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Review and Validation of Correlative Analysis of the Geometric Parameters of an Automotive Master Leaf Spring Performance

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Abstract: *Considering shapes in designs does not only end in aesthetics and streamlining in aerodynamics, but also is a consideration of structural effects on rigidity, strength propagation in absorbing both the external and internal stresses due to the prevailing factors like impact, vibration, dynamic and static pressures. Streamlining is shelving the external pressures as to maximize fuel economy through loss or reduction of drag. The automotive main leaf spring is elliptical having two eyes characterized with width (w), thickness(t), span (l), radius of curvature (r) and made of steel material. A correlative analysis is conducted on these parameters using Pearson correlation coefficient(C) under a load (P) of 0.5KN by the application of well-known versatile Hooke's law of elasticity with application of Solid Works. Two CAE knowledge based softwares –Creo Element and Ansys were utilized in this analysis to validate the results obtained from SolidWorks and statistical analysis. The statistical tool–Pearson correlation coefficient was employed and it revealed a positive correlation analysis of the Correlation analysis carried out with the simulation data, produced Correlation coefficients of 0.997539666, 0.988660899, 0.994500728,0.99721782, 0.996183593 & 0.999965163; showing a very strong correlation between the variables. Since the Correlation coefficient obtained is greater than the corresponding critical value of Correlation coefficients, at 5% and 1% changes which were 0.878 and 0.959; respectively, (under 0.1 tailed test of type1 error) for the correlation degree of freedom of 3, it follows that this research runs only 1% chance of being wrong in the relationship, so it is determined. Hence, it will be useful in leaf spring design. Results from Ansys Workbench also shows that geometric parameters have influenced on the performance of the leaf spring with the distinct values of displacement(δ), maximum principal stress and maximum Von Mises stress.*

Keywords: *Leaf Spring, Geometric Parameters, Correlative Analysis*

INTRODUCTION

Researches are going into geometry or shape, as this does not only mean the beauty of the end product, but it is also for protection, energy maximization, along with savaging cost of both production and utilization (Asha S, et. al., 2015). A spectrum of scientists and engineers have researched on the amazing treasure hidden in nature found in streamlined shape of fishes, insects, mollusks' shells etc. The amazing strength hidden in the shapes of mollusks shells help them to adapt to the harsh conditions in their environment. Test and analysis that were conducted by engineers on two seashells revealed that the bivalve shells' exterior directly stresses towards its hinge and outer edges, but the spiral shells have their curve exterior directing stress towards their core and wide top. It is an implication that these points of pressure concentrations are to protect the mollusk from harm. This was also run with 3-D printer to produce shell shapes. The results showed that natural seashells' complex surfaces nearly double their ability to withstand pressure when compared to the simple shapes. Commenting on the application of this research, an American scientist says, "if you wind up driving a shell-shaped car someday, it'll be both stylish and designed to protect the soft bodies inside" (Awake, 2017). The comfort of occupants in automotive design is paramount, and the leaf spring plays the role of protecting the occupant and the vehicle from the dangers inherent in vibration. Vehicle dynamics requires suspension systems to damp or absorb vibrations in the course of transition from one place to the other. Suspension systems are inevitable in motor vehicle engineering for the safety of the vehicle over wear and tear, and the comfort of the occupants. Hence, the components in the suspension system are necessary in the vehicle. These components could be the leaf spring, helical compression spring, dash pot etc. They found their various applications in different vehicles and sizes. Leaf springs are formed by bending (Khurmi R.S., et. al., 2000). They are made of long strips of steel which are named as Leaf. The long leaf is called Master Leaf with eyes at its both ends. The leaf spring or laminated spring is also called flat spring or carriage spring with a number of flat plates called leaves of varying lengths bound together by means of clamps and bolts. One end is fixed to the chassis frame; the other end is fixed to the shackle spring. The spring will get elongated during expansion and shortened during compression. This change in length of spring is compensated by the shackle. The U-bolt and clamps are located at the intermediate position of the spring. The bronze or rubber bushes are provided on both eyes on the master leaf.

Types of Leaf Springs:

There are five types of leaf springs

1. Full – elliptic type
2. Semi – elliptic type
3. Three Quarter – elliptic type
4. Transverse Spring type
5. Helper Spring type

1. Full elliptic: The advantage of this type is the elimination of shackle and spring. The lubrication and frequent wear are one of the main drawbacks of this type of springs, (Leevy, G., et. al., 2004).

2. Semi – elliptic: This type is more popular for rear suspension used in 75% of cars (Leevy, G., et. al., 2004).

3. Three – Quarter – elliptic type: This type is rarely used nowadays. It gives resistance, but occupies more space than the other types, (Leevy, G., et. al., 2004).

4. Transverse Type: This type of spring is arranged transversely across the car instead of longitudinal direction. The transverse spring for front axle as shown in figure 1, is bolted rigidly to the frame at the center and attached to the axle by means of shackle at both ends (Leevy, G., et. al., 2004).

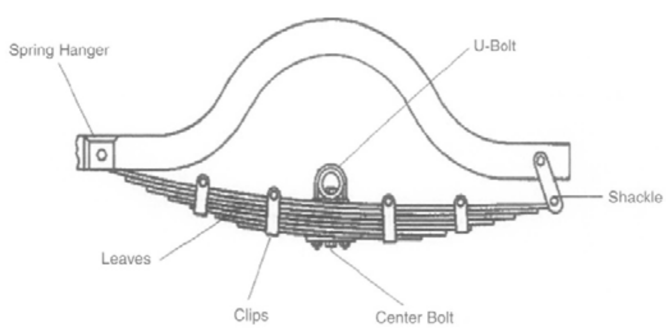

Figure 1. leaf springs assembly and component (Leevy, G., et. al., 2004)

5. Helper Springs:
The helper springs are used in heavy vehicles for rear suspension. When vehicle fully loads the main spring, the helper spring comes into action and absorbs the road shocks. When the load of the vehicle is less, the helper spring will not act and only the main spring absorbs the road shocks (Leevy, G., et. al., 2004).

Need for a Shock Absorber

If the suspension springs are rigid enough, they will not absorb road shocks efficiently, and if they are flexible enough, they will continue to vibrate for longer time even after the bump has passed (Fischer, G., et. al., 1998). Therefore, the springing device must compromise the flexibility and stiffness, so, a shock absorber is needed in Automobile Suspension system.

Types of Shock Absorbers: They are mainly of two types:
1. Mechanical.
2. Hydraulic – a. Van type
b. Piston – (i) Single Acting ii). Double Acting
c. Telescopic type

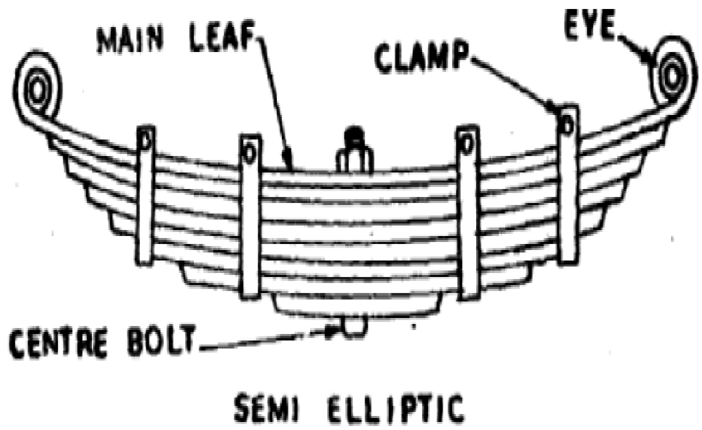

Figure 2. Leaf Spring Assembly (Leevy, G., et. al., 2004)

Aims and Objectives

In specific, these FE and CAE works are investigated using Pearson's correlation to authenticate coherent assertions on the effects of the geometric parameters on the performance of leaf springs in the design of vehicles. The objectives behind this design are outlined as follows:

i. Determine the strength of the effect of the relationship between the geometric parameters of the leaf spring and its load resistive performance.
ii. Know if there is a relationship between the leaf spring geometric parameters and its performance using Pearson's correlation.
iii. Establish hypothetically that geometrical parameters play an important role in the design of the leaf springs.

Scope

This investigation comprises the use of FE and CAE in modeling and simulating the intended project. Displacement , δ (m) observed as a result of application of load, P of 500N on the leaf spring will be determined using Creo Element and Ansys workbench while the geometrical parameters are iterated as the model is fixed at the eyes in each set. The stiffness, S, (N/m) is calculated using the Hooke's law of elasticity.

Pearson's correlation analysis is employed to verify the relationship between each of the geometric parameters and the performance of the leaf spring.

$$P = S\delta \qquad \text{(Khurmi R.S., et al., 2000)}$$

Where
P =the shock load (500N),
S=stiffness of the leaf spring model (N/m),
δ =displacement caused by the application of load (m).

Statement of Problem

It is important to know the parameters- span (L), width (w), radius of curvature (R) and the thickness(t) and their contributions to the performance of a leaf spring during manufacturing. This virtual design work will go a long way to encourage products' development and optimization. The impact of shocks or vibrations on an automobile when it falls into a pot- hole or travelling on a bumpy road is severe on the passengers and the automobile, as they cause wear and tear to the mechanical parts. For a smooth ride that should be comfortable for both the passengers and the automobile, there is a need for an efficient damping system to cushion the effects of inertia of these shock loads. The frequency of vibrations has adverse effects which are dangerous, and should be curbed to authorize the conveniencey, effective use, and durability of the automobile. Therefore, the leaf spring is modeled and simulated to optimize its performance through the consideration of its geometrical parameters that can affect its resistive performance under shock loads using Creo Element and Ansys workbench.

Methodology

This work is done from an existing leaf spring of an automotive. The FE and CAE Works will be done with Creo Element and Ansys workbench where the geometrical parameters are individually iterated while others will be held constant in their nominal dimensions. The correlation analysis done on the effect of each of the geometrical parameters of the leaf spring with the help of Creo Element and Ansys workbench to generate the results under the application of a shock load P=500N to observe the displacement δ(m), and the corresponding stiffness of the spring S(N/m) is calculated.

$$P = S\delta \qquad (1) \quad \text{(Hooke's law)}$$

The displacement, δ (m) and the Maximum von Mises, (N/mm2) or (Mpa) will be recorded. The stiffness K of the spring is calculated from each sample of the model as

$$S = P/\delta \qquad (2)$$

Graphs will be generated to validate the relations, and the correlation coefficients(r) of these parameters will be validated based on the values of the correlation coefficient (r)−1 to 1 (Bumper, 2005), which shows stronger relationship than the time they are close to zero. The percentage change of being wrong in the relationship is determined with the help of critical values of the correlation coefficients.

Assumptions

In the analysis, certain assumptions were made, and are stated as follows:

i. The master leaf spring is assumed to be fixed at the eyes.
ii. The material composition was selected to be AISI316 Annealed stainless steel bar(SS) with Solidworks materials library.
iii. Displacement δ (m) is taking consideration of first impact load and no rebounce.
iv. There is no friction between the body under the test and the applied load

Model

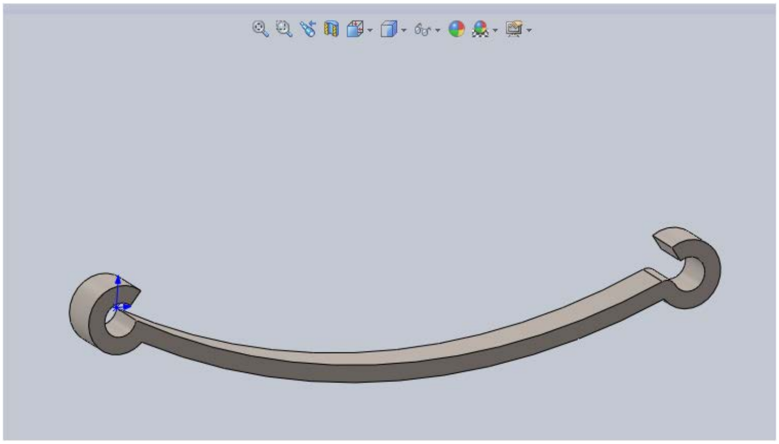

Figure 3. 3-D model for a master leaf with solidworks

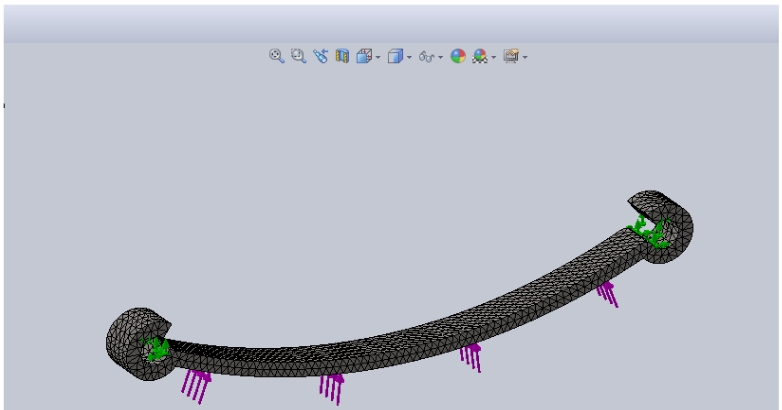

Figure 4. 3-D mesh model for a master leaf with solidworks

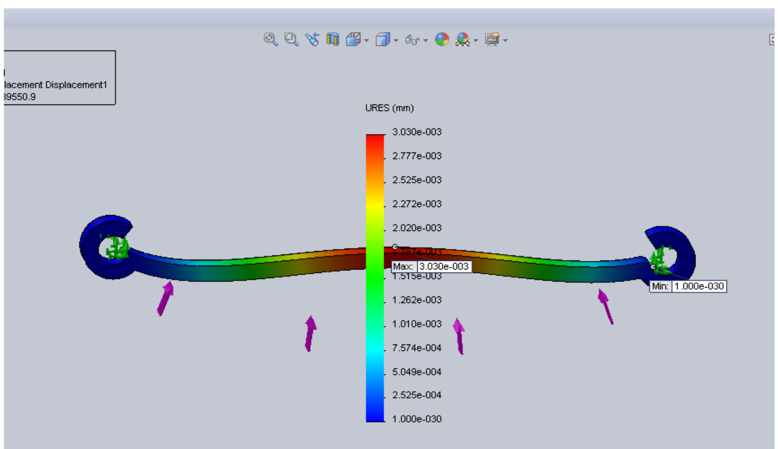

Figure 5. 3-D model of simulated master leaf with solidworks

Results

Tables of results

Table 1. showing displacement δ (m) for respective change in length (L) while R, w, and t are kept constant on application of a load of 500N

S/N	L (m)	DISPLACEMENT, δ x 10^{-6} (m)	STIFFNESS, S, x 10^8 (N/m^2)	MAX.VON MISS N/mm^2
1	1.018	2.83800	1.7618	0.63510
2	0.968	3.00351	1.6647	0.64987
3	0.918	3.17440	1.5751	0.66839
4	0.868	3.34937	1.4928	0.68552
5	0.768	3.69653	1.3526	0.74054

Table 2. showing displacement, δ (m) for respective change in Radius of curvature, R,(m) while L, w, and t are kept constant on application of a load of 500N.

S/N	R (m)	DISPLACEMENT, δ,x 10^{-6} (m)	STIFFNESS, S, x 10^8 (N/m^2)	MAX.VON MISS N/mm^2
1	1.200	2.83800	1.7618	0.63510
2	1.190	2.78935	1.7925	0.63584
3	1.180	2.74043	1.8245	0.63166
4	1.170	2.69169	1.8576	0.63176
5	1.160	2.59529	1.9266	0.62850

Table 3. showing displacement, δ,(m)for respective change in Width, w(m) while L,R and t are kept constant on application of a load of 500N.

S/N	w(m)	DISPLACEMENT, δ, x 10^{-6} (m)	STIFFNESS, S, x 10^8 (N/m^2)	MAX.VON MISS N/mm^2
1	0.075	2.83800	1.7618	0.635100
2	0.065	3.27397	1.5127	0.738975
3	0.055	3.86978	1.2921	0.859368
4	0.045	6.07474	0.8231	1.387800
5	0.035	8.50016	0.5882	1.979050

Table 4. showing displacement, δ, (m) for respective change in thickness, t(m) while L, w, and R are kept constant on application of a load of 500N

S/N	t (m)	DISPLACEMENT, δ, x 10^{-6} (m)	STIFFNESS, S, x 10^8 (N/m^2)	MAX.VON MISS N/mm^2
1	0.030	2.8380	1.7618	0.6351
2	0.025	3.3544	1.4906	0.7817
3	0.020	4.0499	1.2346	1.0255
4	0.015	4.9717	1.0057	1.5455
5	0.010	7.1275	0.7015	2.8586

The correlation analysis

From the resulting graphs of figures1,2,3, and 4, showing various responses of the leaf spring (having considered its geometry to be a function of its length, L, radius of curvature, R, width, w, and thickness, t) it becomes evident that there is a positive correlation between automobile leaf spring performance and its geometry. Thus, the Pearson's Correlation analysis approach, using the relation in equation 3 was applied.

The strength of the relationship giving by the Correlation Coefficient, r, was determined as given by Pearson's correlation analysis of the radius of curvature, R, of the leaf spring and the Stiffness ,S

$$rRS = \frac{\sum RS - \frac{\sum R \sum S}{n}}{\sqrt{\left(\sum R^2 - \frac{(\sum R)^2}{nR}\right)\left(\sum S^2 - \frac{(\sum S)^2}{nS}\right)}} \quad (3)$$

where, rRS= Correlation Coefficient for radius of curvature, R and Stiffness, S
Similarly, this was done for the Correlation Coefficient, r, for the length, L, width, W, and thickness t, with their respective displacements, δ and stiffness, S.

Table 5. Statistical data for the correlation analysis involving the leaf spring stiffness, S and its length L

S/N	S(N/m)	L (m)	S^2	L^2	SL	$(\sum S)(\sum L)$
1	176180000	1.018	3.10394E+16	1.036324	179351240	
2	166470000	0.968	2.77123E+16	0.937024	161142960	
3	157510000	0.918	2.48094E+16	0.842724	144594180	
4	149280000	0.868	2.22845E+16	0.753424	129575040	
5	135260000	0.768	1.82953E+16	0.589824	103879680	
	∑S=784700000	∑L= 4.54	$\sum S^2$=1.24141E+17	$\sum L^2$=4.15932	∑SL=718543100	∑(∑S) (∑L)=3562538000

Table 6. Statistical data for the correlation analysis involving the leaf spring stiffness, S and Radius of curvature, R

S/N	S(N/m)	R (m)	S^2	R^2	SR	$(\sum S)(\sum R)$
1	176180000	1.2	3.10394E+16	1.44	211416000	
2	179180000	1.19	3.21055E+16	1.4161	213224200	
3	182450000	1.18	3.3288E+16	1.3924	215291000	
4	185760000	1.17	3.45068E+16	1.3689	217339200	
5	192660000	1.16	3.71179E+16	1.3456	223485600	
	∑S=916230000	∑R= 5.9	$\sum S^2$=1.68058E+17	$\sum R^2$=6.963	∑SR=1080756000	∑(∑S) (∑R)=5405757000

Table 7. Statistical data for the correlation analysis involving the leaf spring stiffness, S and thickness, t

S/N	S(N/m)	t (m)	S^2	t^2	St	$(\sum S)(\sum t)$
1	1.7618E-08	0.03	3.10394E-16	0.0009	5.2854E-10	
2	1.4906E-08	0.025	2.22189E-16	0.000625	3.7265E-10	
3	1.2346E-08	0.02	1.52424E-16	0.0004	2.4692E-10	
4	1.0057E-08	0.015	1.01143E-16	0.000225	1.50855E-10	
5	7.015E-09	0.01	4.92102E-17	0.0001	7.015E-11	
	∑S=6.1942E-08	∑t= 0.1	$\sum S^2$=8.3536E-16	$\sum t^2$=0.00225	∑St=1.36912E-09	∑(∑S) (∑t)=6.1942E-09

Table 8. Statistical data for the correlation analysis involving the leaf spring stiffness, S and Thickness t

S/N	S(N/m)	w (m)	S^2	w^2	Sw	$\left(\sum S\right)\left(\sum w\right)$
1	1.7618E-08	0.075	3.10394E-16	0.005625	1.32135E-09	
2	1.5127E-08	0.065	2.28826E-16	0.004225	9.83255E-10	
3	1.2921E-08	0.055	1.66952E-16	0.003025	7.10655E-10	
4	8.231E-09	0.035	6.77494E-17	0.001225	2.88085E-10	
5	5.882E-09	0.025	3.45979E-17	0.000625	1.4705E-10	
	$\sum$ S=5.9779E-08	$\sum$ w= 0.255	$\sum S^2$=8.0852E-16	$\sum w^2$=0.014725	$\sum$ Sw=3.4504E-09	$\sum(\sum S)(\sum w)$=1.52436E-08

At, n =5 number of pairs; r >CV.
D. f. = n-2 =3
At 5% change and 1% are 0.878 and 0.959 respectively.
rRδ = 0.997539666,
rSδ = 0.988660899,
rSL = 0.99721782,
rSR=0.994500728,
rSw=0.996183593,
rSt=0.999965163

Since the Correlation coefficient obtained is greater than the corresponding critical value of Correlation coefficient, at 5% and 1% changes are 0.878 and 0.95, respectively (under 0.1 tailed test of type1 error) for the correlation degree of freedom of 3 (Bumper, 2005). It follows that this work runs only 1% chance of being wrong in the relationship, so it is determined. Hence, it will be useful in automobile leaf spring design.

Validation with Ansys Workbench

a. Assumptions

i. The material composition was selected to be structural steel.
iii. Displacement (δ) (m) is taken, considering first impact load and no rebounce.
iv. There is no friction between the body under the test and the applied load.

b. Model

The model was done with Creo Element, and Ansys WorkBench was used to conduct the analysis –static structural analysis.

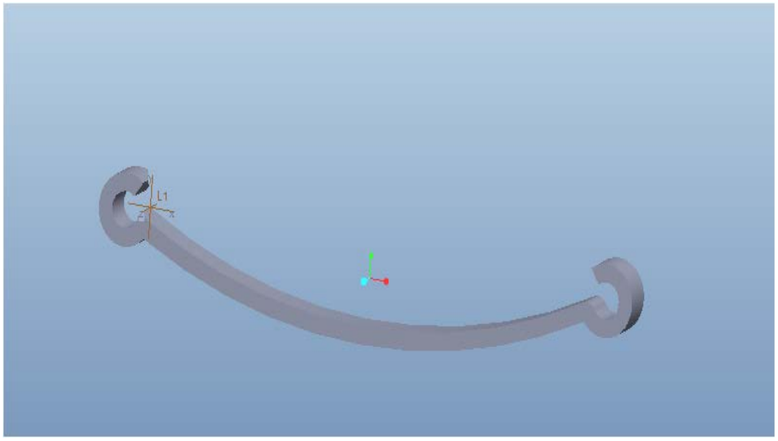

Figure 6. 3-D model for a leaf spring with Creo Element

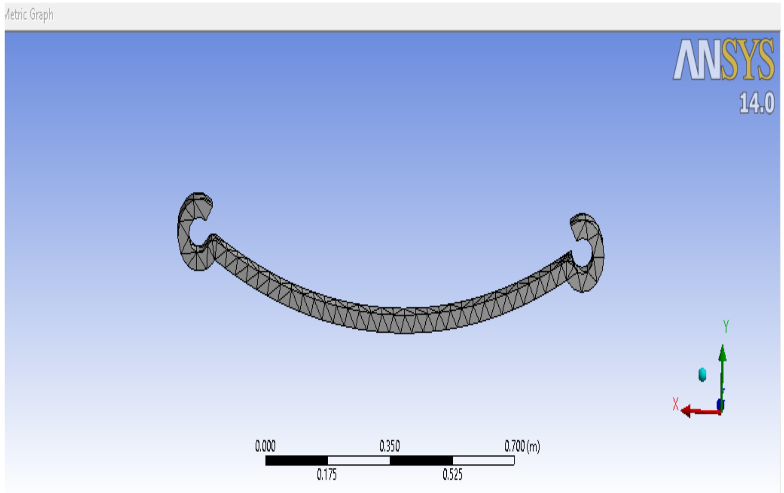

Figure 7. 3-D mesh model for leaf spring with Ansys

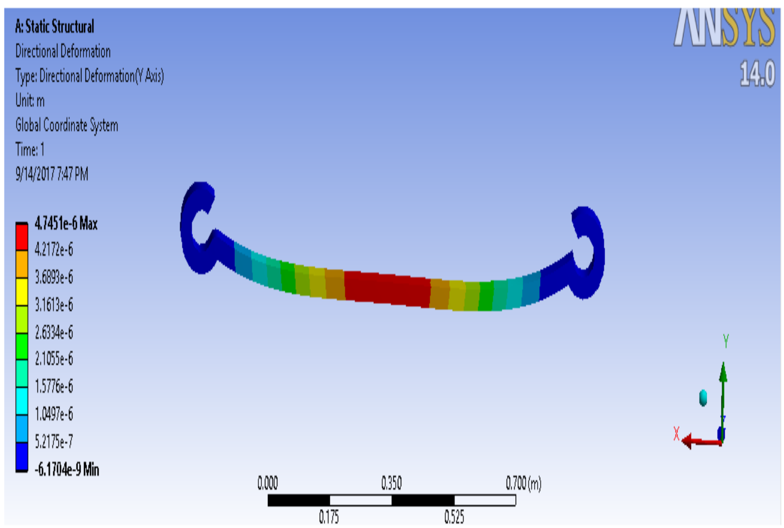

Figure 8. 3-D simulated model for a leaf spring showing deflection in y-axis

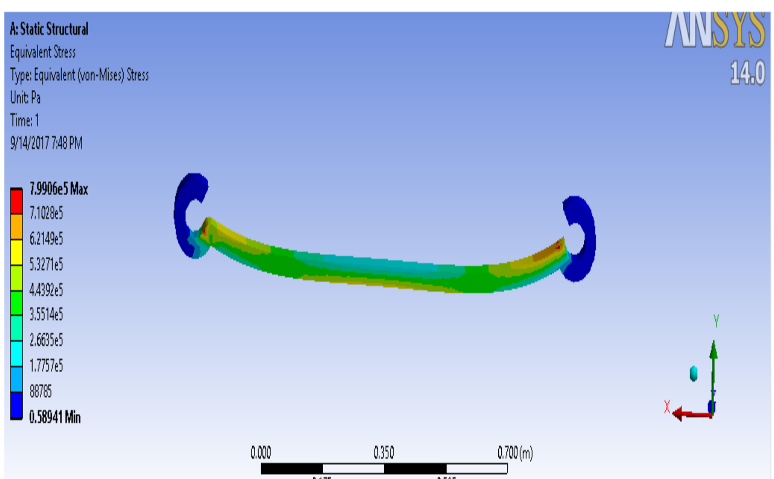

Figure 9. 3-D simulated model for a leaf spring showing Von Mises stress

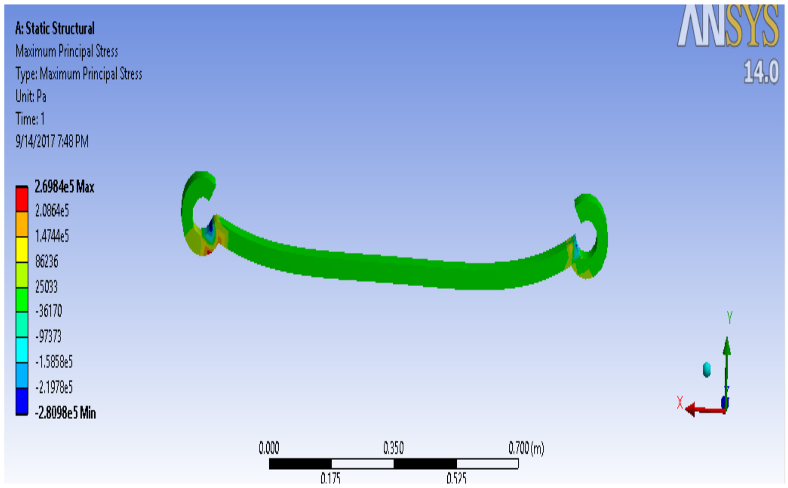

Figure 10. 3-D simulated model for a leaf spring showing Principal stress

Results with Displacement Along the Vertical(Y) Axis

Table 9. Showing Displacement (δ) For Respective Change in Length(L) While R, Wand T Are Kept Constant On Application of a Load Of 500N

S/N	L(mm)	DISPLACEMENT (δ) $\times 10^{-6}$mm	MAX PRINCIPA; STRESS $\times 10^5$N/mm²	MAX.VON MISS $\times 10^5$N/mm²
1	1018	4.2172	2.6984	7.9906
2	968	4.9428	3.7727	8.7834
3	918	5.1367	3.9526	8.7418
4	868	6.4432	3.3675	8.4058
5	768	5.6398	2.1273	9.7968

Table 10. Showing Displacement (δ) For Respective Change In Radius Of Curvature (R) While L, W ,And T Are Kept Constant On Application Of A Load Of 500N

S/N	R (mm)	DISPLACEMENT (δ) $\times 10^{-6}$mm	MAX PRINCIPA; STRESS $\times 10^5$N/mm²	MAX.VON MISS $\times 10^5$N/mm²
1	1200	4.2172	2.6984	7.9906
2	1190	4.6744	1.2226	6.3161
3	1180	4.5961	0.85193	5.2329
4	1170	4.5219	1.1072	5.5648
5	1160	4.4521	1.1081	6.2126

Table 11. Showing Displacement (δ) For Respective Change in Width(W) While L, R, And T Are Kept Constant On Application Of A Load Of 500N

S/N	w(mm)	DISPLACEMENT (δ) $\times 10^{-6}$mm	MAX PRINCIPA; STRESS $\times 10^5$N/mm2	MAX.VON MISS $\times 10^5$N/mm2
1	75	4.7451	2.6984	5.3271
2	65	5.4777	1.4261	7.4771
3	55	6.4779	1.2569	7.3016
4	45	7.9166	1.2844	8.4633
5	35	10.1762	1.5319	9.5745

Table 12. Showing Displacement (δ) For Respective Change in Thickness(T) While L, R, And W Are Kept Constant On Application Of A Load Of 500N

S/N	t (mm)	DISPLACEMENT (δ) mm	MAX PRINCIPA; STRESS N/mm²	MAX.VON MISS N/mm²
1	30	4.7451	2.6984	5.3271
2	25	5.8189	1.5266	7.7052
3	20	7.4532	2.4581	8.0179
4	15	10.3000	4.2192	13.1220
5	10	16.6270	2.0322	16.1562

Graphs representations of both solid works and Ansys analysis

Solid Works

The graphs of the various leaf spring displacement, x (m) against the corresponding radius of curvature, R, and stiffness, k; respectively, for the modeled automobile leaf spring geometry were plotted as shown in figure 3. This is the same in figures 1, 2 and 4 for length, L, width w, and thickness, respectively.

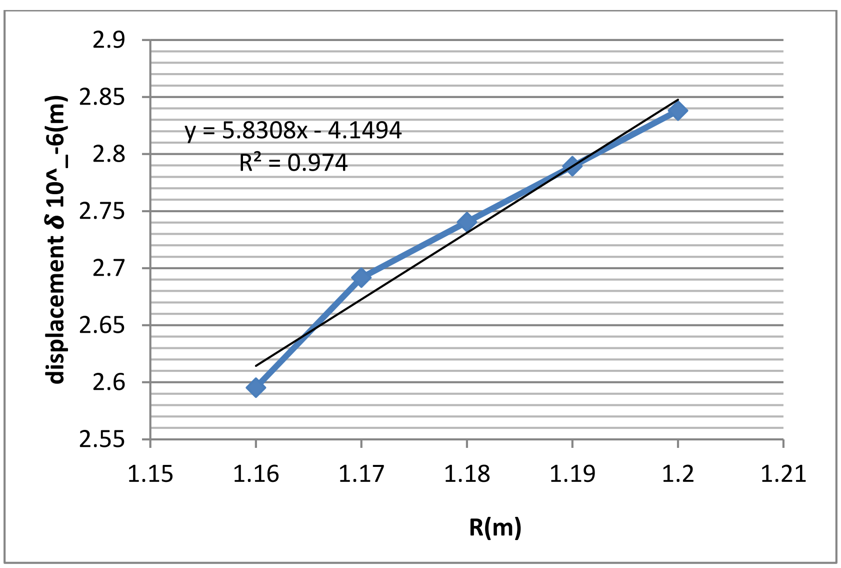

Figure 11. Graph of Radius of Curvature Against Displacement

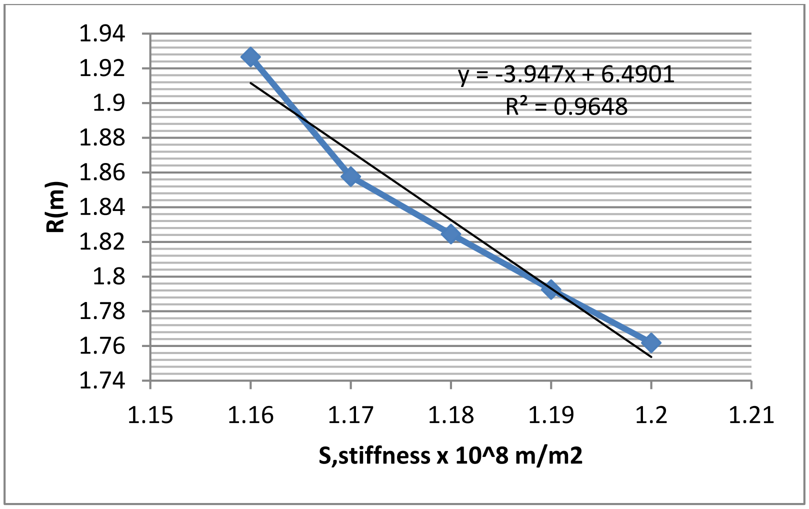

Figure 12. Graph of Radius of Curvature Against Stiffness, S

Graphical Results From Ansys

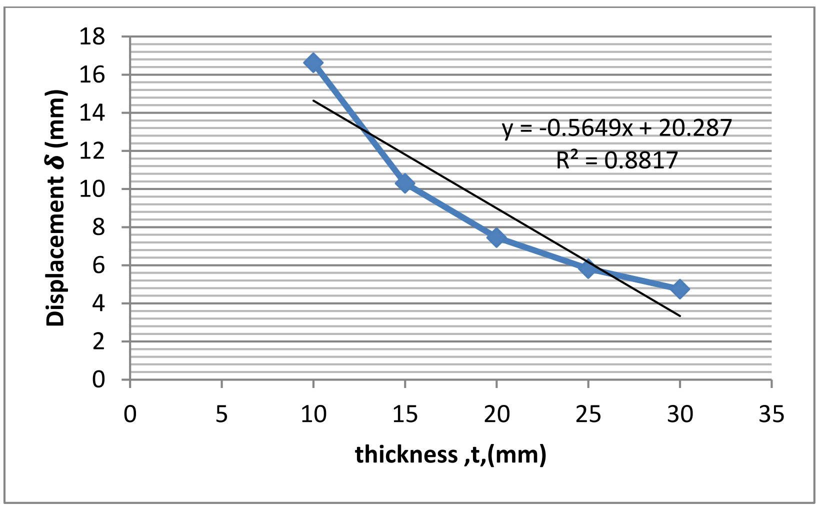

Figure.13. A Graph of Thickness Against Displacement

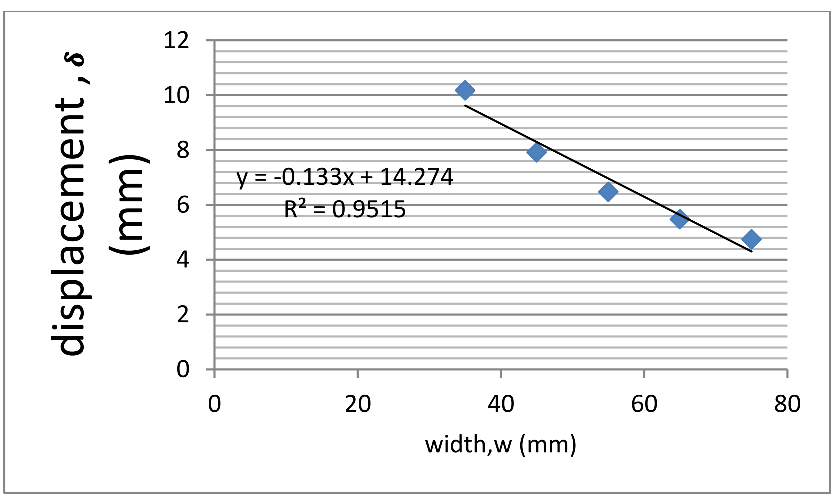

Figure 14. A Graph of Width, w, Against Displacement δ

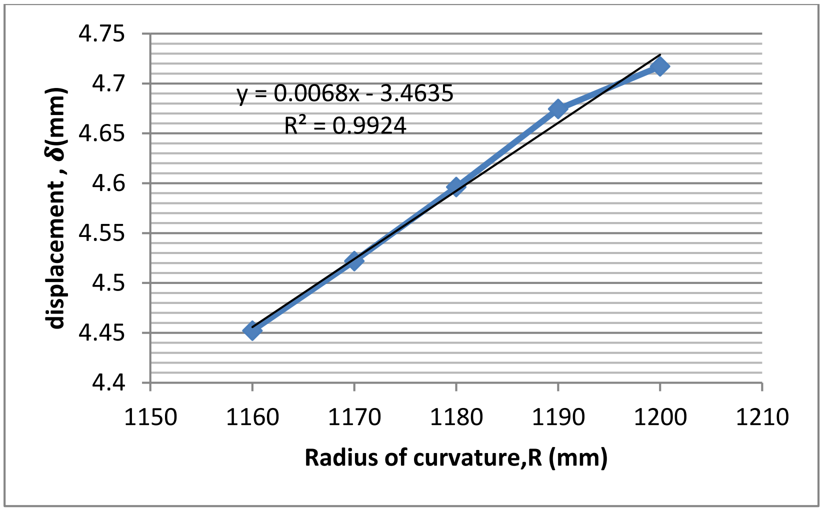

Figure 15. A Graph of Radius of Curvature, R, Against Displacement, **δ**

Conclusion

Tables 1, 2, 3, and 4, reveal the effect of length, radius of curvature, width and thickness of the leaf spring on its performance. It is observed that the displacement,δ, increases with the decrease in length or span, thickness, and width; and it decreases with the decrease in radius of curvature of the leaf spring. From the values obtained from the result generated in table 5 to table 8, using Microsoft excel 2012, it can be seen that they are all greater than the critical values at 3 degree of freedom of 5% and 1% changes, which signifies that there is a strong relationship between the responses of the leaf spring and its geometrical parameters. And a strong inference is drawn that the performance of a leaf spring and other subordinate leaf springs are influenced by their geometrical parameters, hence, they should be considered during designing besides the material composition. Therefore, this can be concluded that geometric parameters have significant effects on the performance of a leaf spring irrespective of its size within an agreeable coefficient using the Pearson correlation coefficient. Besides the material selection, the geometrical parameters should be considered in the design of leaf spring. This is validated by the deflection results, and the stresses' results in table 9 to table 12, and the graphs generated from simulation using Ansys Workbench. Hence, apart from the shape consideration, geometric parameters are necessary in designs of component parts in both mechanical and structural members.

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