



# Automobile Leaf Spring: An Overview

Sarbindu Kumar · A. K. Prasad · M. Prabhakar

Submitted: 19 July 2023 / in revised form: 18 March 2024 / Accepted: 29 March 2024 / Published online: 16 May 2024  
© ASM International 2024

**Abstract** In the present scenario, human safety is one of the most important parameters in design and manufacturing of a vehicle, which is the reason every organization is very keen in ensuring durability and reliability of automobile components. One such critical component in the vehicle is the suspension system consisting of leaf springs whose primary role is to absorb and store strain energy, which can be further released slowly during operation. This plays a vital role in ensuring both human safety and ride comfort. Also, it acts as a structural member to establish linkage between chassis frame and axle. In this paper, we would like to review the previous work done by researchers in the field of leaf spring design, FEM analysis, manufacturing process optimisation, durability testing and failure analysis, alternate material selection (both steel and composite) for weight and cost optimization. Detailed failure mode investigation on modes of failure and its causative factors like improper heat treatment, surface decarburization, hydrogen embrittlement, fretting fatigue and corrosion pitting is discussed. This review provides the improvement scope in current design and manufacturing processes, which will enhance the durability and avoid premature failure of leaf springs. The paper discusses about the additional life enhancement manufacturing processes such as shot peening, ausforming during heat treatment, lubrication improvement and corrosion prevention by using solid lubricants. These processes are proposed to be

considered at design stage itself to optimise the size and weight of suspension by reducing number of leaves for the same vehicle application.

**Keywords** FEM · Leaf spring · Design · Manufacturing · Testing · Failure analysis · Challenges · GVW

## Introduction

As per the Automotive Research Association of India (ARAI), vehicles are broadly classified into two category-M and N type. M category vehicle is used for carriage of passengers and N category vehicle is used for carriage of goods. N category vehicles are further categorised into three variety-N1, N2 and N3 which are explained in below Table 1.

N3 category vehicles are often called as medium and heavy commercial vehicles (M&HCV).

In the area of medium and heavy commercial vehicles, four categories of vehicles are identified depending on their application. These are Truck, Tipper, Tractor-Trailer, and Bus. Truck is used in highway applications for carrying industrial goods; Tipper is used for off road applications like mines, river bed, and stone crusher sites. Tractor-Trailer is used for long haulage application and bus is used for carrying passengers. The present study is focused on the leaf spring used in medium and heavy-duty trucks.

Leaf spring is an important component of automobile suspension system from durability point of view. During the entire operating cycle of storing the strain energy and releasing it, the stress in the spring should not be more than a certain maximum value in order to avoid premature

---

S. Kumar (✉) · A. K. Prasad  
Department of Mechanical Engineering, NIT Jamshedpur,  
Jamshedpur, India  
e-mail: sarbindu09@gmail.com

M. Prabhakar  
Tata Motors Ltd., Mumbai, India

**Table 1** Vehicle categorisation based on GVW

Vehicle category	Gross vehicle weight (GVW)
N1	Less than or equals to 3.5 Ton
N2	Greater than 3.5 Ton and less than or equals to 12 Ton
N3	Greater than 12 Ton

failure. Energy stored by spring is obtained by the area under the load-deflection diagram.

Leaf spring in heavy commercial vehicles is intended to perform many functions which are:

- Carry the vehicle self-weight and payload
- Provide adequate stability and rolling resistance
- Distribute driving and braking forces between brake and axles during vehicle acceleration or deceleration
- Take care of drive and torque windup
- Provide suitable ride comfort and cushioning effect
- Maintain proper steering caster angle in case of front suspension
- Maintain wheel alignment through caster adjustment
- Provide required articulation for tandem axles under different operating conditions

Automobile suspension system is intended to perform multiple functions as listed above and to perform those functions, few desirable characteristics are required in leaf spring which are:

- It should have good balance between deflection and stiffness to obtain both good ride qualities and stability
- It must be compatible with other vehicle components like axles, tyres, chassis frame wheelbase and track. It should have minimum weight to reduce overall kerb weight of vehicle and therefore allowing more payload capacity
- It should have low maintenance and operating costs so that overall cost of ownership for customer is less
- It should minimize tyre wear through proper wheel alignment
- It should maintain both front and rear chassis height so that vehicle ride and handling is maintained

Suspension requirements vary due to the wide variation in loading depending upon the gross vehicle weight capacity of vehicle and also on the type of application like highway or off-road application. As previously discussed, that most of heavy-duty vehicles are equipped with leaf spring type suspension, so next section will focus in some detail on leaf spring types and its applications.

## Types of Leaf Spring used in Heavy Commercial Vehicles

Till date, various designs of leaf spring have been developed which are- Semi-elliptic type, parabolic type, multistage type, Slipper type and Bogie type. All these designs have their own pros and cons. However, this section will only discuss about the modern leaf spring design used in heavy duty truck, tipper, tractor- trailer and buses.

### Semi Elliptical Multi Leaf Spring

This is single stage type leaf spring used in both front and rear suspension. Single stage multi leaf spring as shown in Fig. 1, is defined as those springs which is having constant stiffness in the entire deflection range. Multi leaf springs are used where maximum load is relatively limited and where sudden peak loads are not expected. Most tandem axle suspensions also use multi leaf springs as Bell crank arrangement in which leaf springs are linked together to balance load between two axles during road surface irregularities.

### Parabolic Leaf Spring

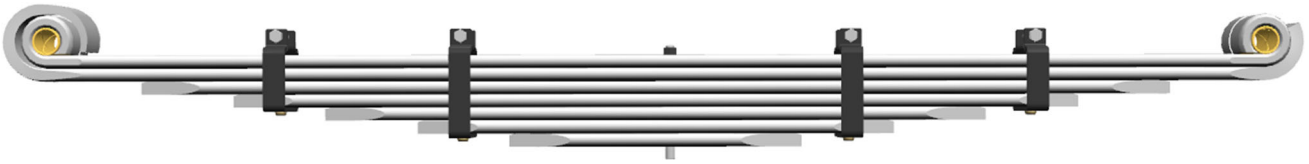
Parabolic spring as shown in Fig. 2, has constant width but each leaf is of variable thickness. It has less interleaf friction, better fatigue life, better resilience and better ride quality. This spring has an added advantage of weight reduction. This is used mostly in front suspension because of better ride and handling.

### Multi-Stage Leaf Spring

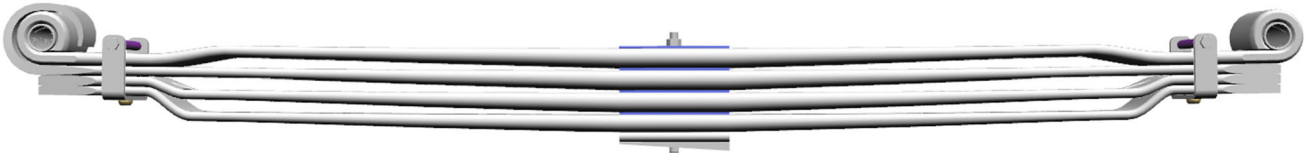
Multi-stage spring as shown in Fig. 3 is defined as those spring which provide variation in stiffness during its operating period. In this type of spring, auxiliary spring is fixed above the main spring. Usually, the auxiliary spring has flat ends and makes sliding contact with its stopper brackets. As the load increases, the auxiliary spring makes contact with its stopper bracket which provides sudden change in the stiffness. This type of springs is used where there is fluctuation in the application loads.

### Slipper Suspension

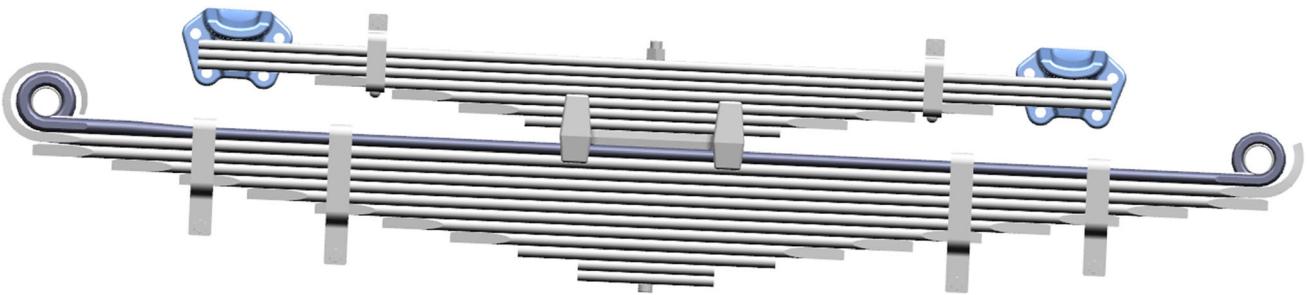
This is also called as “variable rate spring” which provides a variable stiffness because of the use of cam shaped stopper brackets (as shown in Fig. 4). Cam shaped bracket shifts the point of contact when it touches the flat ends of spring. This adjusts the effective length and stiffness of spring.



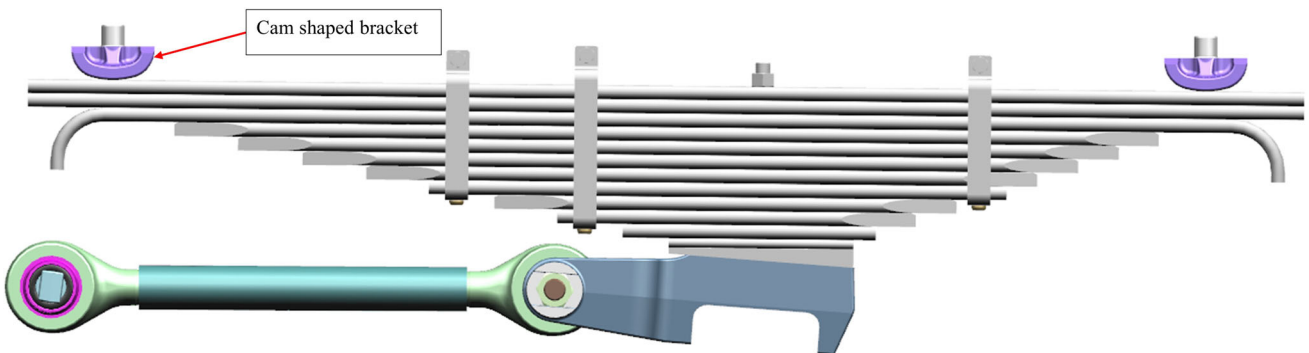
**Fig. 1** Multi leaf spring



**Fig. 2** Parabolic leaf spring



**Fig. 3** Multi-stage leaf spring



**Fig. 4** Slipper suspension

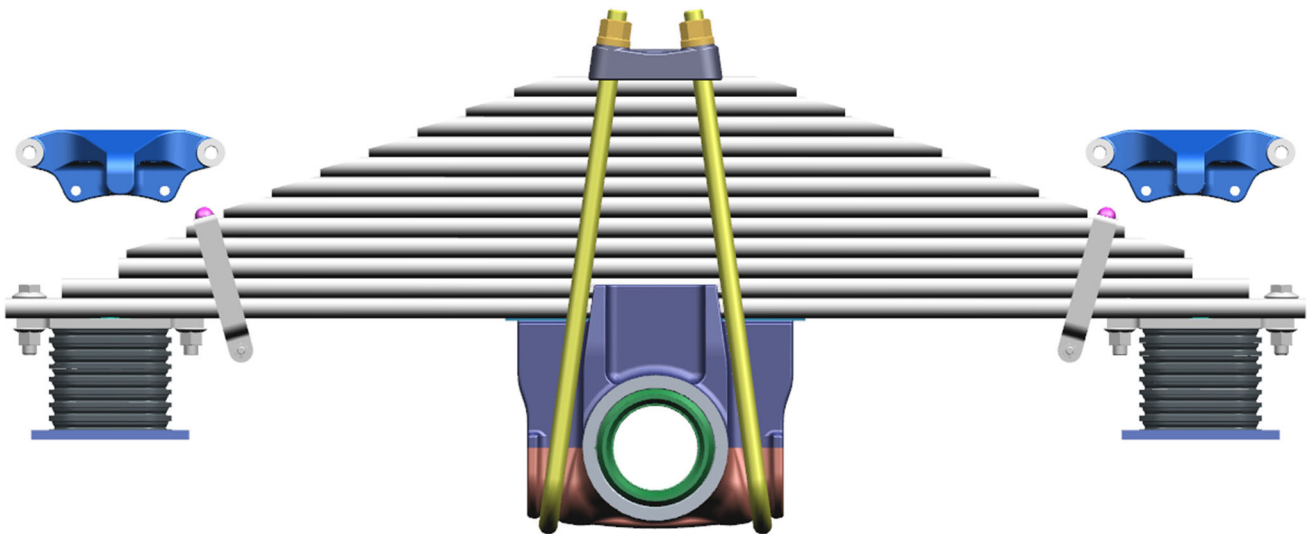
Like multi leaf spring, this is also used in rear suspension. As compared to Bell crank suspension using multi leaf spring, Slipper suspension offers multiple advantages which are:

- Weight reduction
- Low ownership cost because of decrease in greasing joints
- Improved tyre wear because asymmetrical arrangement helps to achieve optimal spacing between the axles

#### Bogie Suspension

This type of spring is relatively stiffer and allows less deflection which is achieved through thicker leaves mounted on axle with the help of bolster and stopper bracket on chassis frame. The leaves are flat at the ends as shown in Fig. 5. This reduces the effective length of the spring which subsequently increases the stiffness. This type of spring is used in rear suspension and provides unique features like:

- Better stability and rollover resistance because of the limited spring deflection



**Fig. 5** Bogie suspension

- Outstanding performance on and off road for tractor and tipper application
- Provides very high articulation and good traction on all wheels
- High rolling resistance and lower ride frequency with rubber bolsters
- High lateral load carrying capacity for cornering and low speed manoeuvres

**Table 2** Leaf spring design dashboard

Input parameters	Output parameters
Unladen front axle weight	Number of leaves to meet spring pack height
Unladen rear axle weight	Length of each leaf
Laden front axle weight (FAW)	Moment of inertia
Laden rear axle weight (RAW)	Stiffness of leaf spring
Chassis height requirement	Load Vs Deflection chart
Leaf spring span requirement	Weight of leaf spring
Material selection	Stress in each leaf
Width and thickness selection	Ride frequency and roll over stiffness

**Leaf Spring Design and Virtual Simulations**

SAE leaf spring design manual and Japanese Industrial Standard explains the detailed design guidelines for different type of leaf spring. Below Table 2 explains the design factors to be considered as input. Present leaf spring design methodology is explained in Fig. 6 with the highlighted box representing proposed modification to achieve better durability strength.

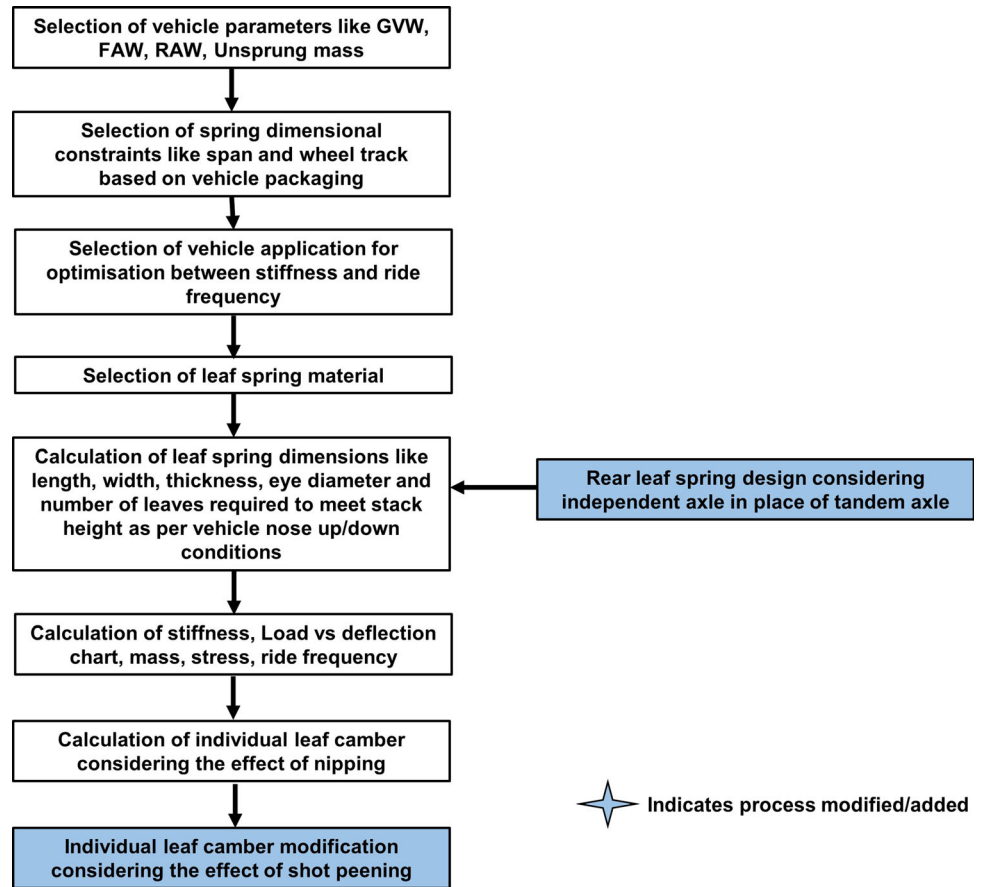
Finite element analysis (FEA) is one of the virtual simulation tools which is very powerful for modeling of complex geometries and irregular shapes in which discretisation can be easily achieved through different meshing technique depending on the geometry. This saves appreciable amount of time during design of a new product. Various researchers have worked on the FEA using different software’s like ANSYS, Hypermesh, Abaqus. Figure 7 depicts the finite element analysis steps used in the research so far for leaf spring.

Shamsaei and Rezaei [39] obtained fatigue life reliability for both steel and composite leaf spring material in longitudinal direction. Road condition input was prepared

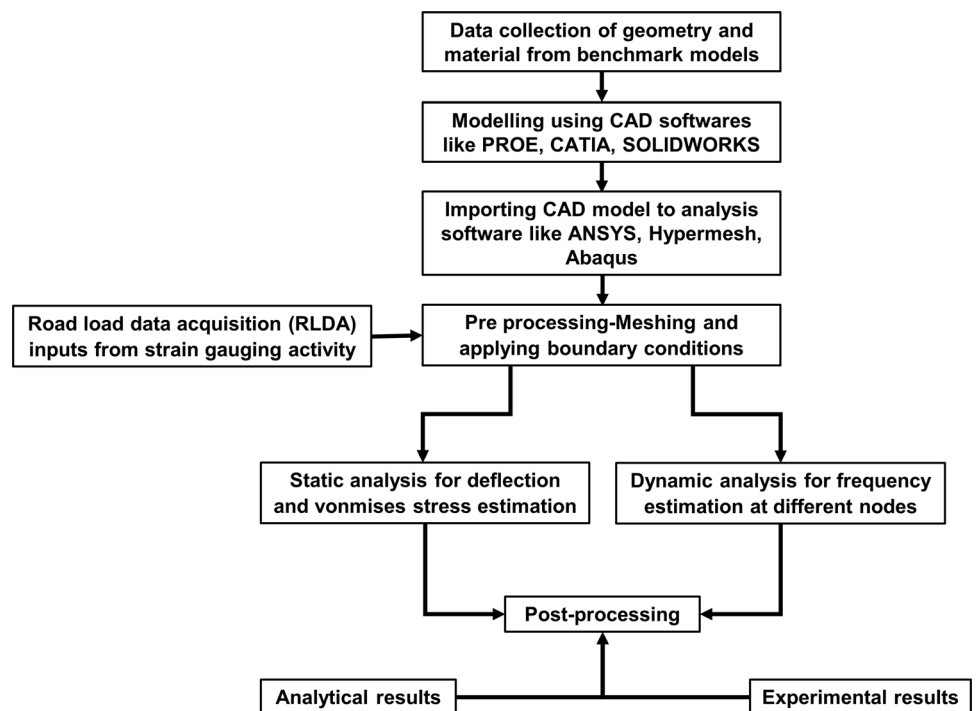
in ADAMS software, and this was taken as an input for simulation in ANSYS. Results demonstrated that under the effect of similar loading condition, the stress experienced by composite spring is lower than the steel one and also weight of the composite spring is on the lower side by approximately 80% as compared to steel material. Also, reliability of composite leaf spring against fatigue rupture is better as shown in Fig. 8.

Kurniawan et al. [10] obtained the differences in fatigue life, equivalent stress and factor of safety for semi-elliptical, trailing and parabolic leaf spring. For all three springs, material used was SUP9. Same maximum load was applied for all three spring and analysis was done in ANSYS considering factor of safety value greater than one, means design is safe. Based on simulation results, it was concluded parabolic leaf spring produced highest fatigue resistance with a cycle of  $10^6$  cycles. Also, it has factor of safety value 1.1336 indicating safe design. Parabolic leaf spring has highest fatigue life as compared to trailing and

**Fig. 6** Process flow chart of present and proposed design methodology

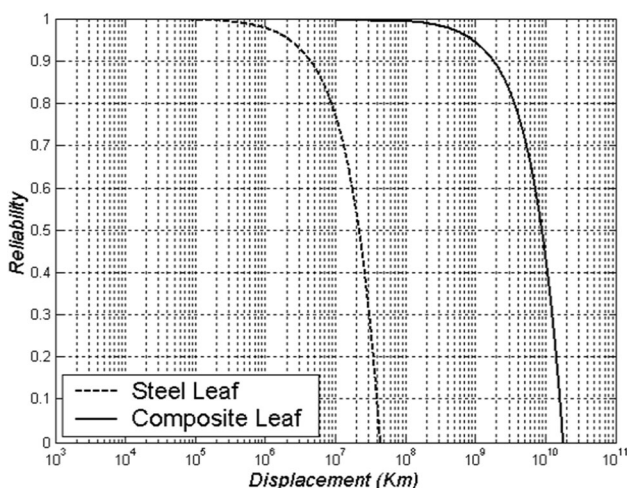


**Fig. 7** Finite element analysis steps



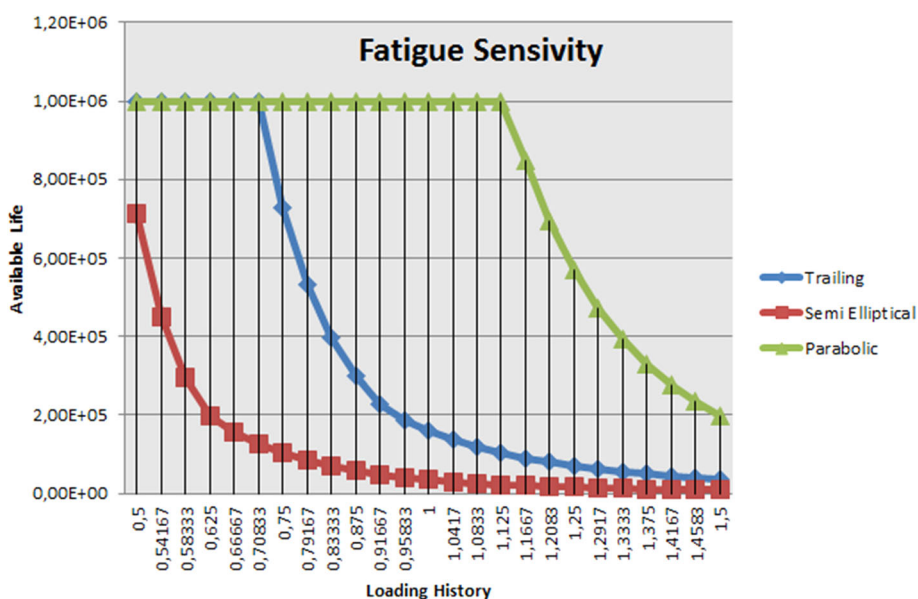
semi-elliptical springs which is shown below in Fig. 9 with the help of fatigue sensitivity chart. Also, stress levels are highest in eye and master leaf depicting the tendency to fail.

Par Johannesson et al. [38] discussed the Wohler curve, which is a plot between resulting numbers of cycles to failure and the load amplitude. The method presented here was based on plotting of the Wohler curve directly from the results of variable amplitude test. Therefore, both the life prediction and evaluation are done at almost identical loading pattern. Statistical uncertainties are also studied in this research.



**Fig. 8** Plot showing fatigue reliabilities of spring [39]. Used with permission of American Society of Mechanical Engineers ASME from Proceedings of the 7th Biennial Conference on Engineering Systems Design and Analysis, 2004; permission conveyed through Copyright Clearance Center, Inc

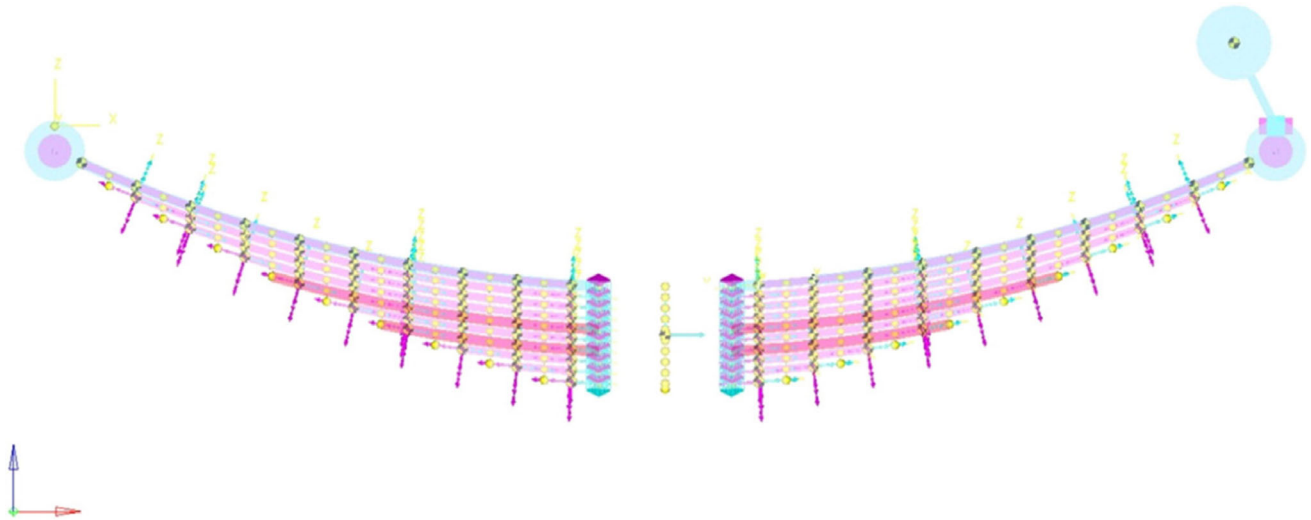
**Fig. 9** Fatigue Sensitivity Graph. Reprinted from (Ref. 10), available under CC BY 3.0 license at IOP Publishing Ltd



Xiaoping et al. [33] introduced the theory of an equivalent stress intensity factor (SIF) range corresponding to  $R = 0$  and a modified wheeler model which is a fatigue crack growth calculation process under variable amplitude loading. The intent of this research was to mark the outcome of loading pattern on fatigue crack growth under the condition of variable amplitude loading. Depending on the equivalent stress intensity factor range, crack growth estimation process based on a modified wheeler model and an improved crack growth governing equation was demonstrated.

Kong et al. [23] analysed the ability of leaf spring eye to sustain failure under the actual on field application of cornering, braking, and pothole striking conditions. In this discussion, the forces applied on the eye were simulated under different loading conditions mentioned above. Polybeam method was used to model leaf spring in multibody dynamic analysis approach as shown in Fig. 10. Simulation for the tensional pulling and torsional forces exerted on eye was performed. The reason behind the use of multibody vehicle dynamic analysis approach is that it can be solved faster by the transient solver. However, FEM was adopted for structural mechanics aspect because multibody analysis could not provide the exact solution in this case. By the help of this analysis, it was estimated that the thickness of eye may be same or higher as compared to leaf thickness.

Wu et al. [43] explained distinct methodologies in the calculation of fatigue damage, typically for random loading. Morrow [47] has proposed a nonlinear damage rule, which is a modification of the Palmgren-Miner linear damage rule by considering functions of stress amplitude



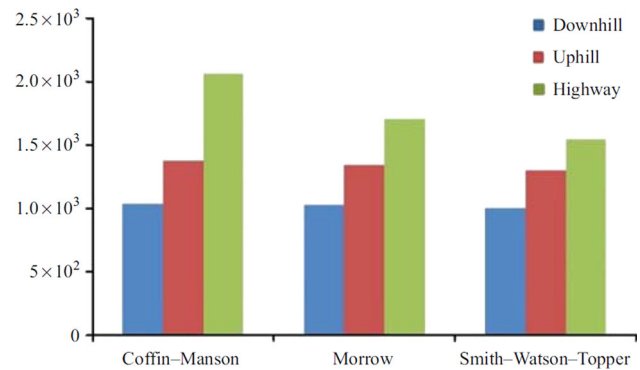
**Fig. 10** Poly-beam model of leaf spring [23]. Reprinted from *Engineering Failure Analysis*, Vol 63, Y.S. Kong, S. Abdullah, M.Z. Omar, S.M. Haris, Failure assessment of a leaf spring eye design under various load cases, Pages 146-159, Copyright 2016, with permission from Elsevier

level as well as functions of stress cycles. As per Morrow, the damage accumulation can be given in equation (1):

$$D = \sum_{i=1}^n \frac{n_i}{N_{fi}} \left( \frac{\sigma_i}{\sigma_m} \right)^d \quad (\text{Eq 1})$$

where  $n_i$  is the applied stress cycles of  $\sigma_i$ ,  $N_{fi}$  indicates the number of cycles to failure,  $\sigma_m$  is the maximum stress amplitude among all stress amplitudes undergone by a component and  $d$  is the plastic work exponent factor to take care of material sensitivity in variable-amplitude loading. The methods were then checked by the output of low-cycle fatigue tests. Study showed that a “plastic work interaction damage rule” proposed by Morrow gave improved fatigue damage projection when it was compared with Palmgren-Miner rule.

Abdullah et al. [14] predicted fatigue life using Coffin-Manson, Morrow and Smith-Watson-Topper (SWT) strain-life models then later reliability analysis was done using Gumbel distribution. Data were calculated based on three different road terrains-downhill, highway and uphill route. This value was used as an input to calculate fatigue life analytically using above mentioned three model. It was concluded that highway condition produced the highest life as shown in Fig. 11, followed by uphill condition and downhill condition because of the presence of rough road surface during uphill and downhill condition. Reliability analysis was done using Gumbel distribution. The Coffin-Manson model revealed wider bell shape in comparison to other two model and also showed the lowest distribution peak which demonstrates steady-state failure mode. On the reverse, the SWT model depicted a narrow shape of probability density function plot as shown in Fig. 12.

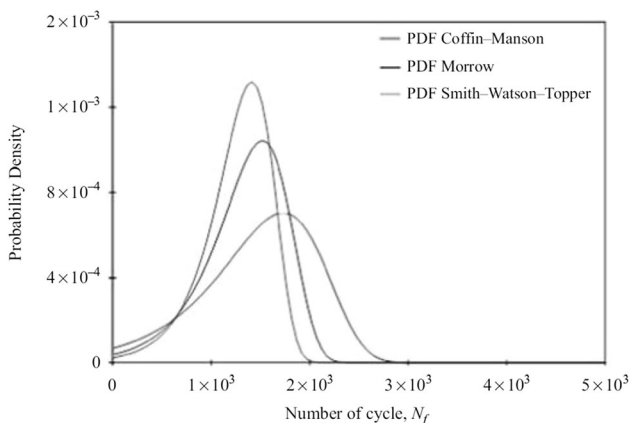


**Fig. 11** Predicted life on different terrains [14]. Used with permission of Emerald Publishing Limited, from Fatigue life-based reliability assessment of a heavy vehicle leaf spring, Lennie Abdullah et al, Vol. 10(5), 2010; permission conveyed through Copyright Clearance Center, Inc

Mehmet Bakir et al. [24] presented a methodology for detailed durability evaluation of leaf spring with CAE technique. This was explained with the help of optimized design of leaf spring with lesser leaves which can withstand the same forces and retain its strength like the original one. Original leaf spring was having four number of leaves and new design leaf spring was having three number of leaves as shown in Fig. 13. BLAFES software was used and the results were further verified with the help of elastokinematic calculations based on multi body simulations (MBS). It was noticed that there is roughly 6-7% increase in the stiffness of new design as compared to the older one. Measured wheel forces on test vehicle with help of force transducer was used as an input for MBS model. FEM calculation was done in Abaqus and obtained that, the maximum stresses on the proposed design is lower by 20%

as compared to the original design. This reduction in the maximum stresses can be considered as an improvement in the durability characteristics till the time fatigue calculation was not done. However, the results of the fatigue life calculations with FEMFAT derive an entirely different conclusion and showed that though stress is less in new design leaf spring, the damage values obtained in the old and new leaf spring design are extremely close.

Tan et al. [11] studied the failure of leaf spring having four leaves through static, modal and harmonic response analysis using ANSYS software. Leaf spring considered for the analysis was having one master leaf supported by three companion leaves. The result demonstrated that the conservative load for leaf spring is 15000N, and the peak point of deformation is near to the eye when maximum 3000N of load was applied. This highest deformation point is shifted to the leaf spring center when 15000N of load was exerted. Also, fifth mode is having maximum natural frequency of 534.86 Hz with eye zone identified as critical to failure.



**Fig. 12** Probability density function distribution [14]. Used with permission of Emerald Publishing Limited, from Fatigue life-based reliability assessment of a heavy vehicle leaf spring, Lennie Abdullah et.al, Vol. 10(5), 2010; permission conveyed through Copyright Clearance Center, Inc

**Summary**

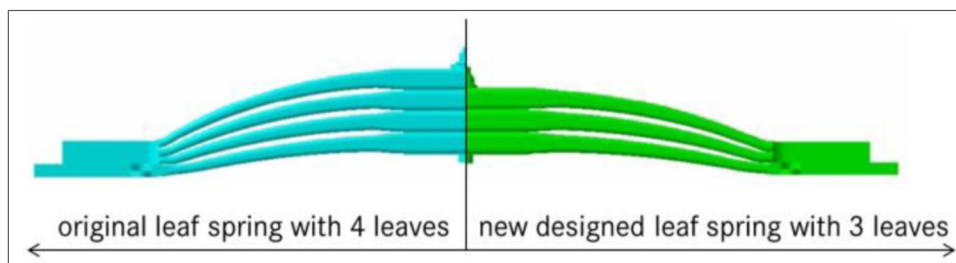
Based on the previous research done on leaf spring design and finite element analysis, below points can be summarised:

- Composites can be used as material for leaf spring of vehicles with low payload capacity because of added advantage of weight saving and reliability against sudden fatigue rupture
- Master leaf eye is considered as the location of maximum stress concentration as shown in Fig. 14. So, special attention is required in eye design, fabrication and material selection. Thickness of eye may be considered same or higher as compared to leaf thickness during design
- Maximum damage values are considered as the governing factor for fatigue life rather than maximum stress
- Few extra full-length leaves to be used along with master leaf as shown in Fig. 15 for better stress distribution in master leaf

**Leaf Spring Manufacturing**

Leaf spring manufacturing process is basically divided into three segments-before heat treatment (shearing and cold punching), heat treatment and surface treatment. Present and proposed manufacturing process flow of semi-elliptical type leaf spring is explained below in Figs. 16 and 17, respectively.

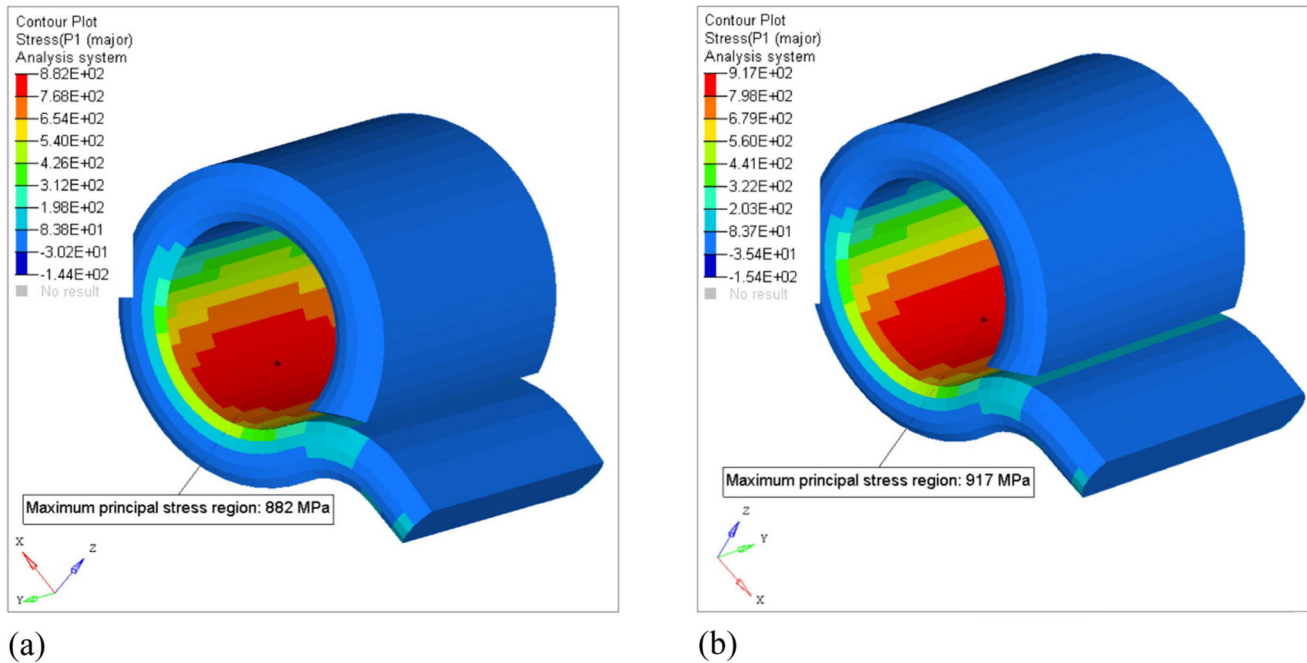
Bock and Justusson [19] discussed a modified ausform process, which considerably improved the fatigue life of spring steels. Three different steel grade is used which are SAE 1052, SAE 5150, and SAE 5160. This ausform process is basically a combination of metal deformation with heat treatment i.e., deformation of austenite before



**Fig. 13** General overview of both leaf springs [24]. Used with permission of SAE International, from Comprehensive Durability Assessment of Leaf Springs with CAE Methods, Bakir, Mehmet;

Siktas, Murat; Atamer, Serter, 2014; permission conveyed through Copyright Clearance Center, Inc

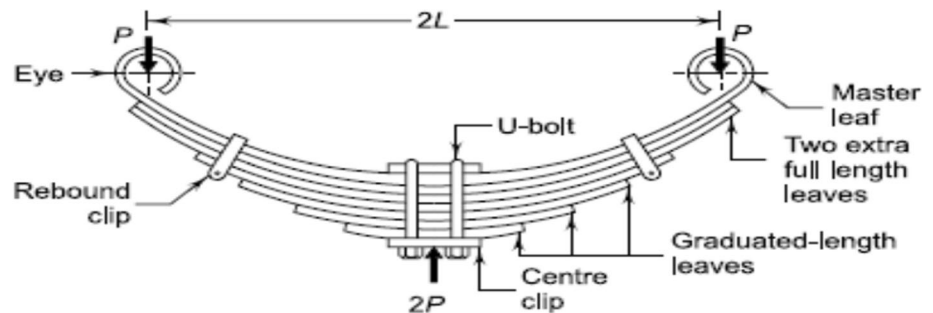




**Fig. 14** Principal surface stress on leaf eye (a) 17 mm thick, (b) 16 mm thick [23]. Reprinted from *Engineering Failure Analysis*, Vol 63, Y.S. Kong, S. Abdullah, M.Z. Omar, S.M. Haris, Failure

assessment of a leaf spring eye design under various load cases, Pages 146-159, Copyright 2016, with permission from Elsevier

**Fig. 15** Extra full-length leaves with master leaf



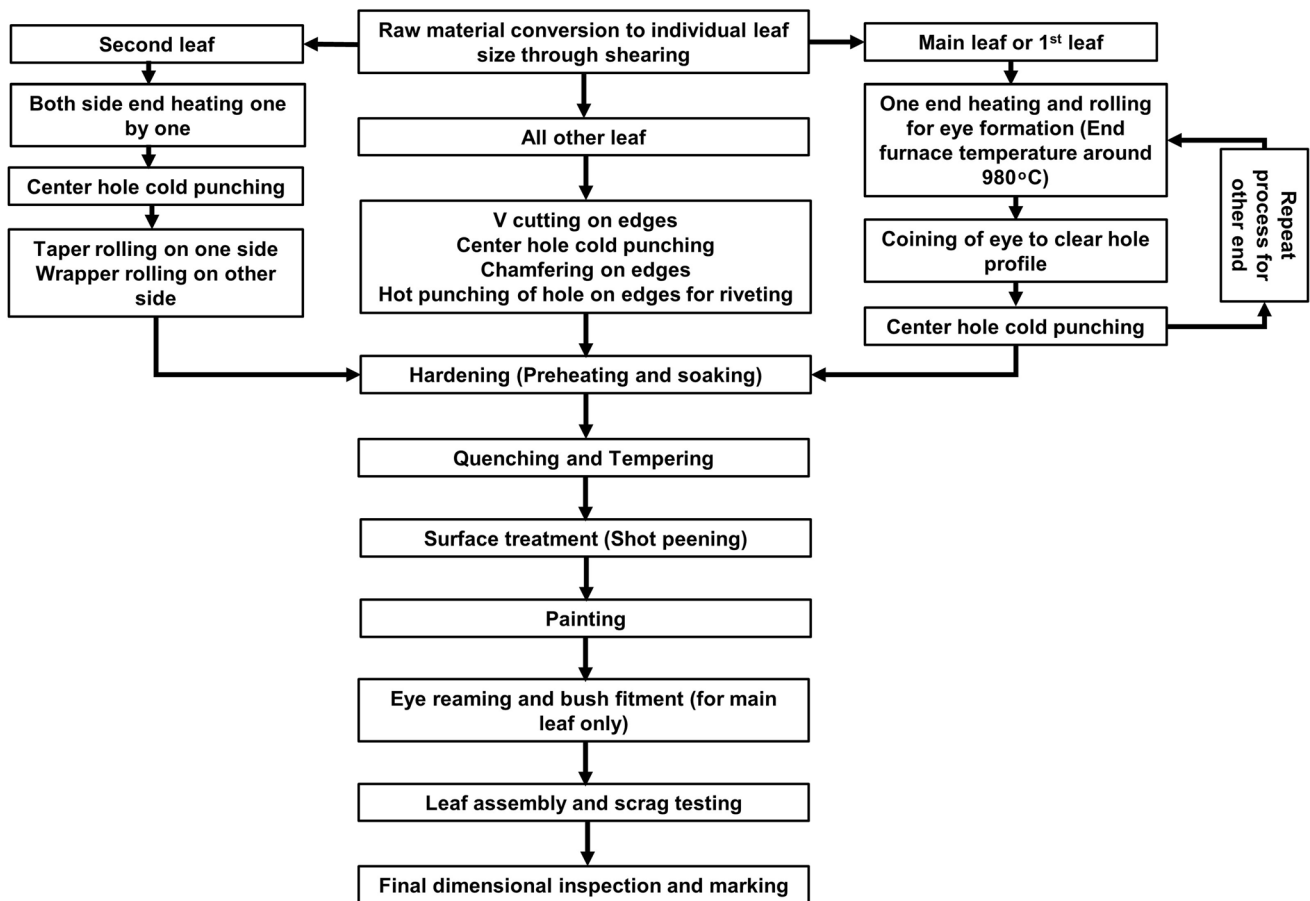
quenching to martensite. Below is the process schedule of ausform process:

- (1) Austenitisation at 1550 F (1 hr/in. of thickness)
- (2) Deformation to be done by rolling in the temperature range of 1350 to 1550 F
- (3) Quenching at room temperature
- (4) Tempering to the required hardness

The portion of deformation directly affects the fatigue resistance. The more the deformation, the more fatigue life is increased. The result of deformation on fatigue life is shown in Table 3. Generally recommended is minimum 50% deformation. The fatigue life variation of only heat-treated and through modified ausformed process for different grade of steels is shown in Fig. 18. It can be seen that slope of two curve is parallel with only difference is that the modified ausformed steel curve is moved up by 30000

psi showing the rise in maximum stress and permissible stress range while maintaining same 100,000 cycle minimum life. Since, fatigue life is improved by ausform process, so spring with a smaller number of leaves can be used in the same vehicle as earlier. This makes the suspension system lighter. Additional benefit of ausform process is that even after getting an initial crack, it takes sufficiently long time for crack propagation and growth and eventually for the condition where load loss becomes 5% or more. This further enhances life.

Scuracchio et al. [29] investigated some improvement in leaf spring shot-peening recipes. Double shot peening technique was used using smaller (0.3 mm) diameter second peening shots. This double peening technique demonstrated improvement in durability of product and also in the weight saving. The obtained  $B_{50}$  life results are 50% higher as compared to the single peening samples (as



**Fig. 16** Present process flow of semi elliptical type leaf spring manufacturing

shown in Fig. 19). 22% of the reduction in spring weight was achieved maintaining same fatigue life with improved shot peening technique.

Tekeli [41] worked on the influence of surface treatment on durability of SAE 9245 grade steel. The fatigue strength results for two different conditions (unpeened and peened) were compared as shown in Fig. 20. It was observed that there is improvement in the fatigue life by about 30% because of shot peening operation. 20–25A (Almen strips) was the selected peening intensity. Any further rise in the peening intensity led to a lower fatigue strength as shown in Fig. 21. The reason for this decrease in fatigue strength is the formation of cracks at the surface due to over peening which removes the compressive residual stressed layer.

Todinov [42] discussed the development of unfavourable stresses on the surface of Silicon-Manganese springs used in automotive suspension. Net residual stress on the leaf spring surface should be compressive but sometimes it results out into tensile nature because of the two reasons which are- loss of carbon and the difference in microstructure at the surface and the core. The residual stresses have been continuously monitored at different stage of spring manufacturing-quenching, tempering and

shot peening. During quenching, residual stress patterns can be illustrated by continuum model which says that if during quenching operation, the total plastic strain produced during thermal contraction is smaller than that produced during transformation expansion; the net residual stress at the surface will be tensile. If the reverse is true, the result is compressive. Tensile residual stress from quenching superimposes with the compressive residual stress obtained from surface treatment and this form the net effect which may be compressive or sometimes tensile because of improper shot angle during shot peening. In order to avoid the effect of unfavourable residual stresses, two controls need to be applied in process: One is preventing decarburisation during austenitising and second is the selection of a smaller impact angle during shot peening because smaller the angle is, the larger the transmitted impact energy and larger is the compressive residual stress.

Malikoutsakis et al. [7] discussed the effect of heat treatment and shot peening performed during the manufacturing of parabolic springs on fatigue life of downsized specimens which are modelled to be shorter in dimension as compared to the actual sample in order to reduce the spring travel which consequently increase the testing

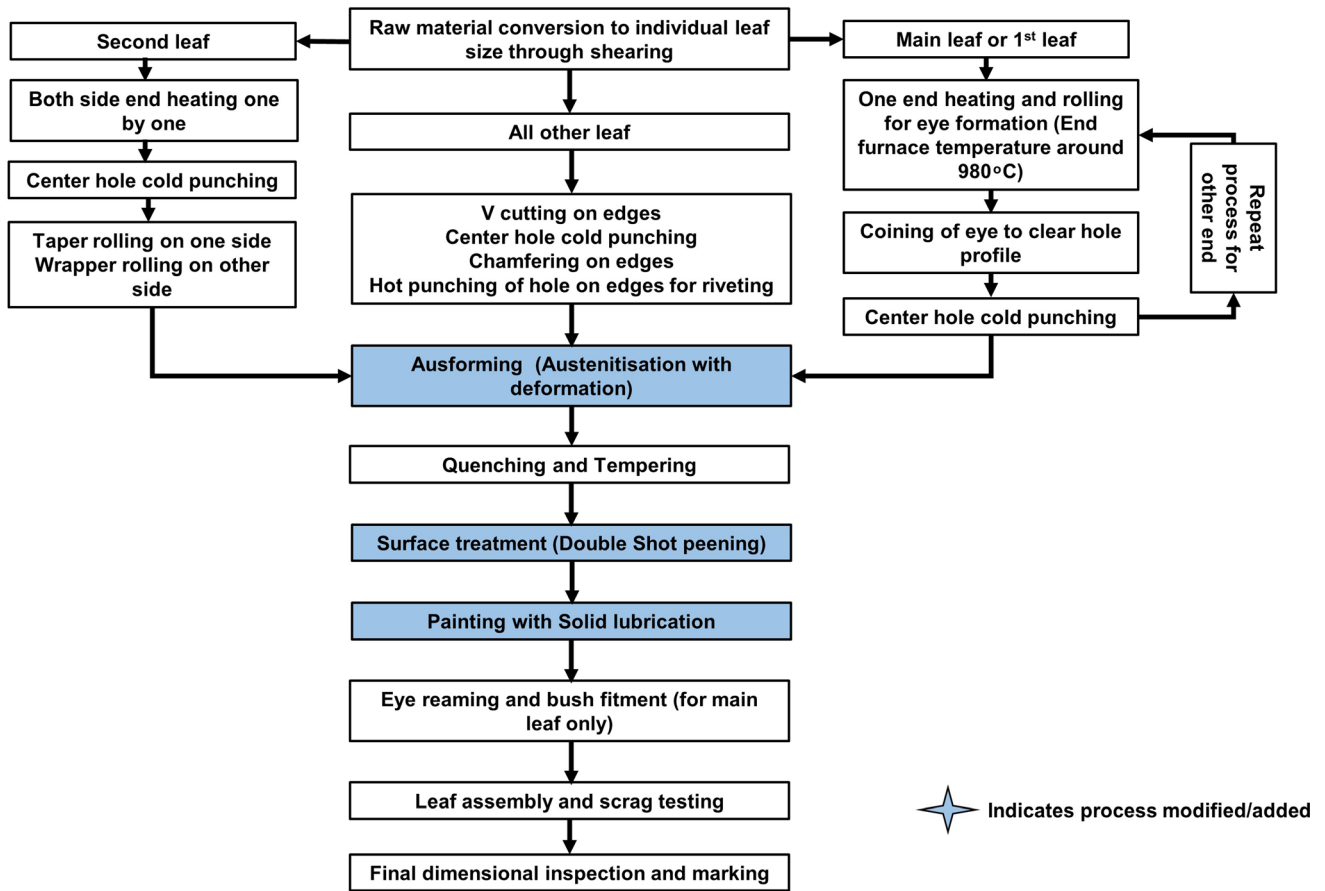


Fig. 17 Modified process flow of semi elliptical type leaf spring manufacturing

Table 3 Impact of deformation on B<sub>10</sub> and B<sub>50</sub> life [19]

(Stress range: 100,000-225,000 psi)

Steel grade	Process	Hardness (R <sub>c</sub> )	Life (in 1000 Cycles)		
			Minimum	B <sub>10</sub>	B <sub>50</sub>
SAE 5160	No deformation	48	14	12	19
SAE 5150	30% deformation	49	51	50	82
SAE 5150	45% deformation	49	69	68	110
SAE 5150	60% deformation	49	103	95	144
SAE 5150	75% deformation	49	85	90	95

Used with permission of SAE International, from Lightweight Leaf Springs, Bock, R. A.; Justusson, W. M., 1968; permission conveyed through Copyright Clearance Center, Inc

frequency in test rig. Two specimens were serially produced such that both samples is having similar level of decarburization as a negative effect of heat treatment. One is subjected to single shot peening and another one is subjected to double shot peening. This is achieved with the help of four turbines launching a mass of 500 kg per turbine in one minute. This assessment was supported with macro and micro hardness measurements in convergence

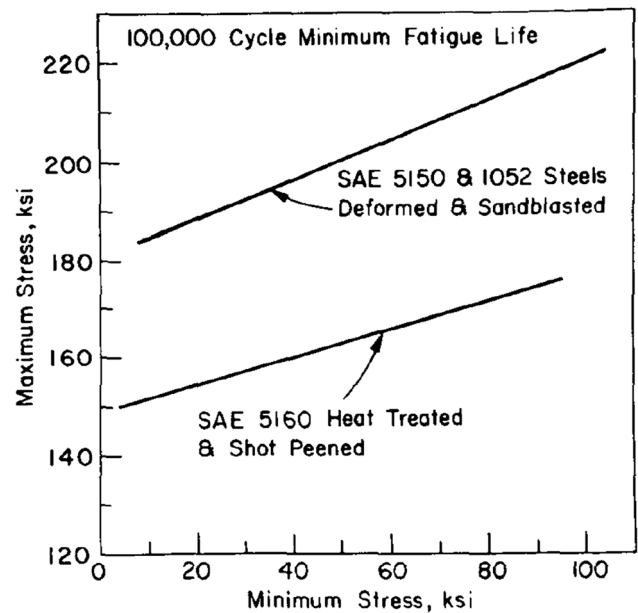
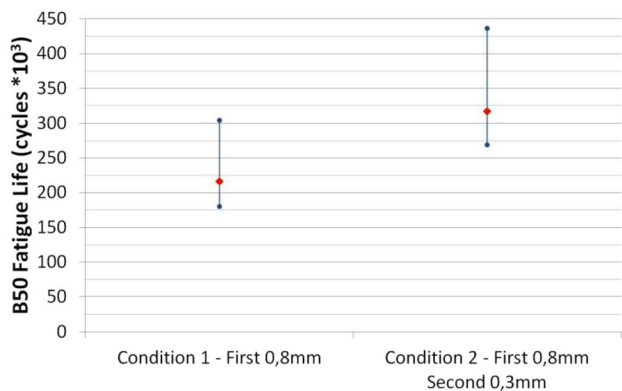
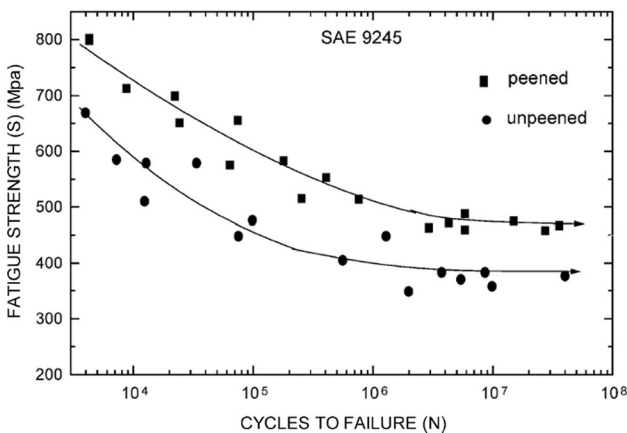


Fig. 18 Comparison of stress range for different grade of steels when processed through different technique [19]. Used with permission of SAE International, from Lightweight Leaf Springs, Bock, R. A.; Justusson, W. M., 1968; permission conveyed through Copyright Clearance Center, Inc



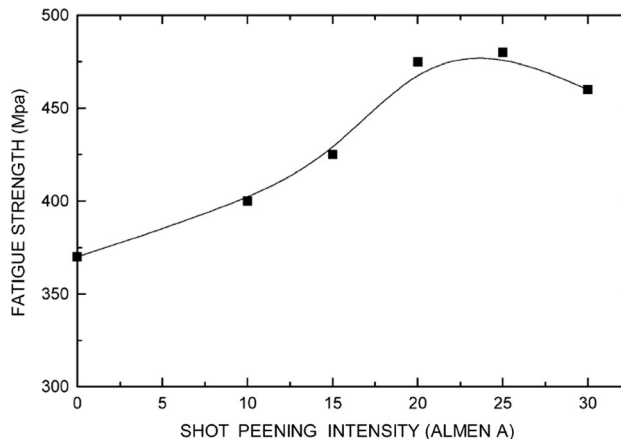
**Fig. 19** B<sub>50</sub> life comparison between single peening and double peening [29]. Used with permission of SAE International, from Leaf Springs Durability Analysis and Weight Reduction through Double Peening, Scuracchio, Bruno Geoffroy; Barbosa, Robinson Ferrari; Curitiba, Jose Roberto, 2012; permission conveyed through Copyright Clearance Center, Inc



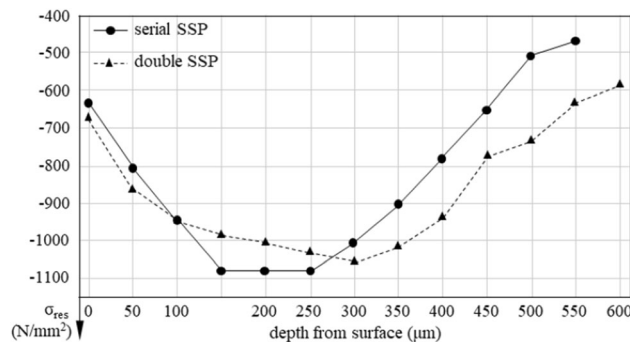
**Fig. 20** S–N curves comparison [41]. Used with permission of Elsevier Science & Technology Journals, from Enhancement of fatigue strength of SAE 9245 steel by shot peening, S.Tekeli, Vol 57(3), 2002; permission conveyed through Copyright Clearance Center, Inc

with roughness. Figure 22 shows residual compressive stress distribution over the depth from the surface for both the specimen. It was concluded that controlled heat treatment process and double shot peening technique significantly improves the durability life of spring.

Sohn et al. [40] proposed a new fatigue design criterion and test method for leaf spring assembly of light commercial vehicle (LCV). In this method, stress and displacement of leaf spring were measured first through strain gauging and then through road load response activity. The maximum load and displacement of leaf spring



**Fig. 21** Effect of peening intensity on fatigue strength [41]. Used with permission of Elsevier Science & Technology Journals, from Enhancement of fatigue strength of SAE 9245 steel by shot peening, S.Tekeli, Vol 57(3), 2002; permission conveyed through Copyright Clearance Center, Inc



**Fig. 22** Effect of peening intensity on fatigue strength. Reprinted from Ref. 7, available under CC BY 4.0 license at EDP Sciences

**Table 4** Fatigue test condition of leaf spring assembly (Adapted from Ref. 40)

Parameter	Values
Test equipment model	Instron 880
Actuator capacity	490.5 KN
Control mode	Displacement
Frequency	0.2-3.0 Hz

was defined which is taken further for deriving the fatigue load-life relation with mentioned test condition in Table 4. Also, a 3-point bending fatigue test was conducted to investigate the effect of compressive residual stress developed due to shot peening operation. To further investigate the effect of compressive residual stress induced due to shot peening operation, two kinds of test

specimens were fabricated (with and without shot peening) from a lot under same manufacturing process.

## Summary

Based on the previous research done on leaf spring manufacturing processes, below points can be summarised:

- Ausform process improves the fatigue properties of spring steels
- Double shot peening technique significantly improves the fatigue life of spring
- Shot peening parameters like ball diameter, peening intensities, impact angle plays important role in the generation of compressive residual stress

## Leaf Spring Testing and Failure Analysis

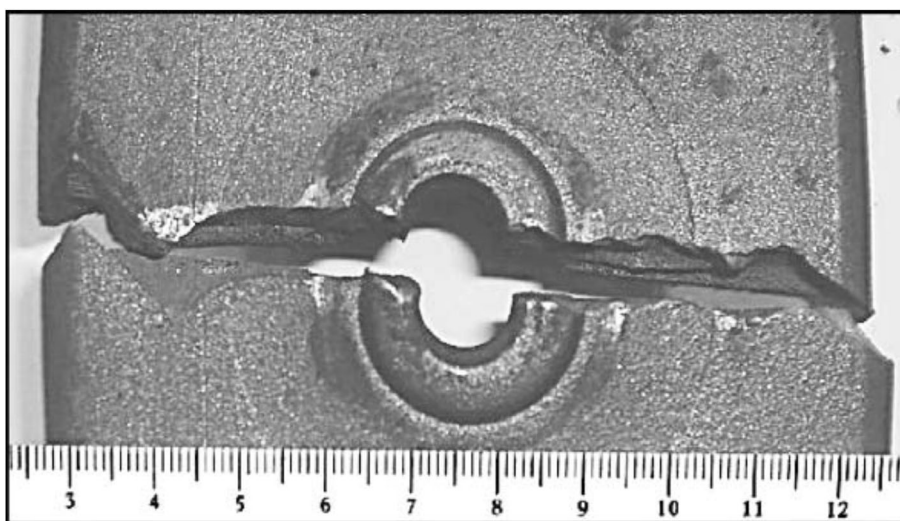
Fuentes et al. [32] studied the premature fracture of the leaf spring as shown in Fig. 23. Reasons were identified, and solutions were proposed to avoid failure. Fatigue failure in the region of the central hole was observed, which was further studied and discussed. Macroscopic examination of the failed surface was done and it was concluded that, because of improper heat treatment resulting in surface decarburization, the microstructure was not uniformly tempered martensite. Additionally, a fatigue test was conducted for different samples with different designs of central holes (i.e., cup-shaped, flat round, rectangular holes), and the best result was obtained with flat round holes.

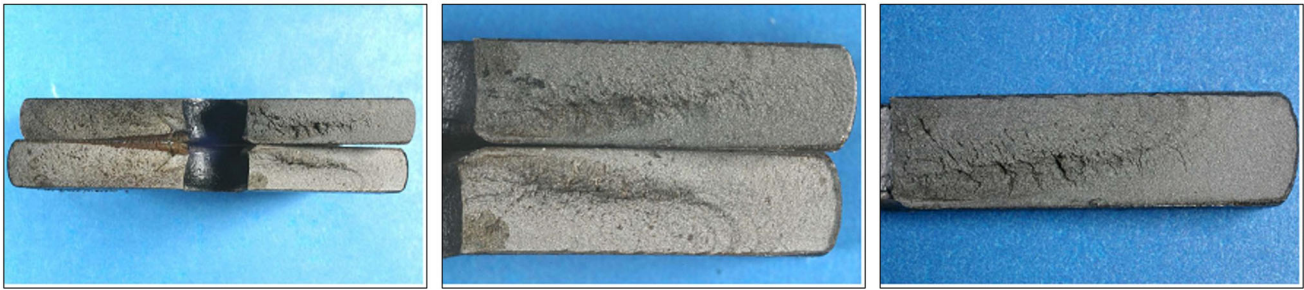
Husaini et al. [8] investigated the affecting parameters behind leaf spring failure in a truck. The gross vehicle weight (GVW) of vehicle supplies initial compressive force to the suspension, and the compressive force imposed on the suspension system also depends on the irregularities on the road. Greater the irregularities, greater is the force imposed. Hardness of the failed sample was measured in both vertical and horizontal direction on Rockwell hardness testing machine. The hardness value obtained proves that the material is AISI 5150. Using FEM, Stress Intensity factor ( $K_I$ ) was obtained at crack tip which was further compared with fracture toughness ( $K_{IC}$ ) of AISI 5150 material. Observed  $K_I > K_{IC}$  is giving indication for crack propagation. Two probable reasons for failure were concluded which are:

- Maximum load on the leaf spring was larger than maximum standard spring load
- Stress intensity factor obtained from FEA is greater than fracture toughness of the material considered

Laroiya et al. [34] discussed a very interesting failure mode which is rare in leaf spring. Brittle fracture due to delayed hydrogen stress cracking or hydrogen embrittlement has been discussed. The failure occurs even before the spring is assembled into the vehicle, i.e., during transit only or immediately after the vehicle assembly process. Most of the failures were happening on the main leaf at the center bolt location, as shown in Fig. 24. Hardness and chemical composition of all failed sample was investigated and found within normal limits. Hydrogen content was measured in two failed sample which was also found within normal range of 5–8 ppm. The failure surface patterns and failures did not agree with quench cracking, temper embrittlement, tempered-martensite embrittlement,

**Fig. 23** Photograph of the fractured second leaf of a specimen [32]. Used with permission of Elsevier Science & Technology Journals, from Premature fracture in automobile leaf springs, Fuentes, J.J.; Aguilar, H.J.; Rodríguez, J.A.; Herrera, E.J., Vol 16(2), 2009; permission conveyed through Copyright Clearance Center, Inc





**Fig. 24** Visual presence of hydrogen stress cracking [34]. Used with permission of SAE International, from Hydrogen Embrittlement Failure in Suspension Leaf Springs, Laroia, Sunil, 2007; permission conveyed through Copyright Clearance Center, Inc

and blue brittleness. This indicated that some other factors are contributing in failure. Microstructure examination was performed and found that no decarburization, no metallic inclusion was observed. So, these reasons were also eliminated. Further, SEM was used to investigate the fracture surface showing intergranular fracture with grain boundaries which is an indication of hydrogen stress cracking. Then on few samples, hydrogen was supplied artificially by dipping in HCl for one hour duration with electrolytic current applied and tested. Result gave no further failure.

Staco et al. [15] investigated failure of saddle (top plate) as shown in Figs. 25 and 26 and found that U-bolt improper material and heat treatment caused the thread slip. This cause torque loosening and ultimately resulted in saddle failure. Mainly experimental investigation was done through test rig and strain gauge to measure the stress in U-bolt during torquing and during normal rig testing.

Krason and Wysocki [21] studied the effect of friction in the form of temperature rise in leaf spring. Rig testing was conducted and temperature at different leaf location was captured through thermal imaging camera. It was concluded that the time changes in the temperature difference are not linear. The greatest temperature increase occurs at the initial stage of test and stabilises at certain level in due course of time as shown in Fig. 27 and Table 5. The friction is the main cause of temperature increase on the spring surface. The higher the friction, the higher the temperature in the given area. Location of maximum temperature increase was identified depicting maximum friction at that location. The revealed temperature increase will not affect the changes that occurred during forging and thermal treatment because these processes occur at much higher temperature (500–1200 °C) range.

Mukhopadhyay et al. [44] studied failure of leaf spring caused because of lapses in manufacturing process. Optical microscope and SEM were used to check the microstructure of failed samples. SEM examination showed that the point of failure started at one edge, and then propagated over a period of time under continuous fatigue loading. The



**Fig. 25** Bottom view of the top saddle [15]. Reprinted from Mariusz Staco et.al, Failure Analysis of a Damaged U-Bolt Top Plate in a Leaf Spring, Proceedings of the 14th International Scientific Conference, Pages 736-743, 2019, Springer Nature

martensitic forming temperature for any steel can be obtained from equation (2):

$$Ms(C) = 561 - 474(C) - 33(Mn) - 17(Ni) - 17(Cr) - 21(Mo) \quad (\text{Eq } 2)$$

where ( ) denotes weight% in the chemical composition.

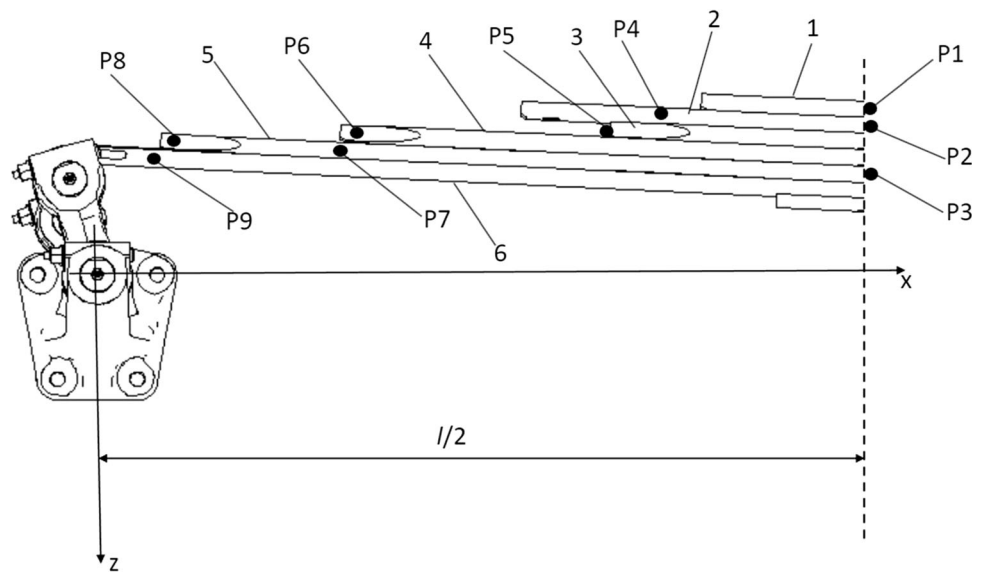
It was concluded that failure occurred due to a poor quenching operation which generated quench cracks as shown in Fig. 28. Also, this failure is supported by grain boundary embrittlement because of the availability of different inclusions.

Santika et al. [45] discussed detailed procedure of durability testing of leaf spring sample from two different manufacturers. Constant load amplitude was the control mode selected for leaf springs durability test. The load was repeated between 8.08 KN bump load and 2.45 KN rebound load. But the stress obtained at both the leaf springs were different. Evaluation using S-N diagram provided that first spring sample has met the expected life, while second spring sample failed to meet the expected

**Fig. 26** U-bolt thread damage [15]. Reprinted from Mariusz Staco et.al, Failure Analysis of a Damaged U-Bolt Top Plate in a Leaf Spring, Proceedings of the 14th International Scientific Conference, Pages 736-743, 2019, Springer Nature



**Fig. 27** Scheme of left half of double-leaf spring without load: (3–6) designation of leaves of the main spring; (1–2) designation of additional spring; (P1–P9) location of the points of temperature measurement

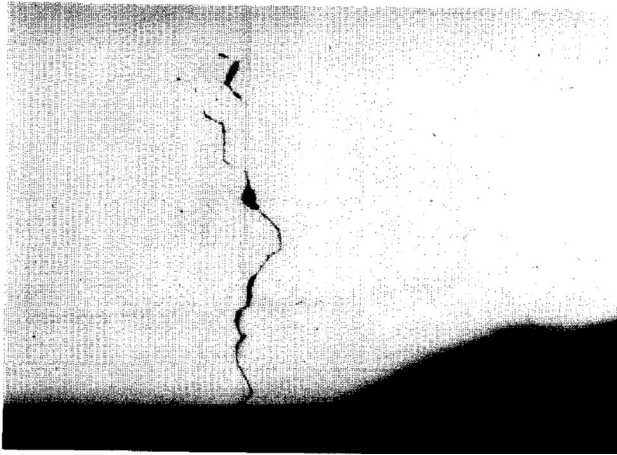


**Table 5** Points of measurement and their description (Adapted from Ref. 21)

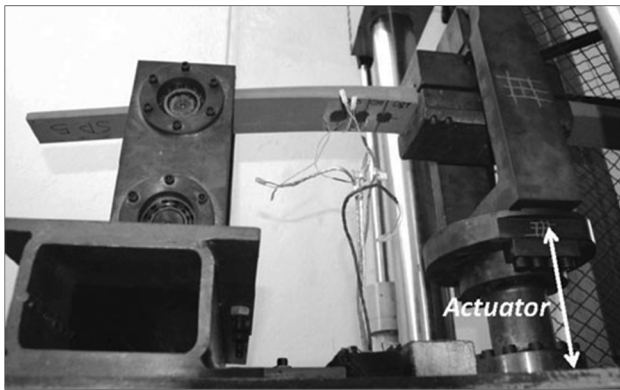
Measurement Point	Temperature at the measurement point in (°C) at different time t									
	0	40	130	160	190	220	250	280	310	340
P1	19.5	20.5	21.3	21.7	21.9	22.2	22.5	22.7	23.0	23.0
P2	19.5	20.4	21.3	21.7	21.9	22.2	22.5	22.6	23.0	23.1
P3	19.5	20.3	21.3	21.6	21.9	22.1	22.5	22.6	23.0	23.2
P4	19.5	20.5	21.5	21.9	22.1	22.3	22.6	22.8	23.1	23.2
P5	19.5	21.9	23.1	23.7	24.0	24.3	24.6	24.7	24.9	25.1
P6	19.5	22.6	23.9	24.3	24.7	25.1	25.3	25.4	25.6	25.7
P7	19.5	22.3	23.5	24.2	24.6	24.7	25.0	25.2	25.4	25.6
P8	19.5	22.3	23.5	24.0	24.3	24.5	24.8	24.9	25.2	25.3
P9	19.5	22.3	23.4	23.9	24.2	24.3	24.6	24.8	25.0	25.2

life. Also, it was observed that first sample has higher stiffness and interleaf friction but at the same time lower deflection as compared to second sample. Fracture analysis demonstrated that fatigue fracture starts at center bolt

location which may be further increased by slag inclusions and porosity. Durability test on three shock absorbers (telescopic double acting type) were also conducted in close



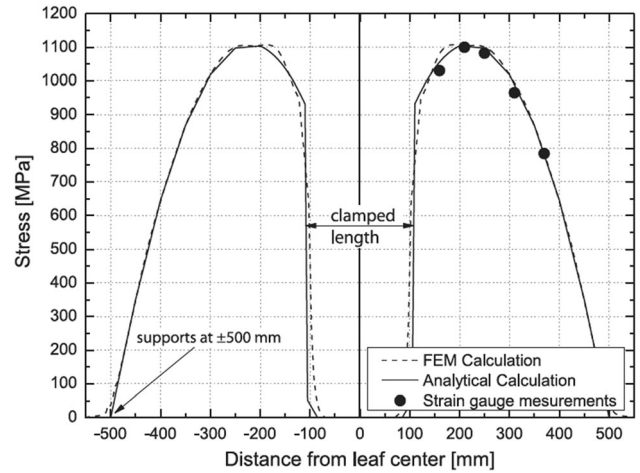
**Fig. 28** Crack along transverse direction [44]. Used with permission of Elsevier Science & Technology Journals, from Premature failure of a leaf spring due to improper materials processing, Mukhopadhyay, N.K.; Das, S.K.; Ravikumar, B.; Ranganath, V.R.; Ghosh Chowdhury, S., Vol 4(3), 1998; permission conveyed through Copyright Clearance Center, Inc



**Fig. 29** Test rig for fatigue experiments on leaf springs [30]. Used with permission of John Wiley & Sons - Books, from Fatigue assessment and failure analysis of shot-peened leaf springs, Fragoudakis, R.; Saigal, A.; Savaidis, G.; Malikoutsakis, M.; Bazios, I.; Savaidis, A.; Pappas, G.; Karditsas, S., Vol 36(2), 2013; permission conveyed through Copyright Clearance Center, Inc

loop servo hydraulic durability testing machine in which sinusoidal loading method were used.

Fragoudakis et al. [30] have done fatigue test for the shot peened spring and results were compared with the ideal sample. Fatigue rig testing methodology was discussed in detail. Stress was measured during rig test through strain gauge activity as shown in Fig. 29. Three stress-analytical, FEM and experimental were compared and witnessed that all three are almost matching as shown

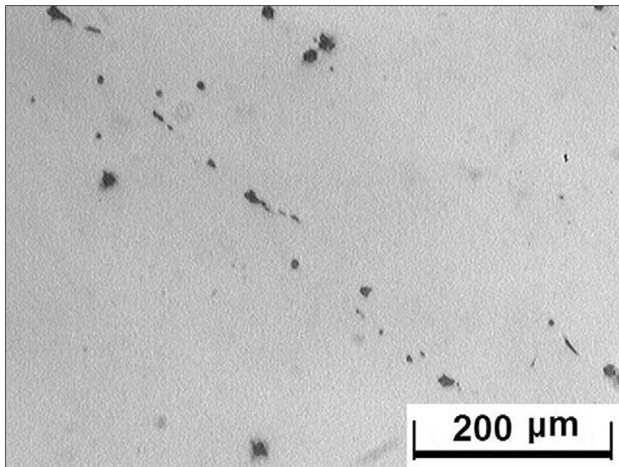


**Fig. 30** Comparison of stresses on the leaf spring [30]. Used with permission of John Wiley & Sons - Books, from Fatigue assessment and failure analysis of shot-peened leaf springs, Fragoudakis, R.; Saigal, A.; Savaidis, G.; Malikoutsakis, M.; Bazios, I.; Savaidis, A.; Pappas, G.; Karditsas, S., Vol 36(2), 2013; permission conveyed through Copyright Clearance Center, Inc

in Fig. 30. Failure observed at the location having maximum stress. Failed surface analysis was done which included-microstructure examination, crack propagation path, hardness measurement through Vicker’s micro hardness which was further confirmed by Rockwell tester. Analytically  $\sigma$ -N Graph was plotted using Goodman or Haigh Fatigue failure theory. It was concluded that decarburization is found in both the tension and compression surfaces of the leaves which is responsible for loss of mechanical resistance and hardness.

Fragoudakis et al. [22] discussed the influence of heat treatment process on the microstructure of steel leaves. The study aimed to obtain fatigue life curves to show the effect of heat treatment and shot peening on fatigue strength. The raw material was having surface decarburization layers which is normal in the case of hot rolled spring steels. Heat treatment process (Austenitisation, Quenching and Tempering) temperature and timing was adjusted in such a way that complete martensite formation (100%) takes place. Both micro and macro hardness measurement of the sample after heat treatment and shot peening was done with the help of Schimidzu hardness tester and Wilson Rockwell hardness tester, respectively. Residual stresses were measured down to a depth of 500  $\mu\text{m}$  of the shot-peened specimen through X-ray diffraction technique. Micro hardness examination showed surface decarburization effects and measured the decrease in strength but they did not give any information related to the transformation of martensite during heat treatment.





**Fig. 31** Presence of non-metallic inclusions [31]. Used with permission of Elsevier Science & Technology Journals, from Failure analysis on the collapse of leaf spring steels during cold-punching, Peng, Wenyi; Zhang, Jian; Yang, Xiangjie; Zhu, Zhenghou; Liu, Sanqiu, Vol 17(4), 2010; permission conveyed through Copyright Clearance Center, Inc

Peng et al. [31] studied failure analysis of the collapsed leaf spring during cold punching operation. Both macroscopic and microscopic hardness measurement was done. Brittle cleavage transcrystalline fracture mode was revealed for flat spring steel during the cold punching operation. The inhomogeneous lamella pearlites are the prime reason for this kind of failure. The second reason of collapsing fracture is because of non-metallic inclusions as shown in Fig. 31 which can form microcracks. Two suggestions were proposed in order to resolve the condition of sudden collapsing fracture which are:

- (1) Hot rolling parameters should be controlled in such a way that uniform fine lamella pearlites are obtained
- (2) Addition of Aluminium should be limited and furnace lining to be taken care of which further reduces non-metallic inclusions

Fragoudakis et al. [25] discussed the performance of a 56SiCr7 leaf springs at different stages of the manufacturing process based on the microstructure and surface characterization of the steel. The effect of surface decarburization and shot peening on the microstructure change prospect and its contribution to fatigue life was discussed. A few samples of only heat treatment and a few samples of both heat treatment and shot peening were taken for rig testing, and the number of cycles to fracture was discussed for all. Micro-hardness measurements in below Fig. 32 show that shot peened surfaces have similar hardness levels at the surfaces as compared to raw material specimens and heat-treated specimens, but show an increasing trend as the

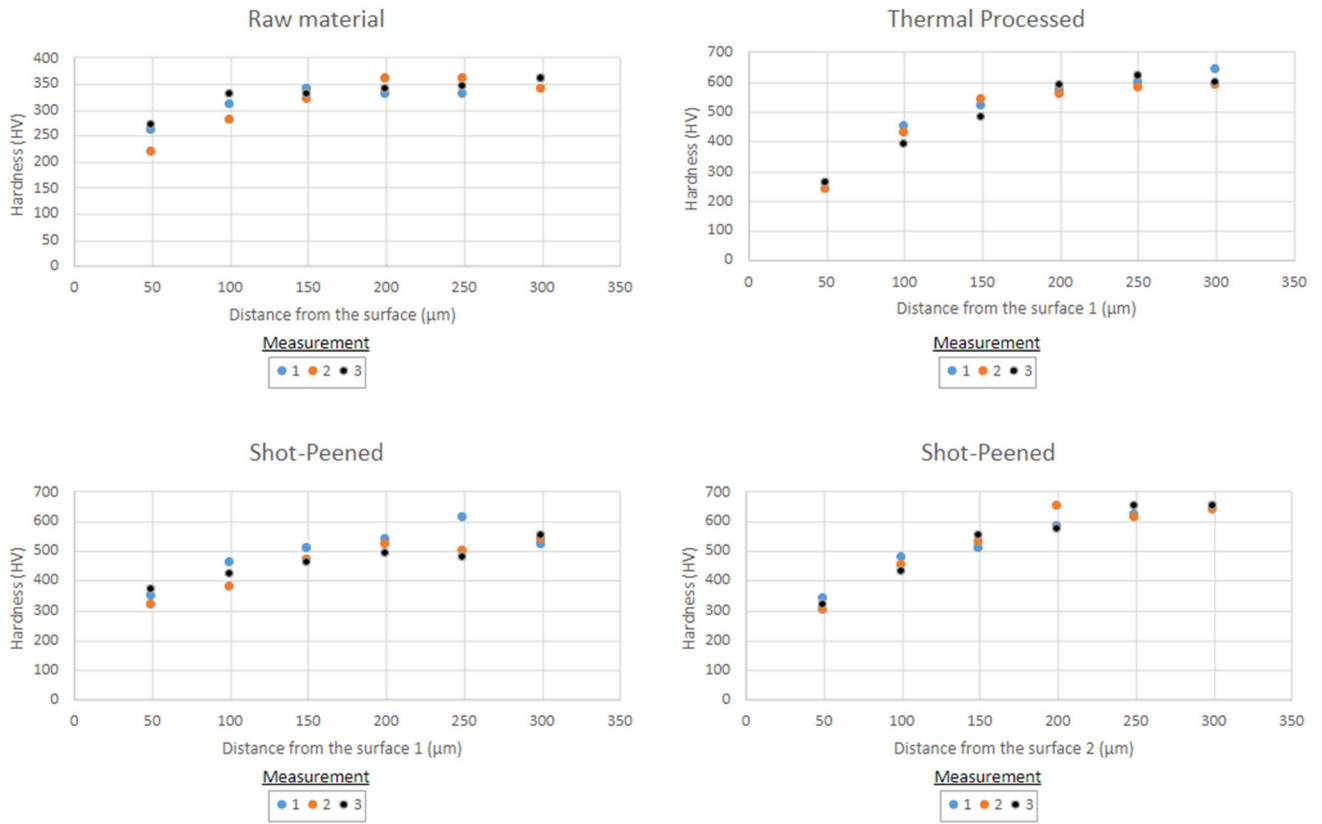
distance from the surface increases. The heat-treated specimen has a very low surface hardness due to decarburization. It was concluded that surface treatment improves fatigue life twice as much as heat-treated samples.

Karditsas et al. [26] studied the design of serial parabolic leaf spring having two leaves used in the front axle of heavy commercial vehicles having load bearing capacity of 9.2 Tons. For FEM analysis, real operating condition (vertical loading and braking as shown in Fig. 33) was considered. Target or permissible stress value was experimentally obtained from S-N Wohler curve. And, S-N Curve was obtained by means of 4-point fatigue bending tests.

James et al. [2] discussed the case study of environmental embrittlement of multi leaf springs made from 60Si2Mn Steel. Multiple cracks generated due to corrosion pits and fatigue failures were witnessed at the early service kilometres of vehicle. The phenomenon was evident during the cleaning process that appeared because of transporting animal feed using trucks. The main reason of the failures was corrosion pitting as shown in Fig. 34, which is further triggered by the environmental embrittlement component leading to subsequent crack initiation and growth. Severity of pitting has been impacted by the inclusions as shown in Fig. 35 which resulted in to hydrogen-induced environmental embrittlement.

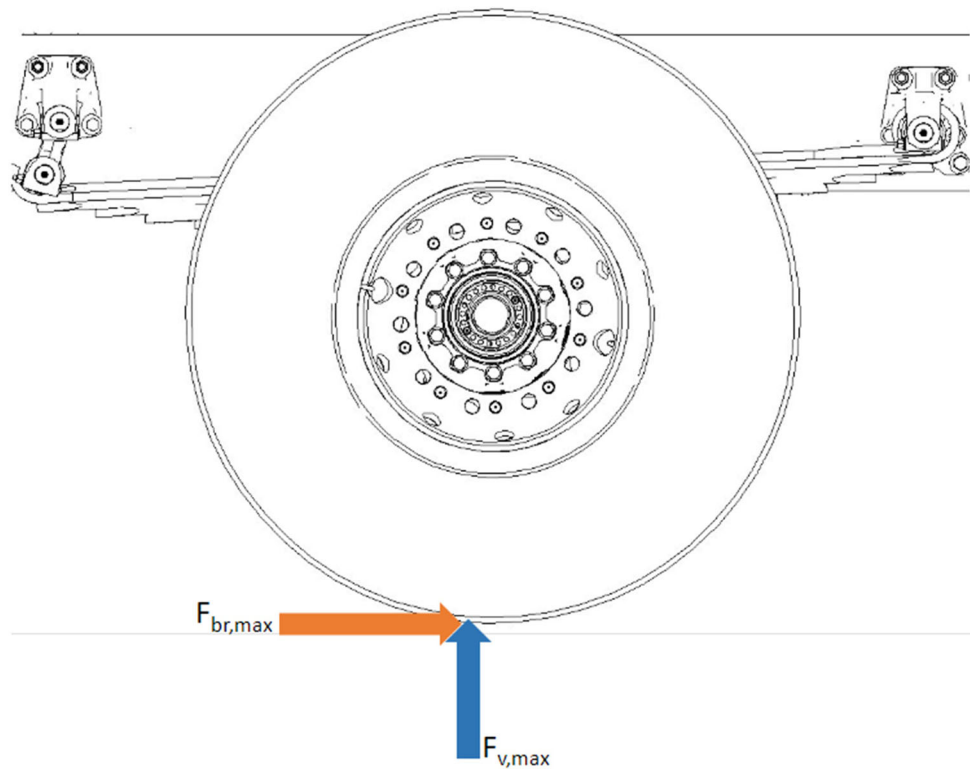
Kai-ming et al. [27] discussed the design of test rig. A Gantry type of test bench was prepared which can perform stiffness tests, permanent deformation tests and fatigue tests. The spring is fixed on the test bed with the help of suitable fixture and the hydraulic powerpack system delivers power to the loading mechanism. The control system gives command to servo hydraulic actuators through central processor. Power pack of hydraulic system generates sufficient pressure responsible for the movement of servo hydraulic actuators as soon as the command is given from the computer control system. Sensor attached to loading mechanism provides displacement and load monitoring log. With the coordination of all the three systems, the above-mentioned tests can be performed. Details of test fixture and system working flow diagram is shown in Figs. 36 and 37, respectively.

Kong et al. [28] worked on the variable amplitude loading (VAL) design to simulate durability conditions of a parabolic leaf spring. FEM method indicated the critical area of the spring in terms of stress where strain gauging can be done. After Rossette type strain gauging, bus was allowed to run in different road condition to capture data. This data was processed further using “ncode design life software”, and spring fitted on loaded bus was giving this input for test. This way VAL test was conducted. At the end, FEM was used to calculate stiffness and fatigue life.



**Fig. 32** Micro-hardness profiles measured on shot peened specimen, raw material specimen and only thermally treated specimen

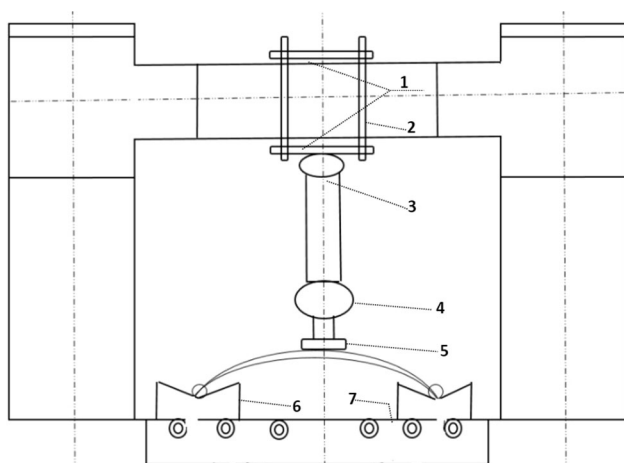
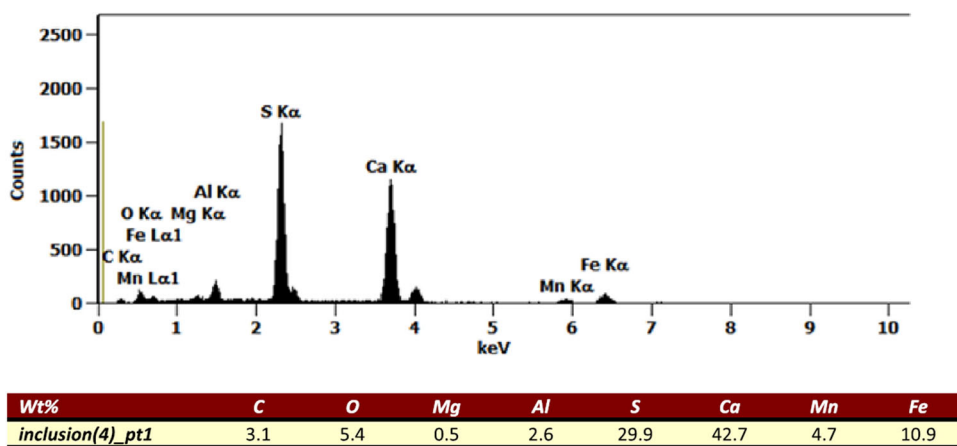
**Fig. 33** Loads occurring from straight ahead driving and braking



**Fig. 34** Spring tension surface showing corrosion [2]. Used with permission of Elsevier Science & Technology Journals, from Embrittlement failure of 51CrV4 leaf springs, James, M.N.; Hattingh, D.G.; Matthews, L., Vol 139, 2022; permission conveyed through Copyright Clearance Center, Inc



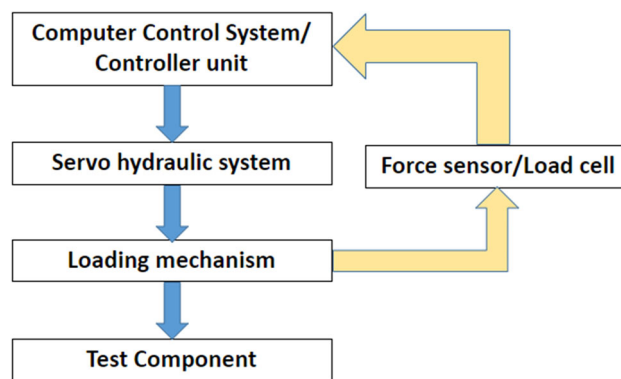
**Fig. 35** Graph showing small inclusions count [2]. Used with permission of Elsevier Science & Technology Journals, from Embrittlement failure of 51CrV4 leaf springs, James, M.N.; Hattingh, D.G.; Matthews, L., Vol 139, 2022; permission conveyed through Copyright Clearance Center, Inc



1. Upper junction plate 2. Studs 3. Pin board 4. Force sensor 5. Lower junction plate 6. Sliding mechanism 7. Guide rail

**Fig. 36** The test fixtures

Nataraj et al. [12] analysed failure mode of a leaf spring by performing visual examination and fractography with the help of SEM. FEA simulation software is used to perform static analysis and life cycle estimation



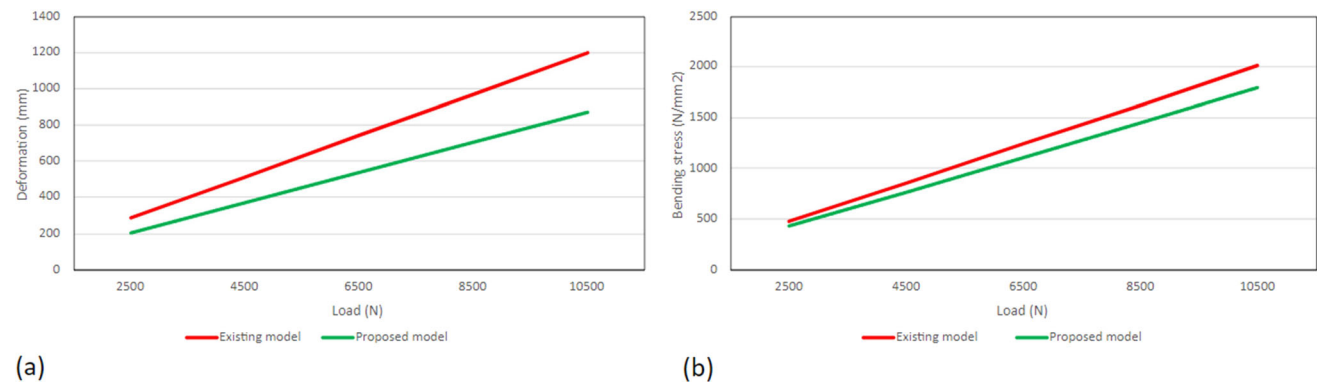
**Fig. 37** The system working flow diagram

considering two different material. The main purpose of this analysis was to decrease the bending stress and enhance the durability. Existing material was 50Cr1V2 and proposed material was 50Si2Mn90. In the proposed model, number of leaf and thickness was also modified as shown in Table 6. SEM analysis proved that cyclic loading was responsible for fracture. FEM simulation results indicated that there is a good amount of reduction in stress in the proposed design as shown in Fig. 38.

**Table 6** Leaf spring design parameters (Adapted from Ref. 12)

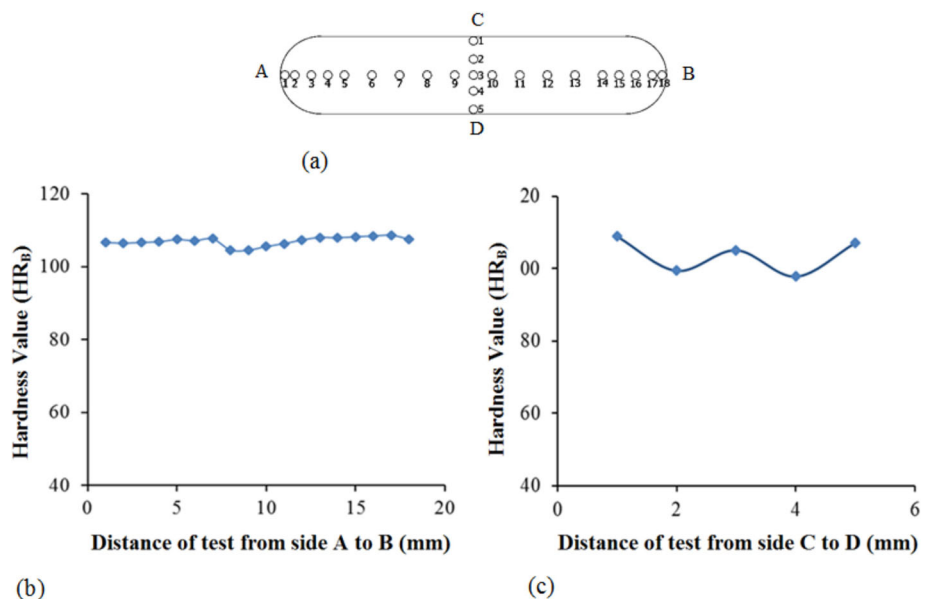
Material	50Cr1V23 (Existing)	50Si2Mn90 (Proposed)
Span length (eye to eye), (mm)	1340	1340
U-bolt spacing, (mm)	80	80
Free camber at no load condition, (mm)	96	96
Full length leaf count	2	2
Total leaf count (N)	<b>8</b>	<b>6</b>
Thickness of individual leaf, (mm)	<b>10</b>	<b>12</b>
Width of each leaf, (mm)	70	70
Maximum load in metal-to-metal position, (N)	10,500	10,500
Safety factor	2.0	2.0
Weight, (kg)	<b>34.9</b>	<b>33.8</b>
Span	Front/Rear-1150/ 1220 mm	
Width	Front/Rear-70 mm	

Bold values highlight changes in both the columns of existing and proposed material



**Fig. 38** Comparison of deformation and bending stress for existing and proposed model

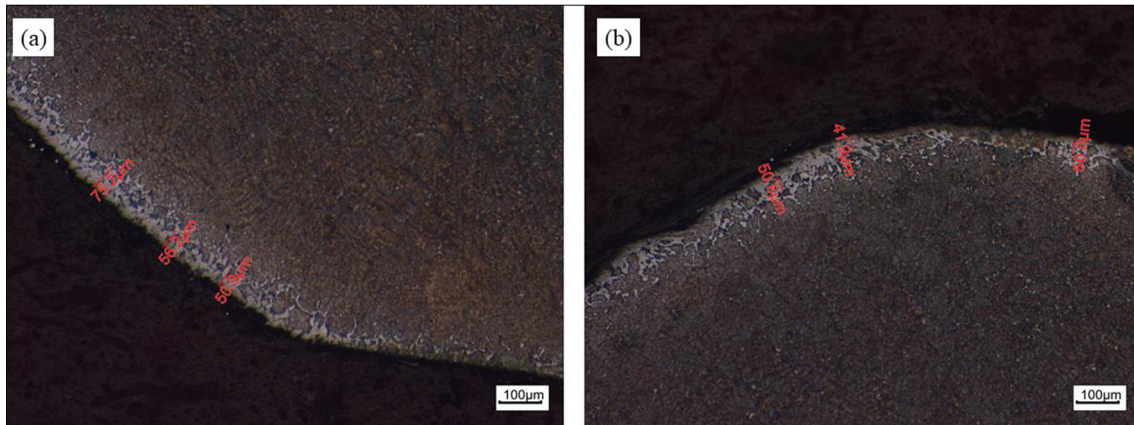
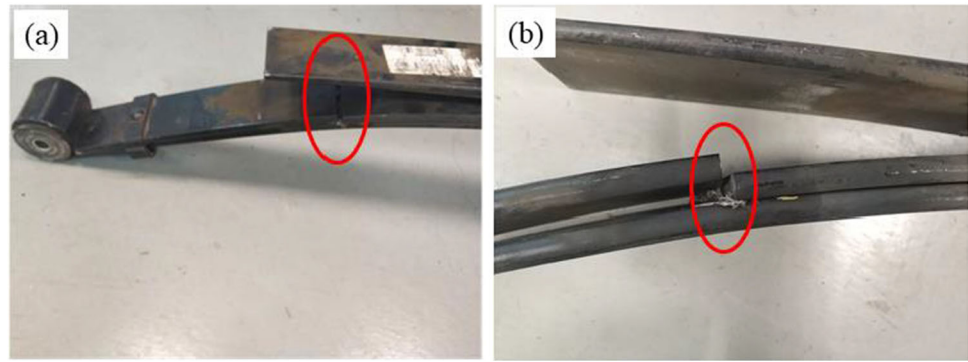
**Fig. 39** (a) Hardness test point marking on leaf. (b) Curve of hardness from A to B. (c) Curve of hardness from C to D. Reprinted from Ref. 16, available under CC BY 3.0 license at IOP Publishing Ltd



Husaini et al. [16] investigated the reason of failure of the leaf spring by obtaining stress intensity factor ( $K_I$ ) occurred at the crack tip. The stress intensity factor ( $K_I$ ) value obtained was greater than the value of fracture toughness ( $K_{IC}$ ) of selected AISI 5150 materials. This result is an evidence of crack propagation which may be considered as one of the reasons of failure. The aim of this study was to investigate the reasons of spring failure used in the diesel trucks through experimental and analytical tool. It was observed that hardness in the close vicinity of center bolt hole was lower as compared to the outer side of the spring surface as shown in Fig. 39. This concluded that the leaf spring center is tougher as compared to other areas. Hence, this spring is prone to fracture.

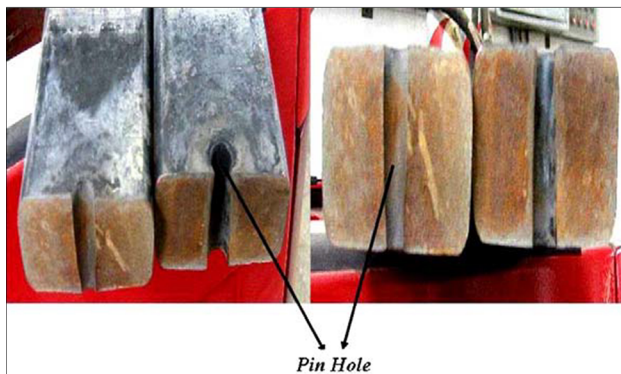
Cheng et al. [3] studied the fatigue fracture phenomenon on the graduated spring leaf of a two-layer leaf spring as shown in Fig. 40. Investigation on the surface fractography was done through a scanning electron microscope. The micro hardness tests were performed on the cross-sectional surface to examine the surface decarbonization effects as

**Fig. 40** Companion leaf showing fracture location [3]. Used with permission of Elsevier Science & Technology Journals, from The fracture of two-layer leaf spring: Experiments and simulation, Cheng, Guang; Chen, Kaiyuan; Zhang, Yu; Chen, Yuanchang, Vol 133, 2022; permission conveyed through Copyright Clearance Center, Inc



**Fig. 41** (a) Decarbonization layer close to crack initiation site. (b) decarbonization layer away from the crack initiation site [3]. Used with permission of Elsevier Science & Technology Journals, from The fracture of two-layer leaf spring: Experiments and simulation, Cheng, Guang; Chen, Kaiyuan; Zhang, Yu; Chen, Yuanchang, Vol

133, 2022; permission conveyed through Copyright Clearance Center, Inc



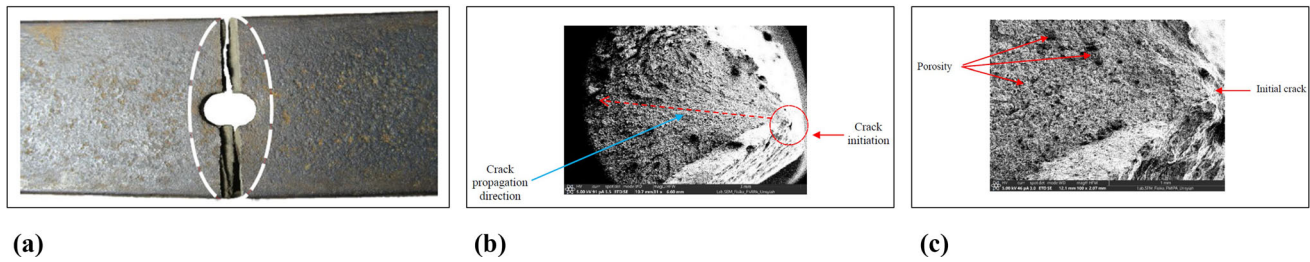
**Fig. 42** Macroscopy of fracture surface [35]. Used with permission of Elsevier Science & Technology Journals, from Failure analysis of the suspension spring of a light duty truck, Eryürek, I.B.; Ereke, M.; Gökseml, A., Vol 14(1), 2007; permission conveyed through Copyright Clearance Center, Inc

shown in Fig. 41. 3-D dynamic simulation was done to show failure pattern of the leaf spring. Through fractography analysis, the areas showing initiation of crack, fatigue rupture zone and shear lips were identified. This

simulation also confirmed that the shear lips zone are present along the width direction and fatigue zones are present along the thickness direction. It was concluded that there are two ways to improve the durability of leaf spring for this case. These are: either providing additional improved surface treatments or fitting insulation between each leaf.

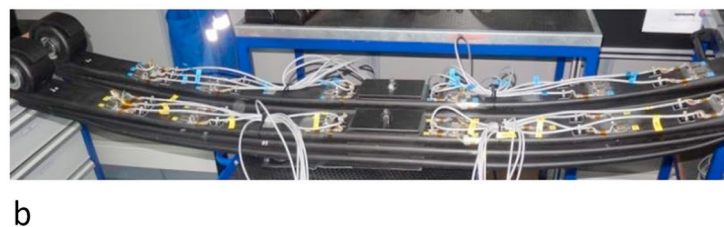
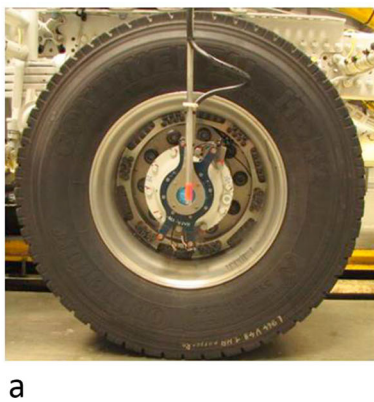
Eryurek et al. [35] analysed the failure of rear leaf spring of light duty truck. Brittle fracture was observed around the pin hole as shown in Fig. 42. After chemical and microstructural analysis, high amount of sulphur was found in the form of MnS inclusions which led to decrease in fracture toughness and this can be considered as the most probable reason for fracture. The fatigue safety factor was too low because of the notch effect and leaf spring design parameters. This can cause a sudden brittle fracture. FEM analysis was used to obtain solution so that such kind of failure mode can be eliminated in future.

Husaini et al. [1] analysed the reason of leaf spring failure in the 110 PS engine capacity truck. Visual and fractographic observation, hardness test, chemical



**Fig. 43** (a) Broken leaf spring material. (b) Fractographic image of the initial crack. (c) Porosity and initial crack [1]. Reprinted from Husaini; Anshari, Rully, The analysis of the failure of leaf spring used

as the rear suspension system in 110 PS diesel trucks, Vol 2613(1), 2023, with the permission of AIP Publishing



**Fig. 44** (a) Wheel force transducer. (b) Strain gauging on the leaf spring [20]. Reprinted from Procedia Engineering, Vol 213, Mehmet Bakir, Basaran Ozmen, Caner Donertas, Correlation of Simulation, Test Bench and Rough Road Testing in terms of Strength and Fatigue

Life of a Leaf Spring, Pages 303-312, Copyright 2018, with permission from Elsevier

composition test was done. Some small holes or porosities were found on the material surface which have the tendency to decrease the strength of a component. This presence of initial defect led to the propagation of cracks as shown in Fig. 43. Also because of overloading, the stress intensity factor analysis depicted that stress intensity factor ( $K_I$ ) and the fracture toughness ( $K_{IC}$ ) of the leaf spring material are very close to each other which is also responsible for crack propagation and fracture.

Aggarwal et al. [36] discussed the effect of fretting fatigue in semi elliptical and parabolic steel leaf springs. Small amplitude periodic movement of two solid leaves in contact under pressure is responsible for fretting fatigue which can be decreased by improving surface treatment characteristics through controlled shot peening or double shot peening, reducing interleaf friction through metallic coatings such as graphite. Structural damping of sample can be measured with the help of experimental set up. Because of the higher damping factor and almost negligible fretting fatigue in parabolic leaf spring, fatigue life of tapered leaves is found to be higher as compared to straight leaves of semi-elliptical leaf spring.

Bakir et al. [20] discussed the correlation between simulation, rig test and vehicle level testing considering strength and fatigue life of a leaf spring. This reduces the time and development cost of new designed leaf spring. Strain gauges were applied on the leaf spring (as shown in Fig. 44) to take the reading of forces and moments with the help of wheel force transducers. This data was used as an input for both test rig measurement and also in multibody simulation model. Further fatigue life was calculated through FEMFAT software.

Deulgaonkar et al. [4] discussed all the failure aspect of a suspension leaf spring used in heavy duty trucks and buses. FMEA technique has been incorporated for failure mode analysis to evaluate the root causes. Individual failure mode is given a numerical value (RPN) which is evaluated based on its detection, occurrence and severity as shown in Table 7. From FMEA and Risk priority number (RPN) analysis, it is observed that master leaf, graduated leaf and U-bolts have highest RPN values. To avoid these failures, few recommendations and guidelines were discussed in detail.

**Table 7** RPN evaluation and FMEA of leaf spring components (Adapted from Ref. 4)

Component	Failure mode	Effect	Cause	S	O	D	RPN
Master leaf	Sudden fracture	Improper functioning of suspension system	Unbalanced loads	6	13	7	546
Leaf spring eye	Brass lining worn out	Joint loosening	Impact loads	5	12	3	180
Graduated leaves	Catastrophic fracture	System becomes in operational	Overloading, missed maintenance	8	9	5	360
Shackle	Joint loose	Malfunctioning of leaf spring joint	Shear stresses, poor connection, and loosening of joint	5	5	5	125
Shackle pin	Joint loosening and rattling noise	Component malfunctions	Rust and thread wear	4	6	5	120
Central bolt	Bending and complete shear	Replacement required, performance loss	U-bolt loosening, neglected maintenance, and sudden braking	6	7	3	126
U-bolts	Gradual failure, failure due to corrosion	Replacement required, audible noise	Overloading, loosening of U-bolts, and corrosion	7	8	5	280
Eye bush	Wear failure	Loosening of joint, replacement recommended	Compression, shear stresses and neglected maintenance	6	7	5	210
Holding clamp	Shear failure	Loosening of joint, replacement needed	Unbalanced loads	6	4	3	72

## Summary

Based on the previous research done on leaf spring testing and failure analysis, factors responsible for premature failure of spring can be summarised below:

- Improper heat treatment and surface decarburization
- Vehicle overloading
- Stress intensity factor greater than fracture toughness of particular material
- Brittle fracture due to delayed hydrogen stress cracking or hydrogen embrittlement
- U-bolt improper material and heat treatment resulted in thread slip. This further leads to torque loosening and saddle failure
- Fretting fatigue and temperature rise due to friction
- Corrosion pitting on the shot peened surface layer
- Brittle fracture due to non-metallic inclusions
- Porosity of material

## Leaf Spring Alternate Material for Cost and Weight Optimisation

Senthil Kumar et al. [37] discussed on composite multi leaf spring. Before this, earlier study was done on mono composite leaf spring. Results of both multi leaf spring—one of steel and other made of glass/epoxy composites were compared. First of all, based on same design load input—maximum stress, maximum deflection and maximum stiffness of steel leaf spring were compared with the help of

**Table 8** Stress analysis of steel spring

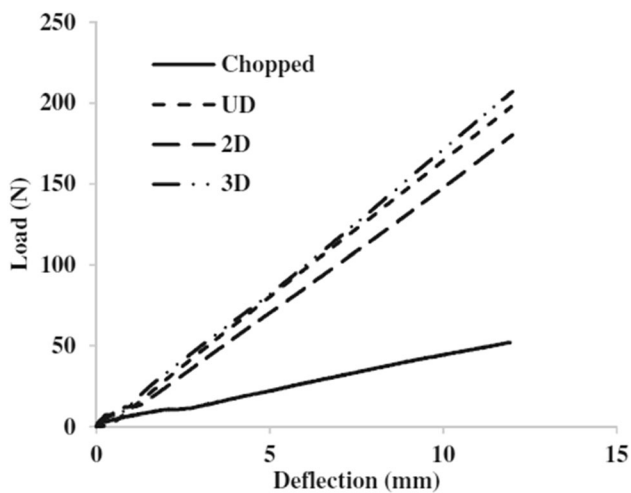
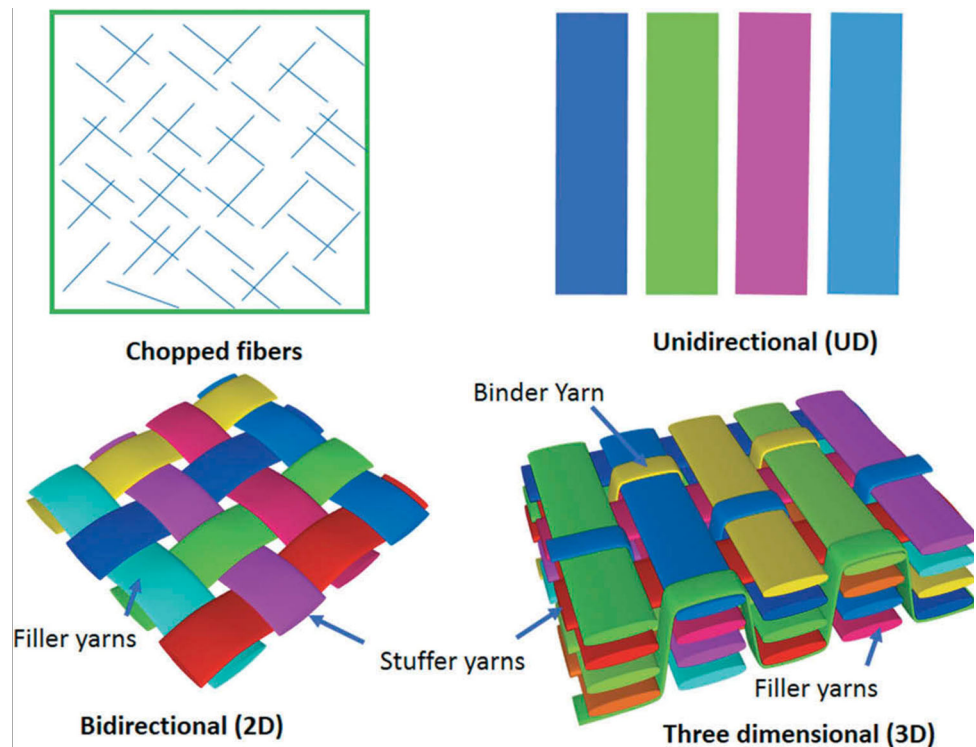
Parameters	Experimental	Analytical	FEM
Load (N)	3250	3250	3250
Maximum stress (MPa)	680.05	982.05	744.32
Maximum deflection (mm)	155	133.03	134.67
Maximum stiffness (N/mm)	20.96	24.43	24.13

Reprinted from Ref. 37, available under CC BY 4.0 license at Materials Science

experimental, analytical and FEM results as shown in Table 8. Then composite multi leaf spring was designed and modelled, further its prototype sample was prepared and tested. E-Glass/epoxy was identified as the composite material for spring based on specific strain energy of steel spring and looking same properties for available composites. Filament winding machine was used during manufacturing of composite leaf spring. Maximum stress in leaf spring of each material was compared based on experimental results. It was concluded that composite leaf spring have 67.35% lesser stress, 65% higher stiffness, 127% higher natural frequency and 68% lesser weight as compared to steel spring. Also, composites show good resistance to moisture and sea water. This material is also suitable for the working temperature range of vehicles, and it can sustain temperatures up to 220 °C.

Khatkar & Behera [17] worked on the analysis of composite leaf spring which is reinforced with various fiber architecture. Four types of composite material were prepared: chopped fibers, unidirectional (UD), bidirectional (2D) and three dimensional (3D) fibers as shown in Fig. 45.

**Fig. 45** Schematic representation [17]. Used with permission of Taylor & Francis Informa UK Ltd—Journals, from Experimental investigation of composite leaf spring reinforced with various fiber architecture, Khatkar, Vikas; Behera, B K, Vol 29, 2020; permission conveyed through Copyright Clearance Center, Inc



**Fig. 46** Load-deflection behaviour comparison [17]. Used with permission of Taylor & Francis Informa UK Ltd—Journals, from Experimental investigation of composite leaf spring reinforced with various fiber architecture, Khatkar, Vikas; Behera, B K, Vol 29, 2020; permission conveyed through Copyright Clearance Center, Inc

Fiber volume fraction and other fabricated properties were calculated for all four types of material. All these four springs were compared based on: tensile properties, load deflection behaviour, hysteresis damping and relaxation behaviour. It was concluded that the performance characteristic of 3-D woven type composite leaf spring was better as compared to other materials as shown in Fig. 46.

Abhishek Pendyala et al. [9] have done design and study of heavy leaf spring under three types of loading pattern which are- Fully reversed load (+P to - P), Zero based load (0 to P), Fluctuating load (- P/2 to - P or + P/2 to + P). Spring material used was Carbon fibre reinforced polymer composite. Three model of leaf spring was prepared with different leaf dimension. Two types of connections were defined for the analysis:

- Between Leaf & Leaf and Between Leaf & Bolt/Nut: Frictional contact
- Between Bolt & Nut: Bonded Contact

Coefficient of friction considered as 0.2. For meshing, a hexahedron element was taken for graduated leaves because of limited complexity and tetrahedron element was taken for the main leaf because of its curved surface. Using ANSYS, Von Mises stress was calculated for all three models and using these Von Mises stress, fatigue life cycle was calculated analytically for all three types of dynamic load discussed in the start. It was concluded that fully reversed load type is considered as worst case for spring analysis.

Chowdhury et al. [18] compared leaf spring of steel with composite mono leaf spring. Stress and deflection analysis was executed in ANSYS for both the material and concluded that composite perform better in every aspect. Maximum stress and weight variation in steel and composite leaf spring is shown in Fig. 47.



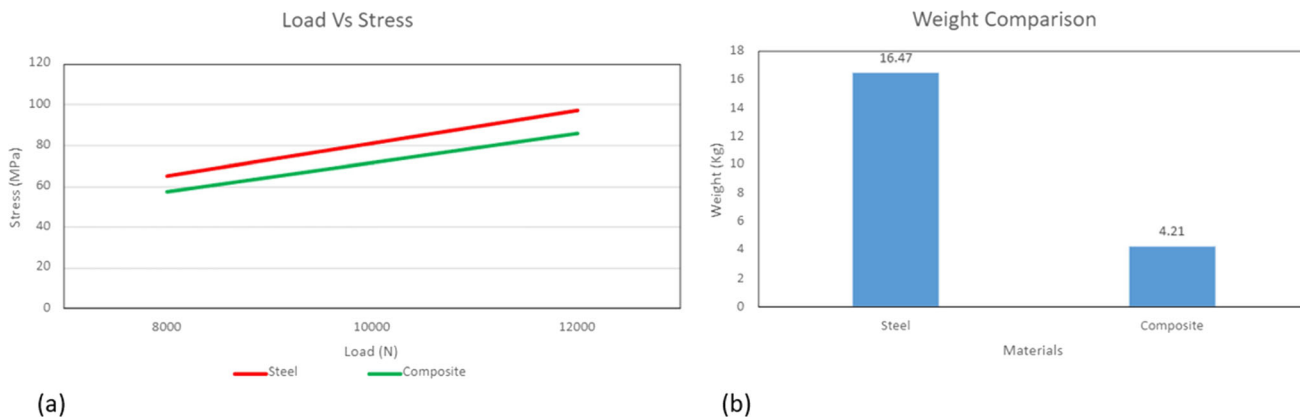


Fig. 47 (a) Stress comparison of leaf spring under different loadings. (b) Weight comparison between steel and composite spring

Table 9 Fatigue life comparison with experimental data [46]

Applied Stress level	Experimental fatigue life (mean of six samples)	Proposed relation	S-N Curve	Basquin's relation
0.6	21000	25050	55360	73580
0.65	14000	9700	10885	10560
0.75	950	880	420	330
0.8	130	180	83	69
0.85	15	23	16	16
0.9	2	1	3	4

Used with permission of SAGE Publications Ltd. Journals, from Fatigue of Composites—Fatigue Modulus Concept and Life Prediction, Hwang, W.; Han, K.S., Vol 20(2), 1986; permission conveyed through Copyright Clearance Center, Inc

Hwang and Han [46] proposed a concept of “fatigue modulus”. Using this methodology, a more relevant equation for determining fatigue life of composite material is given. Here, fatigue life equation is derived in terms of fatigue modulus. Empirical relation using strain life criterion is developed to estimate fatigue life (N) which is given in equation (3):

$$N = [B(1 - r)]^{1/c} \tag{Eq 3}$$

r, B and c are material constants which can be evaluated by the least square method. The proposed theory is verified by comparing obtained fatigue life with experimental data and other relations as shown in Table 9 and Fig. 48.

Wang et al. [13] discussed the different aspects of failure in composite leaf spring. Both static and dynamic stiffness comparison was done between composite and steel leaf spring as shown in Fig. 49. It was suggested that stiffness value of composite leaf spring should be 10-20% higher than corresponding steel leaf spring because due to low suspension stiffness, the vibration displacement of the

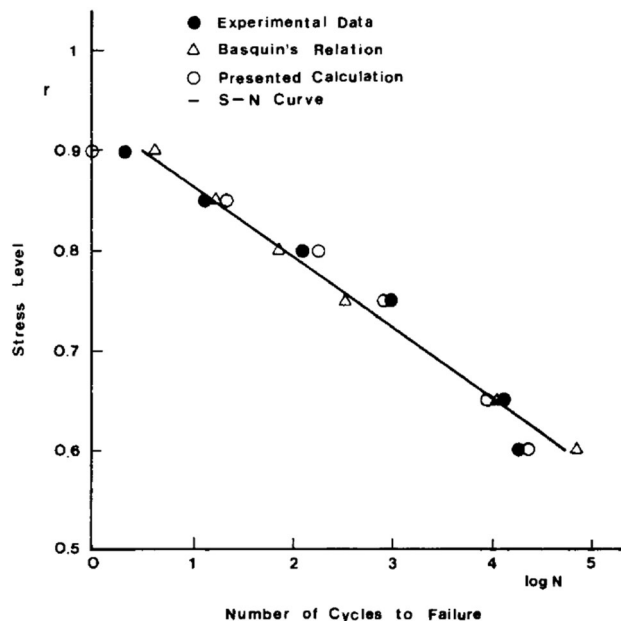
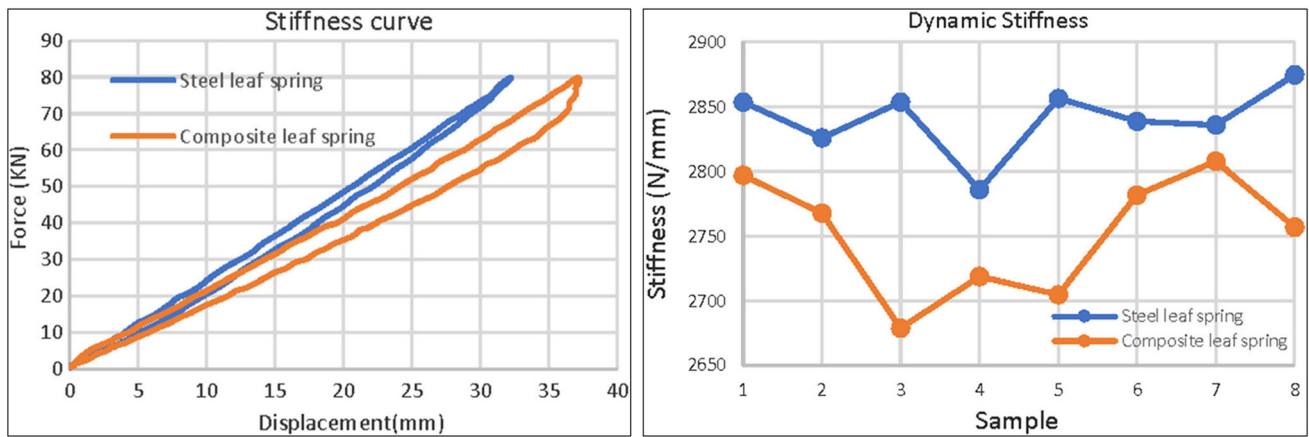


Fig. 48 Fatigue test data and predictions [46]. Used with permission of SAGE Publications Ltd. Journals, from Fatigue of Composites—Fatigue Modulus Concept and Life Prediction, Hwang, Han, Vol 20(2), 1986; permission conveyed through Copyright Clearance Center, Inc

unsprung mass will be increased, which may lead to lifting of wheel above the ground surface and change in wheel orientation. During turning, the vehicle tilt forward and the body tend to roll which is unfavourable for both comfort and stability. Composite leaf spring failure from U bolt region was also discussed and identified failure reason as the stress concentration at the interface between spring body and the cover plate. So, it was proposed that a layer of soft materials can be inserted between the spring body and the saddle plate to distribute stress. This can protect the spring body, top and bottom saddle plate. Also, lamination



**Fig. 49** (a) Static stiffness comparison. (b) Dynamic stiffness comparison [13]. Lubin Wang et al, Failure Analysis of the Longitudinal Composite Leaf Spring, Journal of Failure Analysis and Prevention, Pages 1437-1444, 2020, Springer Nature

failure was discussed and suggested that in order to prevent the failure of leaf spring, the resin glass transition temperature ( $T_g$ ) should be higher than 80 °C so that this temperature is not achieved during working life of spring.

Tadesse et al. [5] demonstrated that composite materials can be used as an alternate material for spring leaf because it provides better weight, good Von Mises stress and better deflection as compared to steel material. Four composite materials: E-glass/epoxy, Carbon epoxy, Graphite epoxy and Bamboo polyester were compared with conventional steel leaf spring. Analytical design calculation was demonstrated and other parameters like displacement, Von Mises stress, strain and weight comparison was demonstrated through FEM.

Kushwah et al. [6] compared the parameters like load bearing capacity, deflection, stress and weight of the composite leaf spring with that of the steel. Deformation and stresses were taken as inputs for design. Also, Taguchi technique was used for the design of experiment (DOE) evaluation considering three variable factors as length, thickness and number of leaves. Based on deformation and stress parameter, carbon epoxy was found to be the best material.

**Summary**

Based on the previous research done on leaf spring alternate materials other than different grades of steel, below points can be summarised:

- E-glass/epoxy, Graphite epoxy, Carbon epoxy and Bamboo polyester can be used as the alternate composite materials for leaf spring but manufacturing

process requires huge initial investment and also mass production feasibility is the concern

- Manufacturing of leaf spring eye is the great challenge in case of composites

**Conclusion**

The study done by us here gives a review on previous research paper based on leaf spring design, manufacturing, finite element analysis (FEA) and alternate material selection for weight and cost optimisation. The review has also shown ways to assess the performance of leaf spring through analytical, computational and experimental methodology. Various manufacturing and infield defects were discussed in detail to understand things gone wrong. There are multiple challenges related to design, manufacturing and field abuse by customers which lead to premature failure of leaf spring. These challenges are categorised into three sections which are: design challenges, manufacturing challenges and field failure challenges. All three are discussed below in detail.

**Design Challenges**

- Need for increase payload capacity of vehicle by converting rear tandem axle into independent axle and robust leaf spring design
- Need for proper selection of leaf spring caster angle in front suspension which is one of the critical parameters of wheel alignment responsible for tyre wear
- Need for robust design of leaf spring eye considering stress limit within the yield strength of material

- Proper selection of paint type and thickness to avoid the effect of corrosion, peeling and blistering
- Weight and cost optimization through selection of alternate leaf spring material which further enhances fluid economy of vehicle

#### Manufacturing Challenges

- Control on heat treatment process: hardening, quenching and tempering for required hardness and microstructure
- Control on the shot peening parameters like shot size, velocity, etc. for required result
- Control on the surface decarburization to get good hardness and fatigue strength
- Nipping of leaf spring and proper assembly of individual leaf to nullify the effect of assembly stress and undesired interleaf gap
- Require detailed study on brittle fracture due to delayed hydrogen stress cracking or hydrogen embrittlement
- Require detailed study on Ausform process which is basically a combination of austenitization, deformation by rolling and quenching followed by tempering

#### Field Failure Challenges

- Failure of leaf spring due to overloading by customer
- Failure of leaf spring and its centre bolt because of U bolt torque loosening
- Non design confirming extra leaf addition by customer resulting in failure of other aggregates like brackets, clamps, axle beam, chassis frame, etc.
- Failure of leaf spring because of environmental embrittlement caused by corrosion pits

To overcome all these challenges, there is a need for leaf spring design and manufacturing process optimization which will further improve the durability and reliability of component.

#### Research Gap

After intensive study of these research papers and recent challenges, it is found that there are few areas in the field of semi elliptical leaf spring which are still unexplored and needs further work to be carried out in this field which forms the basis of research gap. These are:

- Manufacturing process improvement by introducing ausforming process in heat treatment and controlling percentage of deformation during rolling operation to get optimised B<sub>10</sub> and B<sub>50</sub> spring life. This can be further supported by the Double peening surface treatment process in which the control factors like peening intensity, shot diameter, shot angle and turbine discharge rate can be optimised to get a good balance between surface decarburization and residual compressive stress
- Introducing solid lubrication like graphite powder during painting operation to get enhanced surface texture, thereby eliminating the effect of friction, corrosion pitting and fretting fatigue which can be further supported by optimising the baking temperature in paint booth to get improved dry film thickness (DFT) on leaf surface
- Vehicle loading capacity enhancement by converting tandem axle into independent axle through increased axle spacing and design optimisation

As per regulation, tandem axles as shown in Fig. 50 are the two connected axles where the distance between two axles should be less than 1.8 meter and for rigid vehicles, tractor-trailer arrangement it has a maximum load bearing capacity of 21Tonnes. This puts limitation on the maximum gross vehicle weight of vehicle when number of axles is fixed. If we further want to increase the load capacity of vehicle then this tandem axle needs to be converted into independent axle by increasing distance between them to more than 1.8 meter. This way GVW of a vehicle can be increased providing opportunities to carry extra pay load.

Since, load on the axle is increased by increasing axle spacing, this affects the mounting position of leaf spring on chassis which in result changes the leaf spring span, stiffness and bending stresses as shown in Fig. 51. These parameters can be optimized by incorporating the improved design technique and considering ausforming during heat treatment as enhancement in manufacturing process. Table 10 explains the effect of increased axle spacing on leaf spring dimensional parameters and loading capacity.

- Design improvement is required to resolve the problem of U bolt torque loosening which is very obvious phenomenon in leaf spring type suspension system at early service kilometres of vehicle. This can lead to multiple failure mode in leaf spring near center bolt, saddle plate and sometimes U bolt also.

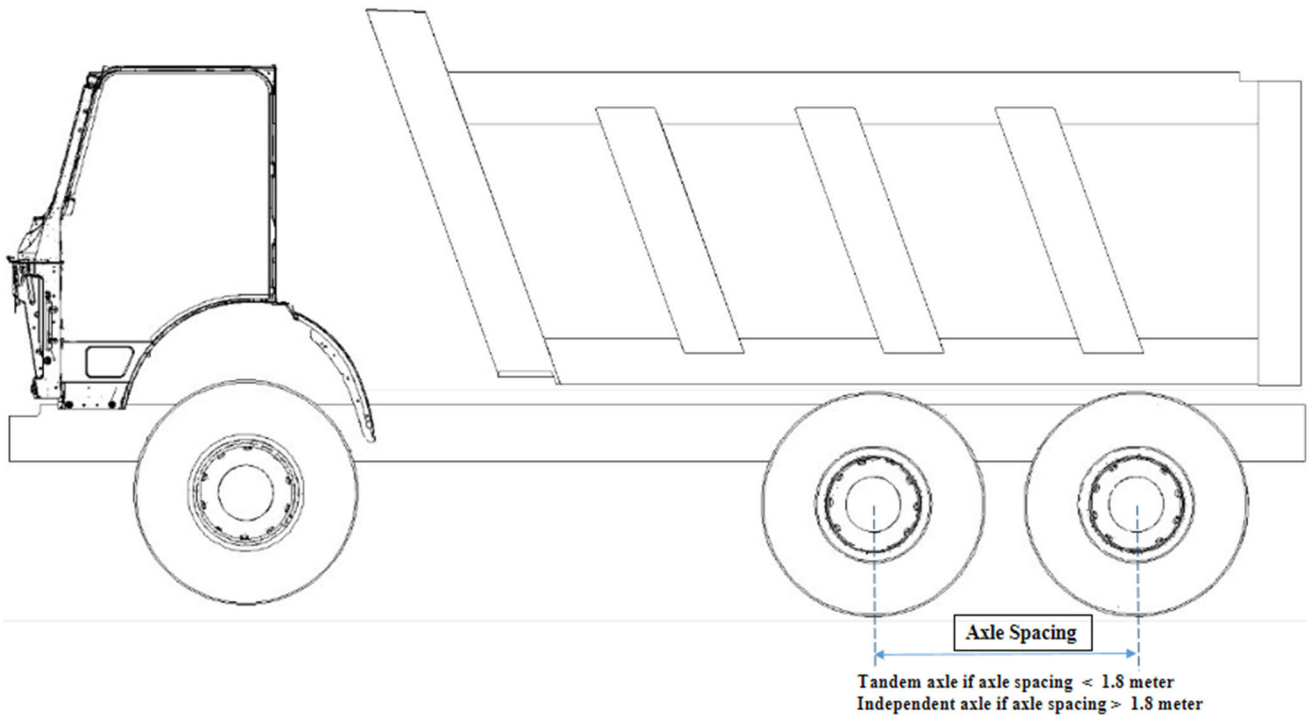


Fig. 50 Rear axle arrangement in multi axle vehicle

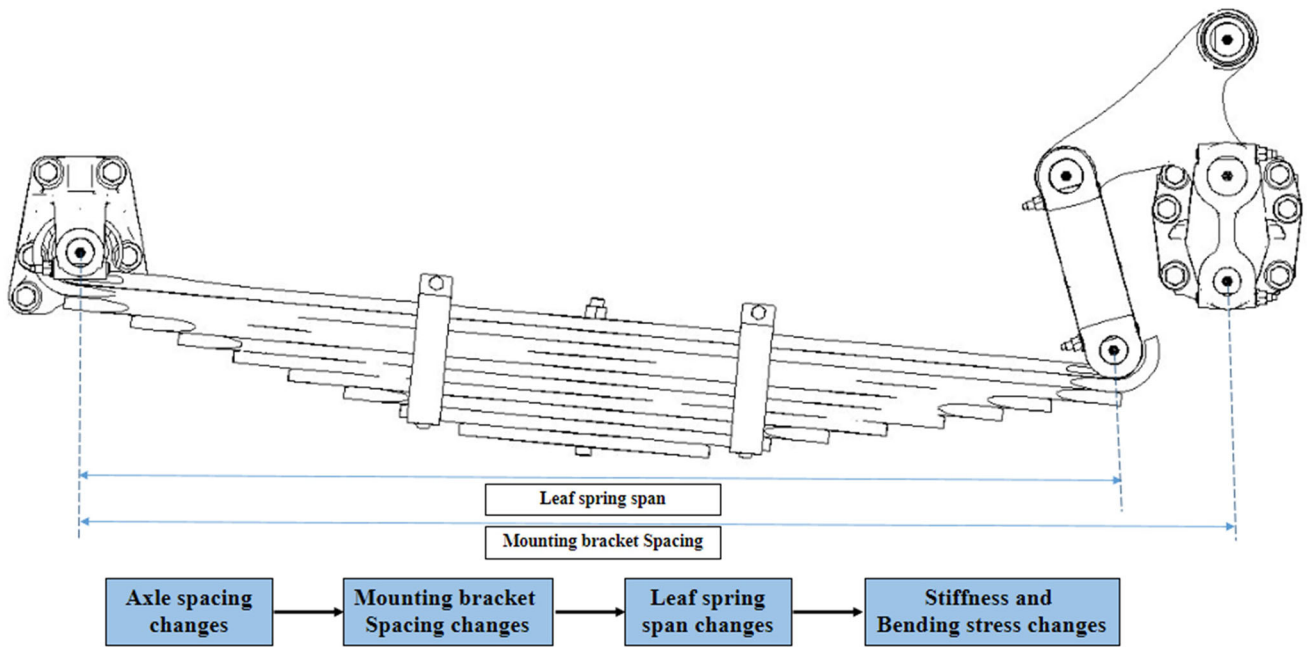


Fig. 51. Change in spring parameters with increased axle spacing

**Table 10** Suspension categorisation as per vehicle application and loading capacity

Vehicle Model GVW		Vehicle application	Front axle suspension type (Mechanical)	Rear axle suspension type (Mechanical)	Rear axle capacity (RAW)		Rear axle spacing (in mm)	
Present	Proposed				Present	Proposed	Present	Proposed
28 Ton	30 Ton	Truck/Tipper (Surface/ Mining)	Semi elliptical multi leaf spring/ Parabolic leaf spring	Truck-Semi elliptical multi leaf spring/Slipper suspension	21 Ton	23 Ton	1350	1830
35 Ton	37 Ton	Truck/Tipper (Surface)		Tipper- Semi elliptical multi leaf spring/ Multi-stage leaf spring/Bogie suspension	21 Ton	23 Ton	1350	1830
42 Ton	44 Ton	Truck/Tipper (Surface)		Both Truck & Tipper-Semi elliptical multi leaf spring/Slipper	21 Ton	23 Ton	1350	1830
48 Ton	49 Ton	Truck/Tipper (Surface)		suspension/ Multi-stage leaf spring	21 Ton	23 Ton	1350	1830

- Weight optimization of vehicles is one of the important parameters for improved payload and better fluid economy. So, there is a further scope of work for choosing composite materials as an alternative to steel for the leaf springs of heavy-duty trucks. Also, the manufacturability of a composite leaf spring eye with a feasible cost solution needs to be studied further.
- The application of leaf springs in cabin suspension system can be studied further from ride and comfort point of view.

## References

- H. Husaini et al., The analysis of the failure of leaf spring used as the rear suspension system in 110 PS diesel trucks. *AIP Conf. Proc.* **2613**, 020001 (2023)
- M.N. James et al., Embrittlement failure of 51CrV4 leaf springs. *Eng. Failure Anal.* **139**, 105971 (2022)
- G. Cheng et al., The fracture of two-layer leaf spring: experiments and simulation. *Eng. Failure Anal.* **133**, 105971 (2022)
- V.R. Deulgaonkar et al., Failure analysis of leaf spring used in transport utility vehicles. *J Fail. Anal. Preven.* **22**, 1844–1852 (2022)
- B.A. Tadesse et al., Design optimization and numerical analyses of composite leaf spring in a heavy-duty truck vehicle. *Mater. Today Proc.* **62**, 2814–2821 (2022)
- S. Kushwah et al., A methodological study of leaf spring by material comparison and Taguchi's DOE. *Int. J. Interact. Des. Manufact. (IJIDeM)*. **16**, 239–252 (2022)
- M. Malikoutsakis et al., (2021) On the effects of heat and surface treatment on the fatigue performance of high-strength leaf spring. in 6th International Conference of Engineering against Failure (ICEAF-VI 2021).
- H. Husaini et al., Failure analysis of a fractured leaf spring as the suspension system applied on the dump truck. *Key Eng. Mater.* **892**, 89–98 (2021)
- A. Pendyala et al., Fatigue life of composite leaf spring assembly. in *IOP Conf. Ser.: Materials Science and Engineering* (2021).
- P. Kurniawan et al., Leaf spring type simulation with finite element method approach. *IOP Conf. Ser. Mater. Sci. Eng.* **1034**, 012015 (2020)
- W.H. Tan et al., Failure analysis of leaf spring for commercial vehicle. in *Proceedings of 8th International Conference on Advanced Materials Engineering & Technology (ICAMET 2020)*.
- M. Nataraj et al., Failure analysis of leaf spring suspension system for heavy load truck vehicle. *Int. J. Heavy Vehicle Syst.* **27**(1–2), 1–17 (2020)
- L. Wang et al., Failure analysis of the longitudinal composite leaf spring. *J Fail. Anal. And Preven.* **20**(4), 1437–1444 (2020)
- L. Abdullah et al., Fatigue life-based reliability assessment of a heavy vehicle leaf spring. *Int. J. Structural Integrity.* **10**(05), 726–773 (2019)
- M. Staco et al., (2019) Failure analysis of a damaged U-Bolt top plate in a leaf spring. *CAE, 2018 LNME Pg. No. (736-743)*.
- H. Husaini et al., Study of leaf Spring fracture behaviour used in the suspension systems in the diesel truck vehicles. *IOP Conf Ser. Mater. Sci. Eng.* **541**(1), 012046 (2019)
- V. Khatkar, B.K. Behera, Experimental investigation of composite leaf spring reinforced with various fiber architecture. *Adv. Compos. Mater.* **29**(2), 129–145 (2019)
- S.K. Chowdhury, and M.K. Islam, (2019) Design and analysis of a composite mono leaf spring. in *Proceedings of the 5th International Conf. in Engineering Research, Innovation and Education Bangladesh*.
- R.A. Bock, W.M. Justusson, Lightweight leaf springs. *SAE Int.* **680412**, 1443–1452 (2018)
- M. Bakir et al., Correlation of simulation, test bench and rough road testing in terms of strength and fatigue life of a leaf spring. *Proc. Eng.* **213**, 303–312 (2018)
- W. Krason, J. Wysocki, Investigation of friction in dual leaf spring. *J. Friction Wear.* **38**, 233–241 (2017)
- R. Fragoudakis et al., Optimizing the development and manufacturing of 56SiCr7 leaf springs. *Int. J. Fatigue.* **108**, 1–12 (2017)
- Y.S. Kong et al., Failure assessment of a leaf spring eye design under various load cases. *Eng. Failure Anal.* **63**, 146–159 (2016)
- M. Bakir et al., "Comprehensive durability assessment of leaf springs with CAE methods" *SAE International 2014-01-2297* (2014).
- R. Fragoudakis et al., Microstructure, surface characterization and fatigue assessment of 56SiCr7 spring steel. *Key Eng. Mater.* **605**, 376–379 (2014)
- S. Karditsas et al., (2014) Leaf springs-design, calculation and testing requirements. in *35th Int. Symposium on Mechanics and Materials, Greece*.
- H.A.O. Kai-ming et al., Design of test bench for automotive leaf spring. *Adv. Mater. Res.* **834–836**, 1718–1722 (2014)

28. Y.S. Kong et al., Fatigue life prediction of parabolic leaf spring under various road conditions. *Eng. Failure Anal.* **46**, 92–103 (2014)
29. BG Scuracchio et.al, (2012) Leaf springs durability analysis and weight reduction through double peening” SAE International 2012-36-0128 (2012).
30. R. Fragoudakis et al., Fatigue assessment and failure analysis of shot-peened leaf springs. *Fatigue Fract. Eng. Mater. Struct.Fract. Eng. Mater. Struct.* **2012**, 1–10 (2012)
31. W. Peng et al., Failure analysis on the collapse of leaf spring steels during cold-punching. *Eng. Failure Anal.* **17**, 971–978 (2010)
32. J.J. Fuentes et al., Premature fracture in automobile leaf springs. *Eng. Failure Anal.* **16**, 648–655 (2009)
33. H. Xiaoping et al., An engineering model of fatigue crack growth under variable amplitude loading. *Int. J. Fatigue.* **30**, 2–10 (2008)
34. S Laroia et al., (2007) Hydrogen embrittlement failure in suspension leaf springs. SAE International 2007-01-4257.
35. I.B. Eryurek et al., Failure analysis of the suspension spring of a light duty truck. *Eng. Failure Anal.* **14**, 170–178 (2007)
36. M.L. Aggarwal et al., Issues in fretting fatigue design of shot peened leaf springs. *Indian J. Eng. Mater. Sci.* **14**, 414–418 (2007)
37. M.S. Kumar et al., Analytical and experimental studies on fatigue life prediction of steel and composite multi-leaf spring for light passenger vehicles using life data analysis. *Mater. Sci.* **13**(02), 141–146 (2007)
38. P. Johannesson et al., Fatigue life prediction based on variable amplitude tests-methodology. *Int. J. Fatigue.* **27**, 954–965 (2005)
39. N Shamsaei, D Rezaei, (2004) Comparing fatigue life reliability of a composite leaf spring with a steel leaf spring. in Proceedings of 7th Biennial Conference on Engineering Systems Design and Analysis
40. I. Sohn et al., Fatigue design of leaf spring based on proving ground. *Key Eng. Mater.* **261–263**, 1295–1300 (2004)
41. S. Tekeli, Enhancement of fatigue strength of SAE 9245 steel by shot peening. *Mater. Letter.* **57**, 604–608 (2002)
42. M.T. Todinov, Residual stresses at the surface of automotive suspension springs. *J. Mater. Sci.* **35**, 3313–3320 (2000)
43. W.F. Wu et al., Estimation of fatigue damage and fatigue life of components under random loading. *Int. J. Pres. Ves. Piping.* **72**, 243–249 (1997)
44. N.K. Mukhopadhyay et al., Premature failure of a leaf spring due to improper materials processing. *Eng. Failure Anal.* **4**, 161–170 (1997)
45. P. Santika et al., Durability testing of leaf spring and shock absorber. *SAE Int.* **871**, 284.1-284.8 (1987)
46. W. Hwang, K.S. Han, Fatigue of composites-fatigue modulus concept and life prediction. *J. Compos. Mater.* **20**, 154–165 (1986)
47. J.D. Morrow, The effect of selected sub-cycle sequences in fatigue loading histories. *Random Fatigue Life Predict.* **72**(43), 60 (1986)

**Publisher’s Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Springer Nature or its licensor (e.g. a society or other partner) holds exclusive rights to this article under a publishing agreement with the author(s) or other rightsholder(s); author self-archiving of the accepted manuscript version of this article is solely governed by the terms of such publishing agreement and applicable law.