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FATIGUE LIFE ENHANCEMENT IN CONVENTIONAL MULTI-LEAF SPRINGS USING NEW DESIGN TECHNIQUE AND COMPARISON BETWEEN VKP AND CONVENTIONAL MULTI-LEAF SPRING

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Abstract

A new design technique for designing multi-leaf springs is the subject of this research paper. Automobile industries always search for alternatives to reduce the mass of the vehicle, to increase its performance. A new approach is used for reducing the mass of a conventional multi-leaf spring, and also enhancing its fatigue life. The new spring made by using this approach is called 'VKP spring'. Stress, strain, and total deformation are the designing constraints. 55Si2Mn90 steel and E-Glass/epoxy are used to compare the results of fatigue life of multi-leaf springs, at a range of loads. Modeling is done using FUSION 360 and ANSYS 15 is used to perform static structural analysis.

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1. INTRODUCTION

To increase the performance of a vehicle, mass reduction has become quite a popular subject for research, in automobile industry. Use of glass fiber reinforced plastic in place of steel, is the perfect example of mass reduction and increase in strength of the part. To make riding more comfortable for the user, suspension system of the vehicle is designed to absorb the energy caused by vibrations and sporadic impacts, and then to release it slowly. This energy stored in the suspension system (leaf spring) is called the strain energy. Higher specific strain energy is a recommended characteristic for leaf springs. Strain energy is inversely proportional to Young's modulus and density of the material. Lower the modulus and density; higher the strain energy capacity. This is why E Glass/Epoxy is preferred over steel [1]. It is not feasible to utilize overall strain energy capacity of a leaf spring. This paper suggests a method to increase the stress and strain life of a multi-leaf spring, by slightly decreasing the overall strain energy stored in the spring. This new design method utilizes the material near ineffective length of the multi-leaf spring, to reduce the stress by spreading it uniformly, which conventional multi-leaf spring doesn't.

2. TOOLS USED FOR ANALYSIS

Both the multi-leaf springs are modeled in Autodesk FUSION 360 [3]. ANSYS 15 is used for static structural analysis of both the multi-leaf springs: conventional and VKP. The conditions and parameters used for analysis is same for both the springs. To define the movement of the leaf spring used in this analysis, the constraints used are exactly the same as that of an actual leaf spring in an automobile. The cylindrical eyes of multi-leaf springs are free to rotate about their axes; however, the front eye can move in the X-direction; whereas, rear eye is constrained. Fatigue analysis of multi-leaf spring made up of 55Si2Mn90 steel, is done using fatigue tool in ANSYS 15, and Han and Hwang formula [7] is used to predict fatigue life of E Glass/Epoxy multi-leaf spring [4].

3. CONVENTIONAL MULTI-LEAF SPRING

Multi-leaf springs are made up of master leaf and graduated leaves. The length of the master leaf is used to determine the lengths of graduated leaves. If U-bolts are used then there are two lengths in a multi-leaf spring: effective length and ineffective length. Ineffective length is the length which cannot be used for suspension.

Fig 1: Conventional multi-leaf spring

Dimensions of multi-leaf spring:
Length of master leaf spring (2L) = 1220 mm
Thickness of leaves(t) = 7 mm
Width of leaves(b) = 70 mm

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Camber = 80 mm
Number of full length leaves(n_f) = 2
Number of graduated leaves(n_g) = 8
Total number of leaves(n) = 10

Ineffective length i.e.; the distance between U-bolts is taken as 150 mm. Effective length of the leaf spring can be calculated by the formula:

$$\text{Effective length} = 2L - (2/3)\, l, \quad (1)$$

where l is the ineffective length.
Effective length = 1220 – (2/3) × 150 mm
Effective length = 1120 mm

Formula to calculate length of graduated leaves =

$$\frac{Effective\ length}{n-1} \times \text{leaf number} + \text{Ineffective length}, \quad (2)$$

Leaf number is unity for the smallest leaf, and then increases by one for the next leaf.

Length of smallest leaf = $\frac{1120}{10-1} \times 1 + 150 = 274.44$ mm
Length of 2nd leaf = $\frac{1120}{10-} \times 2 + 150 = 398.88$ mm
Similarly, Length of 3rd leaf = 523.33 mm
Length of 4th leaf = 647.77 mm
Length of 5th leaf = 772.22 mm
Length of 6th leaf = 896.66 mm
Length of 7th leaf = 1021.11 mm
Length of 8th leaf = 1145.55 mm

$$\text{Length of master leaf with eyes} = 2L + 2\pi\,(d + t), \quad (3)$$
$$= 1220 + 2\pi\,(40+7)$$
$$= 1515.16 \text{ mm}$$

where d is the diameter of eye. This type of spring is suitable for heavy truck applications [2].

3.1 Analysis of 55Si2Mn90 Steel Leaf Spring

55Si2Mn90 steel is the most common material used for making leaf springs. High tensile strength along with comparable low modulus of elasticity, makes it a good choice for making metallic multi-leaf springs.

Properties of 55Si2Mn90 steel are [5]:
Young's modulus (E) = 210 Giga Pascals
Poisson ratio (μ) = 0.3
Ultimate tensile strength = 1962 Mega Pascals
Tensile yield strength = 1470 Mega Pascals
Density (ρ) = 7850 kg/m^3

Finite element analysis is performed on ANSYS 15, using above material properties. Experimental and analytical results are not available. The load is applied on the bottom of the multi-leaf spring i.e.; on the bottom face of the smallest leaf. Meshing used in the analysis is kept fine, to get accurate results.

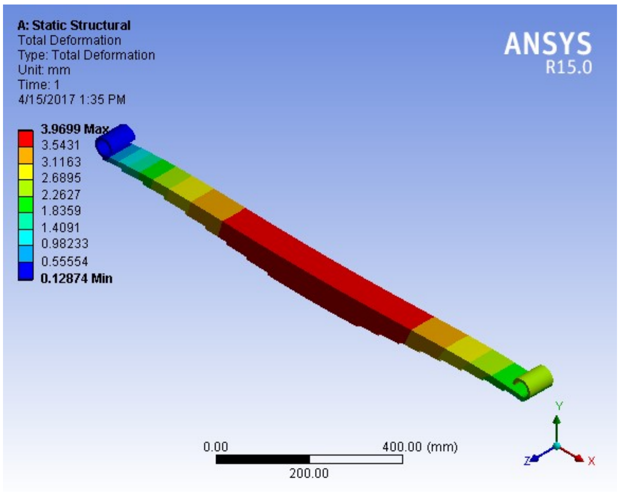

Fig 2: Deformation in the steel spring at load 15000 N.

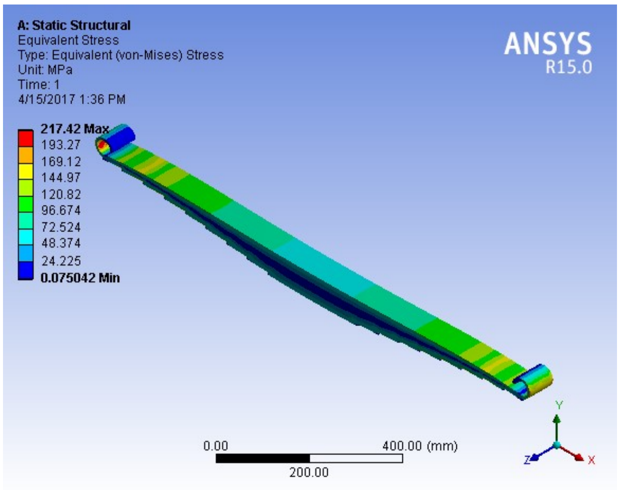

Fig 3: Stress in the steel spring at load 15000 N

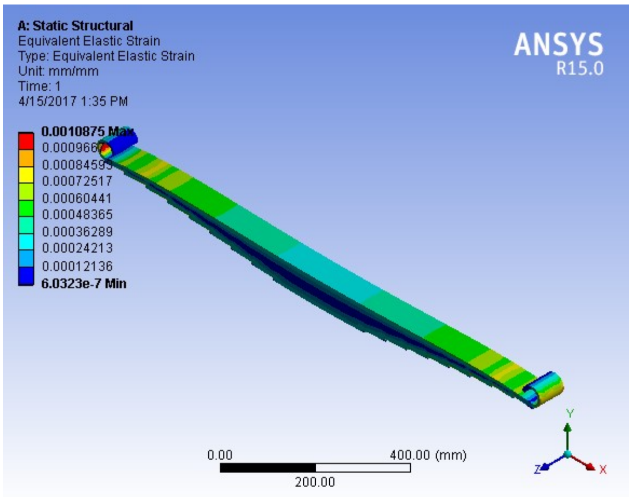

Fig 4: Strain in the steel spring at load 15000 N

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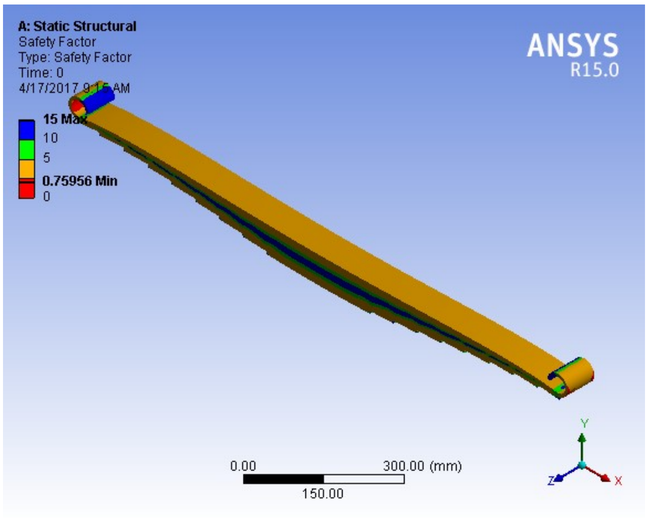

Fig 5: Stress safety factor in the steel spring at 15000 N

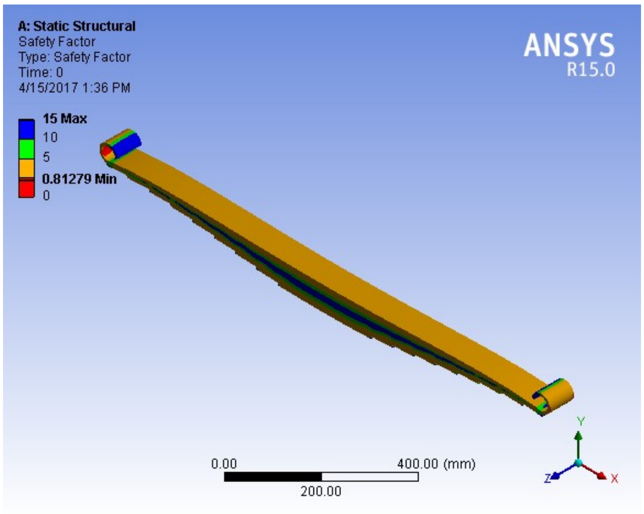

Fig 6: Strain safety factor in the steel spring at 15000 N

3.2 Analysis of E Glass/Epoxy Leaf Spring

E Glass/Epoxy leaf springs make a better suspension system than steel leaf springs because they have a higher specific strain energy capacity than steel leaf springs. Strain energy is given by the equation,

$$S = \frac{1}{2}\frac{\sigma_a^2}{\rho E} \qquad (4)$$

where S is the strain energy, σ_a is the allowable stress, ρ is the density, and *E* is the modulus of elasticity. As per the equation, the material having low modulus of elasticity and density will store more strain energy. The density of steel is approximately 3 times more than the E Glass/Epoxy. Material properties of E Glass/Epoxy are listed in Table 1 [5]. ANSYS results are shown in figures below Table 1.

Table 1: Material properties of E Glass/Epoxy

S No.	Properties	Value
1.	Tensile modulus along X-direction (Ex), MPa	34000
2.	Tensile modulus along Y-direction (Ey), MPa	6530
3.	Tensile modulus along Z-direction (Ez), MPa	6530
4.	Tensile strength of the material, MPa	900
5.	Compressive strength of the material, MPa	450
6.	Shear modulus along XY-direction(Gxy), MPa	2433
7.	Shear modulus along YZ-direction(Gyz), MPa	1698
8.	Shear modulus along ZX-direction(Gzx), MPa	2433
9.	Poisson ratio along XY-direction (NUxy)	0.217
10.	Poisson ratio along YZ-direction (NUyz)	0.366
11.	Poisson ratio along ZX-direction (NUzx)	0.217
12.	Mass density of the material (*ρ*), kg/m^3	2600
13.	Flexural modulus of the material, MPa	40000
14.	Flexural strength of the material, MPa	1200

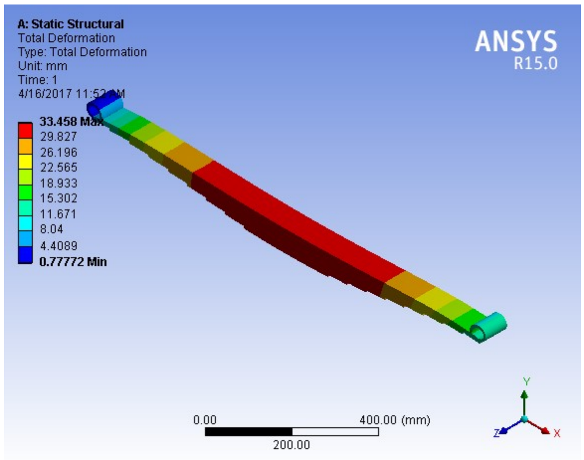

Fig 7: Deformation in E Glass/Epoxy spring at 15000 N

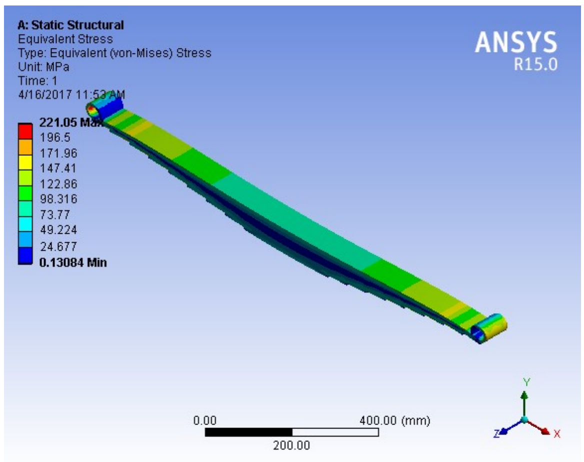

Fig 8: Stress in E Glass/Epoxy spring at load 15000 N

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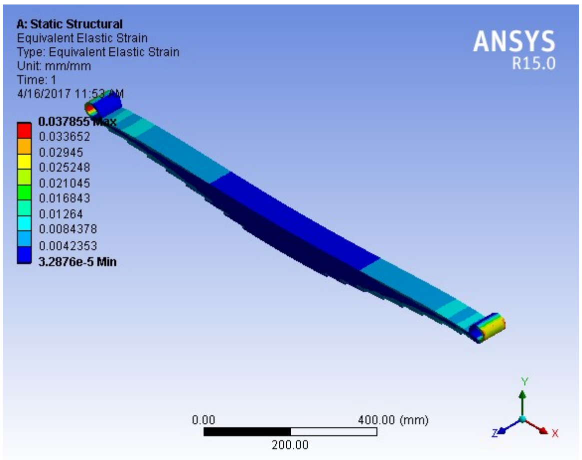

Fig 9: Strain in E Glass/Epoxy spring at load 15000 N

4. VKP MULTI-LEAF SPRING

VKP multi-leaf spring is made by using a different modeling approach as that of a conventional multi-leaf spring. The material in the conventional leaf spring which doesn't participate in the suspension, and reduction of stress and strain, is removed in the VKP spring.

Fig 10: VKP multi-leaf spring.

The width of VKP spring is not uniform; it is decreasing towards the center or ineffective length of the leaf spring. This decrement in width is made to reduce the stress and strain around the eyes of the leaf spring. The width at the rear eye is 70 mm, and it is reduced to 63 mm, at the rear end of the smallest leaf. Similarly, the width at the front eye is 70 mm, and it is reduced to 56 mm, at the rear end of the smallest leaf. This reduction is given by ratios: b/10 and b/5 i.e.; the width is reduced by 7, and again reduced by 14 with respect to b. This reduction ratio is only effective for leaf springs of width greater than 50 mm. Top views of VKP and conventional multi-leaf spring are shown in figures 11 and 12.

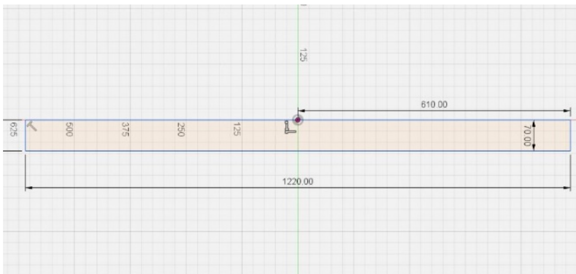

Fig 11: Top view of conventional multi-leaf spring.

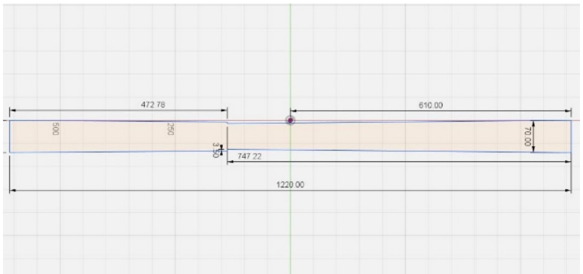

Fig 12: Top view of VKP multi-leaf spring.

4.1 Analysis of 55Si2Mn90 Steel Leaf Spring

The material properties used for analysis of VKP 55Si2Mn90 steel multi-leaf spring are same as that of conventional steel multi-leaf spring. All other parameters are also same including constraints, forces, meshing size etc. ANSYS results of VKP steel leaf spring are shown in figures below.

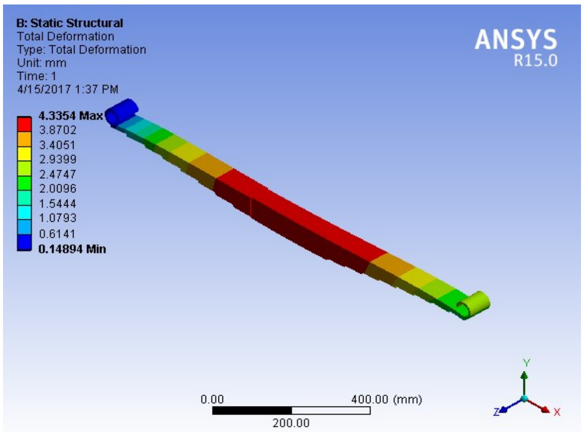

Fig 13: Deformation in VKP steel spring at load 15000 N.

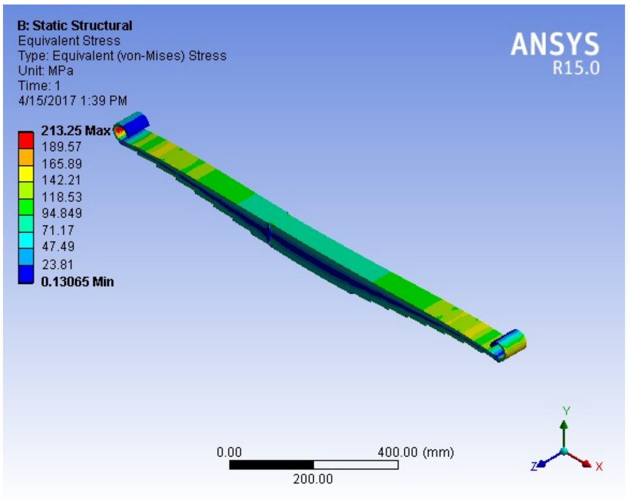

Fig 14: Stress in VKP steel spring at load 15000 N.

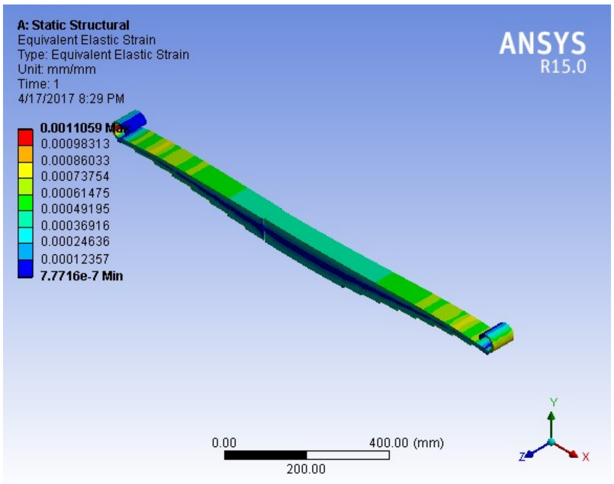

Fig 15: Strain in VKP steel spring at load 15000 N.

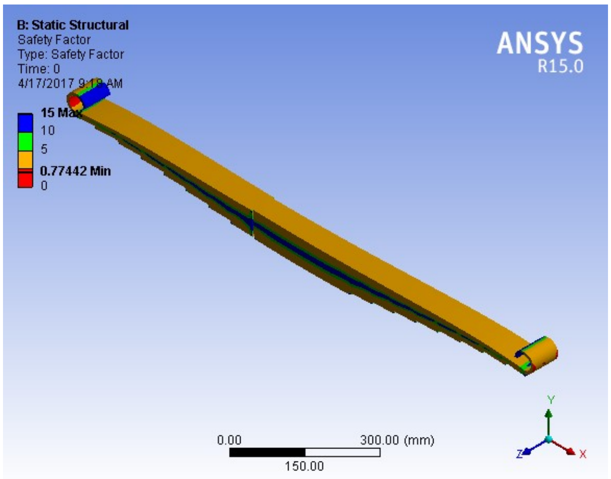

Fig 16: Stress safety factor in VKP steel spring at load 15000 N.

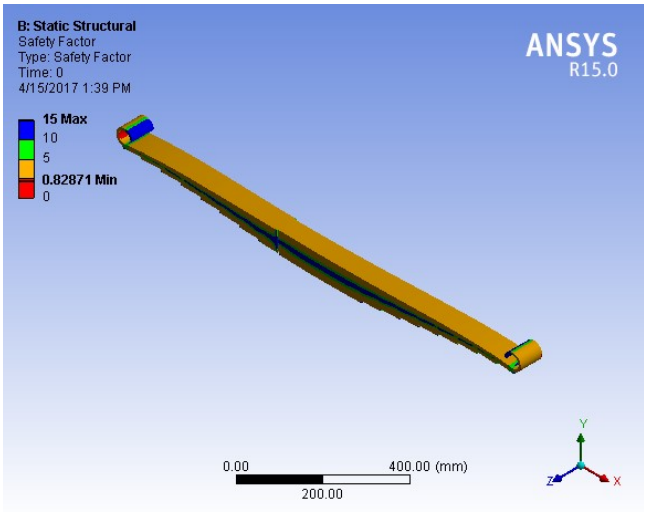

Fig 17: Strain safety factor in VKP steel spring at load 15000 N.

4.2 Analysis of E Glass/Epoxy Leaf Spring

ANSYS results of VKP E Glass/Epoxy leaf spring are shown in figures below.

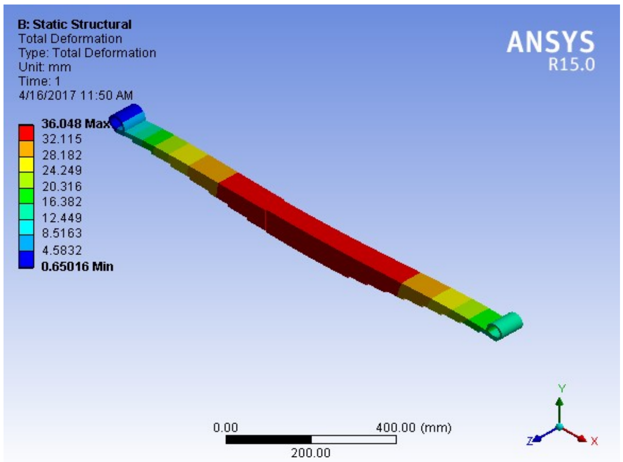

Fig 18: Deformation in VKP E Glass/Epoxy spring at load 15000 N

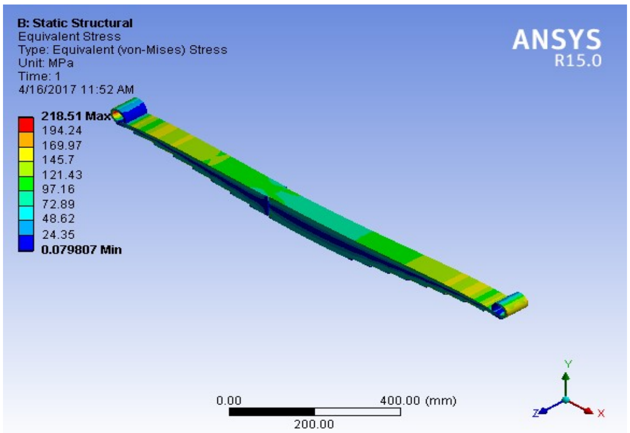

Fig 19: Stress in VKP E Glass/Epoxy spring at load 15000 N

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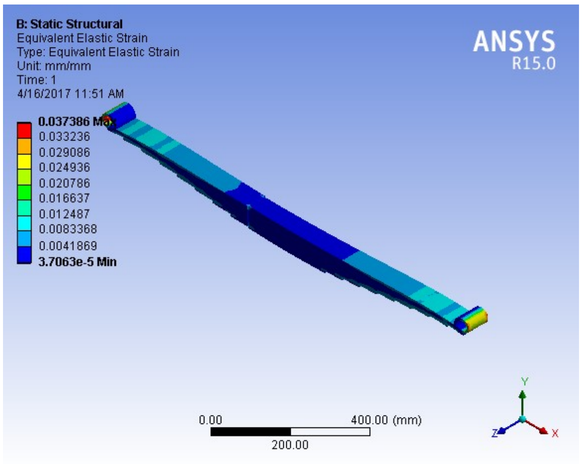

Fig 20: Strain in VKP E Glass/Epoxy spring at 15000 N

5. FATIGUE LIFE COMPARISON BETWEEN VKP AND CONVENTIONAL MULTI-LEAF SPRING

Design constraints at different loads are calculated and used for fatigue life comparison between VKP and conventional leaf spring. Fatigue life results of 55Si2Mn90 steel spring is calculated using ANSYS workbench and fatigue life results of E Glass/Epoxy spring is calculated using Hwang and Han relation.

5.1 Fatigue Life Results of 55Si2Mn90 Steel Leaf Spring

The comparable results of conventional and VKP leaf spring are listed in the Tables 2,3, and 4. Both, stress life and strain life of conventional and VKP spring is calculated. Damage and factor of safety is also calculated and compared for conventional and VKP spring [6].

Table 2: Deformation at different loads (steel spring)

Load (N)	Conventional Spring (mm)	VKP Spring(mm)
20000	5.2932	5.7805
18000	4.7639	5.2025
15000	3.9699	4.3354
12000	3.1759	3.4683
10000	2.6466	2.8903
8000	2.1173	2.3122
6000	1.5880	1.7342
4000	1.0586	1.1561
2000	0.5293	0.5780
1000	0.2646	0.2890

Table 3: Equivalent stress at different loads (steel spring)

Load (N)	Conventional Spring(N/mm^2)	VKP Spring(N/mm^2)
20000	289.90	284.33
18000	260.91	255.90
15000	217.42	213.25
12000	173.94	170.60
10000	144.95	142.17
8000	115.96	113.73
6000	86.97	85.30
4000	57.98	56.86
2000	28.99	28.43
1000	14.50	14.21

Table 4: Elastic strain at different loads (steel spring)

Load (N)	Conventional Spring ($\frac{mm}{mm}$)	VKP Spring ($\frac{mm}{mm}$)
20000	0.0014499	0.0014746
18000	0.0013049	0.0013271
15000	0.0010875	0.0011059
12000	0.0008699	0.0008847
10000	0.0007249	0.0007372
8000	0.0005799	0.0005898
6000	0.0004349	0.0004423
4000	0.0002899	0.0002949
2000	0.0001449	0.0001474
1000	0.0000724	0.0000737

5.1.1 Stress Fatigue Life of 55Si2Mn90 Steel Leaf Spring

Stress fatigue lives of 55Si2Mn90 steel, conventional and VKP spring are calculated using Fatigue tool in ANSYS workbench. The mean stress theory used for fatigue life calculations is Goodman, and load type is Zero-based. Stress component is taken as equivalent (Von Mises) stress for this fatigue life analysis. Table 5 shows minimum stress fatigue life in cycles. Here, maximum life is 1 million cycles (1e6). The springs have their maximum stress life around load 11000 N.

Table 5: Stress fatigue life at different loads (steel spring)

Load (N)	Conventional Spring (cycles)	VKP Spring (cycles)
20000	67570	72369
18000	96372	1.033e5
15000	1.9381e5	2.1499e5
12000	7.5726e5	8.4172e5
10000	1e6	1e6

Damage due to stress is also calculated at different loads. Minimum damage is 1000 and maximum damage at load 20000 is 14799 for conventional leaf spring, and 13818 for VKP leaf spring. Similarly, at load 18000 N, the maximum damage is 10376 for conventional leaf spring, and 9680 for VKP leaf spring. The leaf springs have minimum damage due to stress around load 11000 N i.e.; load at which maximum life is attained. Stress factor of safety at different loads is listed in Table 6. Maximum factor of safety is 15.

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Table 6: Stress factor of safety at different loads (steel)

Load (N)	Conventional Spring	VKP Spring
20000	0.5696	0.5808
18000	0.6330	0.6453
15000	0.7595	0.7744
12000	0.9494	0.9680
10000	1.1393	1.1616
8000	1.4242	1.4520
6000	1.8989	1.9361
4000	2.8483	2.9041
2000	5.6967	5.8082
1000	11.393	11.616

5.1.2 Strain Fatigue Life of 55Si2Mn90 Steel Leaf Spring

Strain fatigue lives of 55Si2Mn90 steel, conventional and VKP spring are calculated using fatigue tool in ANSYS. The mean stress theory used for calculations is Morrow, and Zero-based load type is used. Just like stress fatigue life, the parameters calculated are: Life, damage, and factor of safety. Table 7 shows minimum strain fatigue life in cycles. Maximum life is 1 billion cycles (1e9). The springs have their maximum strain life between load 15000 and 12000 N. Equivalent (Von Mises) stress is taken as stress component for this analysis.

Table 7: Strain fatigue life at different loads (steel spring)

Load (N)	Conventional Spring(cycles)	VKP Spring(cycles)
20000	1.2506e7	1.4640e7
18000	2.9891e7	3.5227e7
15000	1.4674e8	1.7479e8
12000	1e9	1e9

Maximum strain damage at load 20000 N for conventional is 79.964, and 68.306 for VKP leaf spring. Similarly, at load 18000 N, the maximum strain damage is 33.455 for conventional, and 28.387 for VKP leaf spring. Minimum damage is 1. Strain factor of safety at different loads is listed in Table 8.

Table 8: Strain factor of safety at different loads (steel)

Load (N)	Conventional Spring	VKP Spring
20000	0.6096	0.6215
18000	0.6773	0.6906
15000	0.8128	0.8287
12000	1.0160	1.0358
10000	1.2192	1.2431
8000	1.5240	1.5538
6000	2.0320	2.0717
4000	3.0480	3.1077
2000	6.0960	6.2153
1000	12.192	12.430

The fatigue life comparison data of conventional and VKP multi-leaf spring shows the slight advantage of VKP leaf spring over conventional.

5.2 Fatigue Life Results of E Glass/Epoxy Leaf Spring

Designing constraints at different loads are calculated using ANSYS. Further, this data is used to analytically calculate fatigue life of E Glass Epoxy leaf spring using Han and Hwang model [7]. Designing constraints are listed in Tables: 9, 10, and 11.

Table 9: Deformation at different loads (E Glass/Epoxy)

Load (N)	Conventional Spring(mm)	VKP Spring(mm)
20000	44.611	48.064
18000	40.150	43.257
15000	33.458	36.048
12000	26.766	28.838
10000	22.305	24.032
8000	17.844	19.226
6000	13.383	14.419
4000	8.9221	9.6128
2000	4.4611	4.8064
1000	2.2305	2.4032

Table 10: Equivalent stress at different loads(E Glass/Epoxy)

Load (N)	Conventional Spring (N/mm^2)	VKP Spring(N/mm^2)
20000	294.73	291.35
18000	265.26	262.21
15000	221.05	218.51
12000	176.84	174.81
10000	147.37	145.67
8000	117.89	116.54
6000	88.419	87.404
4000	58.946	58.296
2000	29.473	29.135
1000	14.737	14.567

Table 11: Equivalent strain at different loads(E Glass/Epoxy)

Load(N)	Conventional Spring(mm/mm)	VKP Spring(mm/mm)
20000	0.050473	0.049848
18000	0.045426	0.044863
15000	0.037855	0.037386
12000	0.030284	0.029909
10000	0.025237	0.024924
8000	0.020189	0.019939
6000	0.015142	0.014954
4000	0.010095	0.009969
2000	0.005047	0.004984
1000	0.002523	0.002492

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An analytical fatigue model, developed by Han and Hwang is used to predict the number of fatigue cycles to failure, for E Glass/Epoxy leaf-spring. Han and Hwang relation [7]:

$$N = \{B(1-r)\}^{1/C}, \quad (5)$$

Where, N=number of cycles to failure for composite material; B=10.33; C=0.14012; $r=\sigma_{max}/\sigma_u$; σ_u= ultimate tensile strength; σ_{max}= maximum stress, and r is the applied stress level.

Using the above relation to calculate fatigue life of E Glass/Epoxy conventional leaf spring at load 20000 N,

$$N = \{10.33(1 - \frac{294.73}{900})\}^{1/0.14012},$$

N = 1018022 cycles,

where, σ_u=900MPa, and σ_{max} at load 20000 N= 294.73MPa.

Similarly, number of cycles to failure are calculated at different loads, and are listed in Table 12.

Table 12: Fatigue life at different loads (E Glass/Epoxy)

Load (N)	Conventional Spring(cycles)	VKP Spring(cycles)
20000	1018022	1059296
18000	1429248	1478989
15000	2310998	2373412
12000	3625117	3698370
10000	4820855	4899108
8000	6341762	6420299
6000	8257617	8331604
4000	10651622	10710547
2000	13619814	13657600
1000	15353185	15374240

6. CONCLUSION

Conventional and VKP spring are compared using static structural analysis, performed on ANSYS workbench [4]. The analysis has been done on two materials: 55Si2Mn90 Steel and E Glass/Epoxy. For the same load, total deformation or deflection is more in VKP spring than conventional, and the excess deformation can be adjusted in camber, provided to the spring. VKP leaf spring is such designed that it can distribute the load more uniformly than conventional spring, and hence reduce the stress and strain in the spring body. Weight is reduced by 10% in VKP spring as compared to conventional leaf spring. Weight reduction is shown in Figure 21.

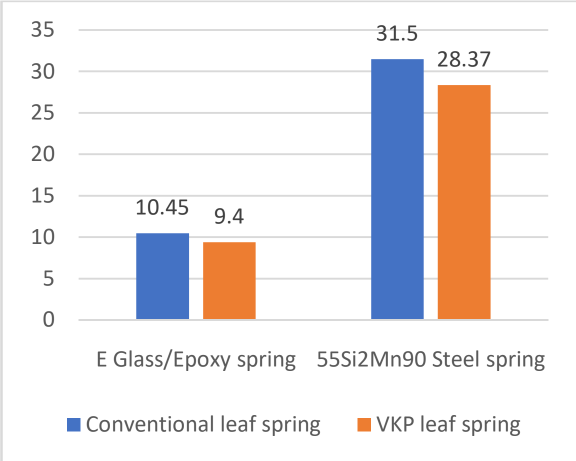

Fig 21: Spring weight comparison between VKP and conventional leaf spring.

Slight increment in fatigue life can also be noticed in VKP spring than the conventional, from the fatigue data obtained. This increment ranges from 7% to 11% for 55Si2Mn90 steel spring, and for E Glass/Epoxy spring, it is in the range 2% to 4%, for the loads between 12000N and 20000N. From the results obtained, it can be predicted that the life of VKP multi-leaf spring is higher than that of conventional multi-leaf spring.

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