in the maximum stresses would be interpreted as a great improvement of the durability characteristics. However, the results of the fatigue life calculations draw a completely different conclusion. The maximum damage values observed on the original and the new leaf spring is quite close to each other, meaning that the fatigue life of both leaf springs is expected to be very similar. The results show that, with the new designed leaf spring with reduced number of leaves, the aimed weight and cost reduction can be achieved without worsening the durability characteristics.

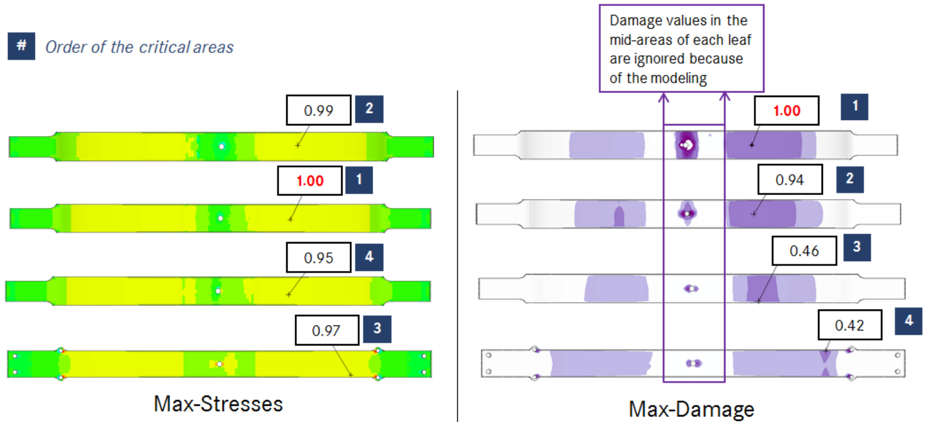

Figure 19. Comparison – new design

The results obtained in this study shows clearly that the stress results do not always represent the durability characteristics of such a component like leaf springs working under highly variable loading conditions. For a comprehensive durability assessment, a multi-channel fatigue life calculation should be performed.

3. Summary/Conclusions

The aim of this paper is to present a methodology for a comprehensive durability assessment of leaf springs with CAE methods, illustrated with a case study in which a new designed cost and weight optimized spring with reduced number of leaves can withstand the forces coming to it and preserve its integrity like the original one. The following statements can be concluded from this project:

- Within the scope of this project, a specified calculation flow is followed in order to reach an accurate comparison between the original and new designed leaf spring.
- After the stiffness and stress results under vertical loading of the leaf spring is calculated with in-house software (BLAFES) based on mathematical calculations, elastokinematic analysis is performed to compare the stiffness values and to prepare a base model for MBS.
- Two separate MBS models are prepared both for the original and new designed leaf spring. The internal forces and moments on the leaf springs are calculated based on the wheel force measurements from a test vehicle at the torture track.
- FEM calculations with Abaqus show that, compared to the original design the maximum stresses on the new designed leaf spring decreases up to 20 %.
- Fatigue life calculations with FEMFAT show on the other hand similar damage results on both original and new designed leaf springs, which means, comparable fatigue life values are to be expected.
- The results show that with the new designed leaf spring with reduced number of leaves the aimed weight and cost reduction can be achieved without worsening the durability characteristics.
- For a comprehensive durability assessment of leaf springs which work under highly variable loading conditions, a multi-channel fatigue life calculation should be performed.

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