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Material and Stress Analysis of Railroad Vehicle Suspension: A Failure Investigation

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Abstract

Suspensions are the important machine element of rail road vehicle which absorb the shocks and vibration during tracking, curving and also protect the axle movement. The helical compression type of spring is used to allow axial deformation and also provide some lateral deformation at curvature. A freight rail vehicle has the frequent failure of primary suspension with major emphasis on the failure of composite spring of central axle of both frames. The failure investigation starts with the material analysis by experimentation for chemical composition for different failed specimen of springs using spectrometer. It is continued to the stress analysis with respect to the mechanical properties of material by analytical and finite element analysis at various loading conditions. The material and stress analysis revealed that the failure occurs due to design incompetency by increase of stresses at curvature and at maximum tractive efforts at various speed.

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Keywords:"Helical spring; Spectrometer; chemical composition; curvature; lateral force; FEA"

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1. Introduction

Railroad vehicles are among the most widely used methods of transporting passengers and goods [Shabana et al., 2008]. The helical suspension spring system has a significant importance on the operation of rail road vehicle, considering the effect of curving/tracking. A rail road vehicle consists of helical type of suspension spring categorize as primary and secondary spring. The complete structure is divided in tow frames and each frame contains three axles. Two sets of primary springs are mounted on each axle box near each wheel but only the composite assembly of inner and outer primary springs is mounted on central axle box of both frames. The failure investigation process relies on collecting failed inner primary spring components for subsequent examination of the cause of frequent failure using a wide array of methods. The spring material is chromium vanadium (50CrV4) emphasizes chemical contents of chromium (0.9-1.2) and vanadium (0.1-0.2). The analysis involves chemical composition of failed specimens of spring obtained by spectrometer, is an instrument used in spectroscopic analysis to identify materials and stress analysis to find the stresses to check the failure criteria by comparing it with the mechanical properties of material in different track condition.

Nomenclature

τ	shear stress
K_s	shear stress correction factor
K_w	Wahl's factor
U	strain energy
y	deflection of spring
k	stiffness of spring
V	speed
R	radius of curvature
φ	track angle
R_A	reaction on wheel A
G	track guage distance
h	track super-elevation
FE	finite element

2. Experimental Spectroscopy Analysis

The failure investigation starts with the chemical composition of the material of failed spring specimens using spectrometer. Total five spring specimens are collected for experimentation which has been failed in the gap of some instances. The surface of specimens polished using emery paper and place on flat base of spectrometer. The omitted ray from spectrometer sparks on spring specimen which provides the results in the form of chemical composition in percentage is shown in table 1. From table1, it is observed that the percentage of vanadium are slightly less for first three specimen and are failed from 1.5 coils to 3 coils from top of the spring which reveals that the springs may fail due to material defects. But from the observation of chemical composition of specimen IV and V, it is found that all chemical contents are as per the requirements of chromium vanadium material, thereafter the springs are failed. This analysis revealed that the springs may or may not be failed due to material defect. Therefore the analysis is necessary to extend toward the stress analysis to check for the design incompetency.

Table1: Chemical composition of spring specimens using spectrometer

Rail Vehicle no.	31097	31097	31068	31072	31105
Spring position	5	17	8	6	18
Spring Specimen	Specimen-I	Specimen-II	Specimen-III	Specimen-IV	Specimen-V
Broken coil From top	$1\frac{1}{2}$	3	$2\frac{1}{2}$	3	From Middle
C (0.47 - 0.55)	0.47	0.475	0.46	0.52	0.45
Si (0.15 - 0.40)	0.24	0.15	0.20	0.35	0.18
Mn (0.7 - 1.10)	0.90	0.74	0.81	0.93	0.82
P (0.035max.)	0.024	0.023	0.025	0.034	0.034
S(0.019- 0.035)	0.019	0.020	0.023	0.035	0.031
Cr (0.9 - 1.2)	1.07	1.09	1.03	0.91	0.97
V (0.1 - 0.2)	0.078	0.075	0.08	0.101	0.13
Hardness	42	32	33	33	32

3. Analytical Stress Analysis of Spring

The maximum stress in the wire may be computed by superposition of the direct shear stress and the torsional shear stress. The stress occurs at the inside fiber of the spring [Shigley and Mischke, 2005].

$$\tau = \frac{8FD}{\pi d^3} + \frac{4F}{\pi d^2} \tag{1}$$

The above equation is rearrange by shear stress correction factor is defined by spring index which is a measure of coil curvature. Therefore the shear stress (τ) and shear stress correction factor (K_s) is defined by following equation [Shigley and Mischke, 2005].

$$\tau = K_s \frac{8FD}{\pi d^3} \tag{2}$$

$$K_s = \frac{2C+1}{2C} \tag{3}$$

Shigley and Mischke (2005) reported, the stress is increases on the inside of the spring due to curvature but also decreases slightly on the outside of spring. This curvature stress is primarily important in fatigue because the loads are lower and there is no opportunity for localized yielding. These stresses can normally be neglected for static loading because of strain-strengthening with the first application of load. It is necessary to introduce the curvature factor in a roundabout way include the effect of the direct shear stress. Therefore K_s is replaced by another K factor known as Wahl's factor, which corrects for both curvature and direct shear. Then this factor is given by the equation [Shigley and Mischke, 2005].

$$K_w = \frac{4C-1}{4C-4} + \frac{0.615}{C} \tag{4}$$

The deflection-force relations are quite easily obtained by using Castigliano's theorem. The total strain energy for a helical spring is composed of a torsional component and a shear component. The strain energy is defined by following equation [Shigley and Mischke, 2005].

$$U = \frac{4F^2D^3N}{d^4G} + \frac{2F^2DN}{d^2G} \tag{5}$$

Then using Castigliano's theorem, total deflection of spring 'y' and spring rate or stiffness of spring 'k' is obtained as follows [Shigley and Mischke, 2005].

$$y = \frac{\partial U}{\partial F} = \frac{8FD^3N}{d^4G} \tag{6}$$

$$k = \frac{F}{y} = \frac{d^4G}{8D^3N} \tag{7}$$

3.1. Structural Force on springs

Primary springs of rail road vehicle acquire total structural load of 100 tonne excluding the unsprung mass of axles, wheels, etc. As per the technical specifications of springs shown in table 2, outer primary springs of central axle are first responsible to acquire total load as its height is 2 mm greater than inner springs and 18 mm than the end axle springs. After 2mm deflection of outer spring the load has been shared by inner spring and after 20mm deflection it has been distributed on the end axle springs and deflected at some instance which is the initial condition of rail road vehicle. Schematically the position of free height of single sided spring structure is shown in figure 1.

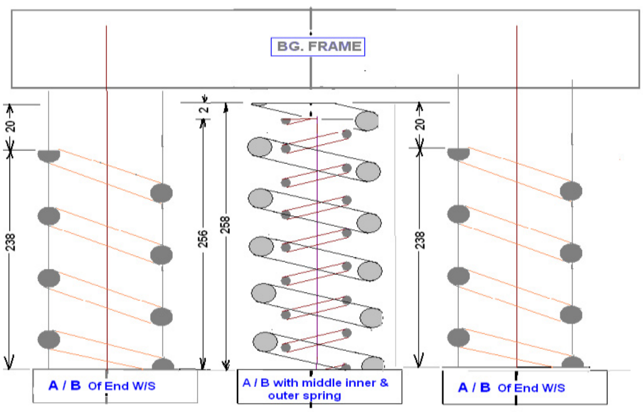


Figure 1: Primary spring Position in rail road vehicle

Table 2: Technical specification of Primary springs

Particulars	Unit	Central Axle outer spring	Central Axle inner spring	End Axle spring
Free length	mm	258.6	252.4	238.8
Outer diameter (D_o)	mm	212	104	221
Mean diameter (Dm)	mm	180.5	87.5	185
Coil Diameter (d)	mm	31.5	16.5	36
No. of active coil	-	3.5	7.5	3
Total No. of coil	-	5.0	9.0	4.5
Pitch	mm	51.72	28.04	53.06
Modulus of Rigidity (G)	N/mm^2	78500	78500	78500
Tensile Strength	N/mm^2		1550-1720	
Density	Kg/m^3	7860	7860	7860

3.2. Axial and Lateral effect on spring

The helical springs are responsible for axial deformation and cause shear stress in the spring due to twisting of coils because of load applied. When the wheel set negotiates a curved track, the outer rail has a larger radius of curvature than the inner rail. This requires the outer wheel to travel larger distance than the inner wheel. When a vehicle travels over a curve with a constant curvature, a lateral force has been acting on spring with the axial force. To reduce the effect of lateral force on the springs the shock absorbers or vertical dampers are provided at end axle springs but there is only one linkage provided at central axle to restrict the sliding of wheels. The link provided can slide the central axle upto 16 mm to negotiate a curve because in Indian Railways only the middle or central axle are responsible for the curvature of rail road vehicle.

The lateral force must be in balance with the centrifugal force due to the track curvature. The centrifugal force tends to push the vehicle out of the curve toward the high rail. Therefore, if the curve has a certain curvature and super-elevation, there is a balance speed at which the component of the centrifugal force is equal to the lateral component of the gravity force, as shown in Figure 2 [Shabana et al., 2008].

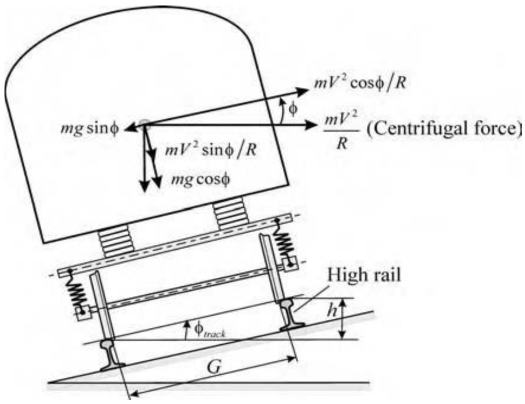


Figure 2: Rail Road Vehicle at Curvature

For instance, if the vehicle is traveling with a speed equal to V over a track that has a radius of curvature R, then at the balance speed, one must have the following relationship [Shabana et al., 2008]:

$$\frac{mV^2}{R}\cos\phi = mg\sin\phi \tag{8}$$

In general, φ in the preceding equation is equal to the track angle φ_{track} plus the roll angle of the car, which is the result of the suspension elasticity. Assuming that φ is equal to φ_{track} and for general track, one can use the following small angle and reaction at one of rail accordingly [Shabana et al., 2008].

$$\sin\phi = \frac{h}{G} \tag{9}$$

$$\mathrm{R_A} = \left(\frac{mV^2}{R}\ \sin\phi\ +\ \mathrm{mg}\cos\ \phi\right)\frac{1}{2} + \left(mg\ \sin\phi - \frac{mV^2}{R}\cos\phi\right)\frac{h}{G} \tag{10}$$

Where h is the track super-elevation and G is the track gage. Therefore, the balance speed is defined as follows [Shabana et al., 2008]:

$$V = \sqrt{\frac{gRh}{G}} \tag{11}$$

Track angle, super-elevation, radius of curvature and equilibrium speed are the various parameters which affect the design and maintenance of horizontal curves. The stress analysis has been carried out at several speed of vehicle i.e. from 60 to 120 km/hr at constant curved track for the radius of curvature of 292m, 252m and critical radius of 175m is depicted in figure 3, 4 and 5. The results indicate that the stresses are reaches to the limiting strength but not exceeded at curvature of 292m. But it has been exceeded at curvature of 252m at the speed above 100 km/hr and at curvature of 175m at speed above 80km/hr. It means the springs may fail if the rail vehicle runs at the constant speed of 100 km/hr at curvature of 252m and at 175m due to increase of stresses which may again increases by introducing the lateral force.

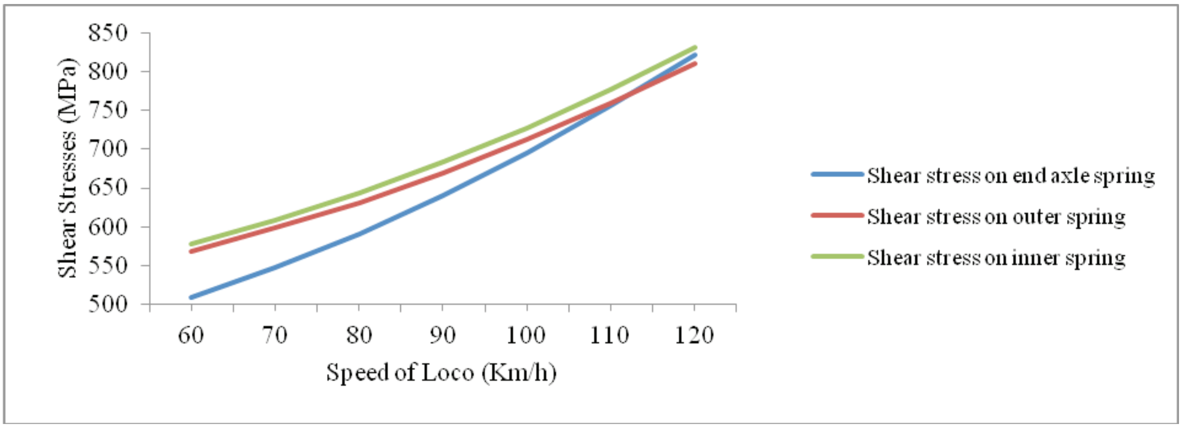


Figure 3: Stress Variation for speed of 60 to 120 km/hr at 292m radius of curvature

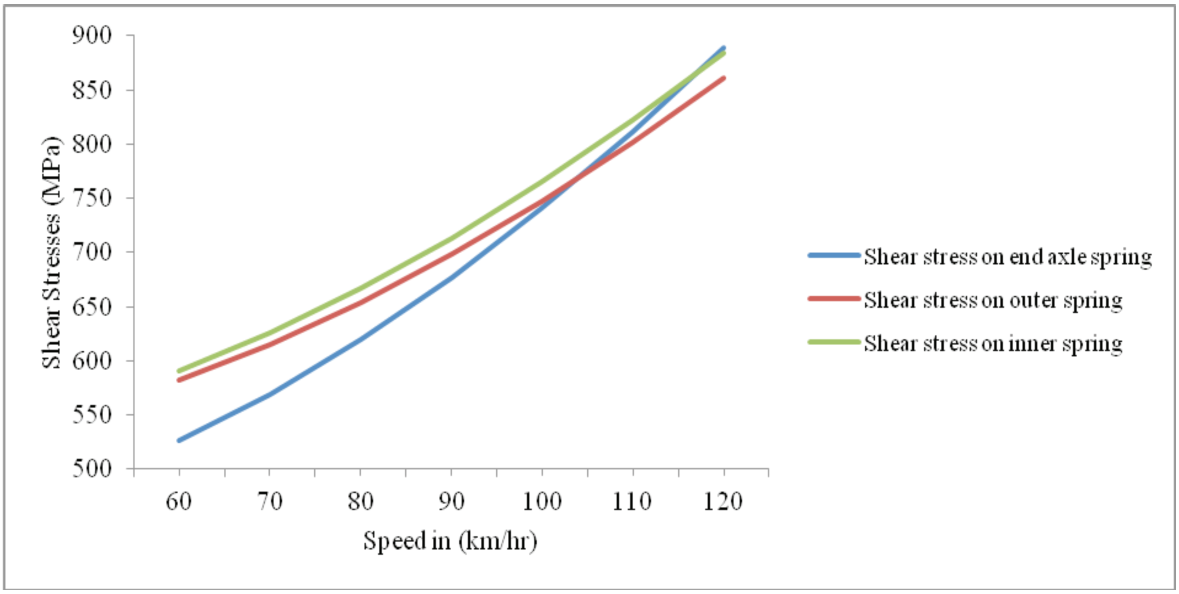


Figure 4: Stress Variation for speed of 60 to 120 km/hr at 252m radius of curvature

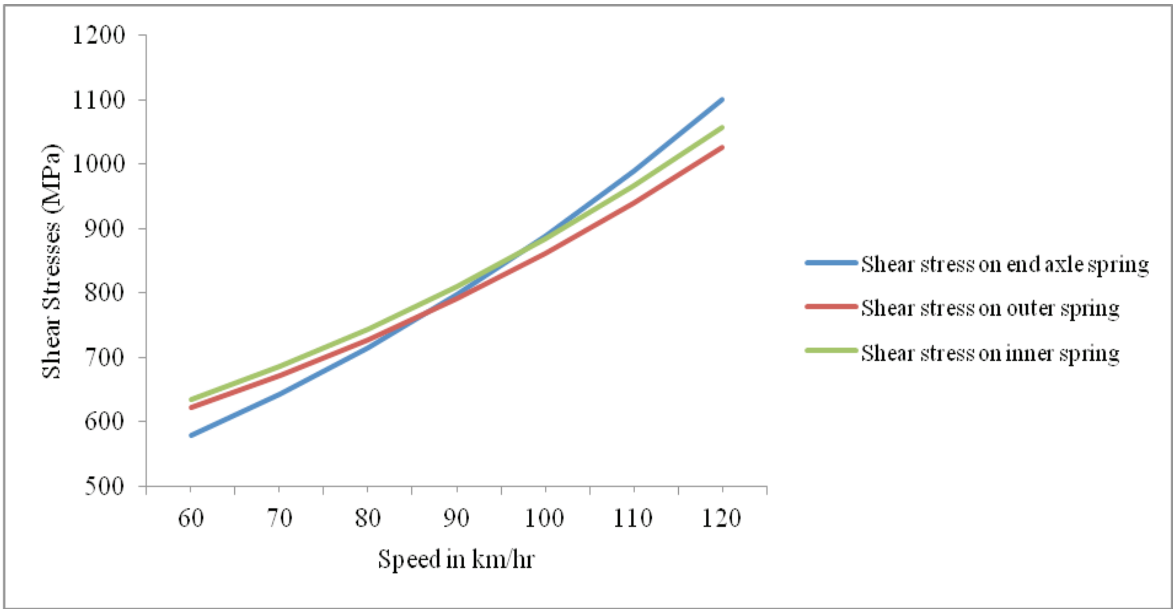


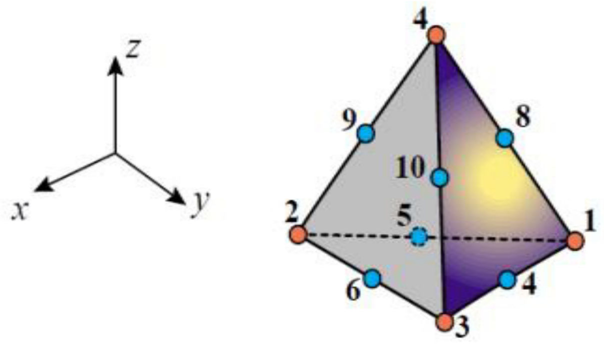
Figure 5: Stress Variation for speed of 60 to 120 km/hr at 175m radius of curvature

4. Finite Element Analysis of Primary Spring

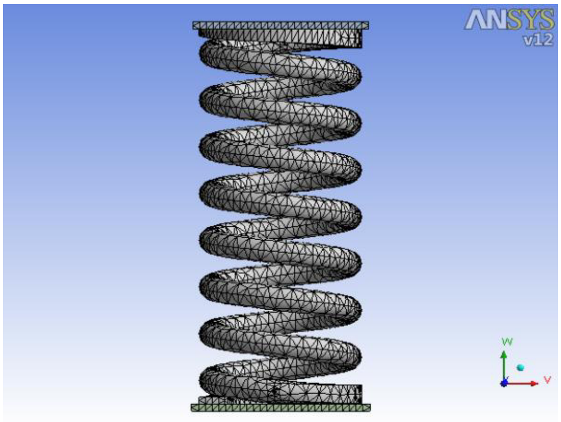
Finite element analysis is widely used in numerical solution of many problems in engineering and technology. Finite element analysis uses the idea of dividing a large body into small parts called elements, connected at predefined points called as nodes. Element behavior is approximated in terms of the nodal variables called degrees of freedom. Elements are assembled with due consideration of loading and boundary condition. This results in finite number of equations. Solution of these equations represents the approximate behavior of the problem. Using the technical specification, 3d model of inner and composite spring is analyzed by FE tool Ansys 12.0. A higher order 3-D, 10-node tetrahedral element having three degrees of freedom at each node: translations in the nodal x, y, and z directions SOLID187 was used [ANSYS, 2009]. According to the lecture notes of quadratic tetrahedron, a mesh of quadratic tetrahedra exhibits wider connectivity than a corresponding mesh of linear tetrahedra with the same number of nodes. The side nodes are not necessarily placed at the midpoints of the sides but may deviate from those locations, subjected to positive-Jacobian-determinant constraints. Each element face is defined by six nodes. This freedom allows the element to have curved sides and faces. An inner spring is meshed with fine meshing having 10823 elements and 23386 nodes and composite spring with 20630 elements and 42330 nodes. A 10-node tetrahedral SOLID187 element and mesh model of primary inner and composite spring is shown in figure 6. As an isoparametric element the quadratic tetrahedron is expressed as,

$$\begin{bmatrix} 1 \\ x \\ y \\ z \\ u_x \\ u_y \\ u_z \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 & 1 & \dots & 1 \\ x_1 & x_2 & x_3 & x_4 & x_4 & \dots & x_{10} \\ y_1 & y_2 & y_3 & y_4 & y_5 & \dots & y_{10} \\ z_1 & z_2 & z_3 & z_4 & z_5 & \dots & z_{10} \\ u_{x1} & u_{x2} & u_{x3} & u_{x4} & u_{x5} & \dots & u_{x10} \\ u_{y1} & u_{y2} & u_{y3} & u_{y4} & u_{y5} & \dots & u_{y10} \\ u_{z1} & u_{z2} & u_{z3} & u_{z4} & u_{z5} & \dots & u_{z10} \end{bmatrix} \begin{bmatrix} N_1^e \\ N_2^e \\ N_3^e \\ N_4^e \\ N_5^e \\ \vdots \\ N_{10}^e \end{bmatrix} \tag{12}$$

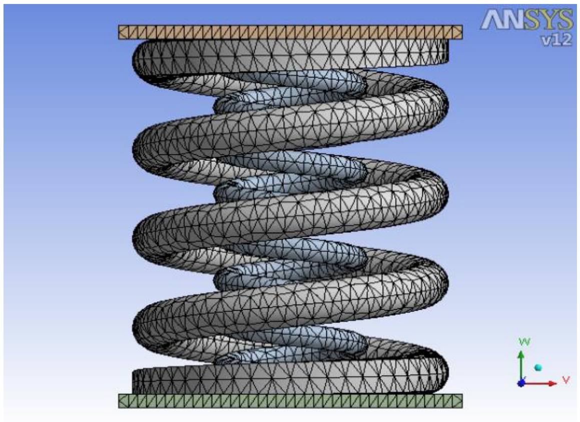
The FE analysis was carried out for both axial and lateral forces acting on the spring. For the analysis purpose the plate with higher rigidity was mounted on the top and below the spring for axial loading and fixed up the displacement. First inner spring is analyzed by considering the axial forces calculated analytically at straight track and also at curvature. The maximum shear stresses are obtained by FE analysis are validated with analytical results for the betterment of further results at various loading condition which will compare with the results calculated. The investigation further call for the FE analysis of composite spring for lateral loading as composite structure of spring bear complete axial and lateral load at curvature. The figure 7 depicts boundary condition for each of the cases and elemental stresses at each load along the length of inner spring is shown in figure 8 and composite spring for axial loading and axial and lateral loading both are shown in figure 9 and figure 10 respectively.



(a)

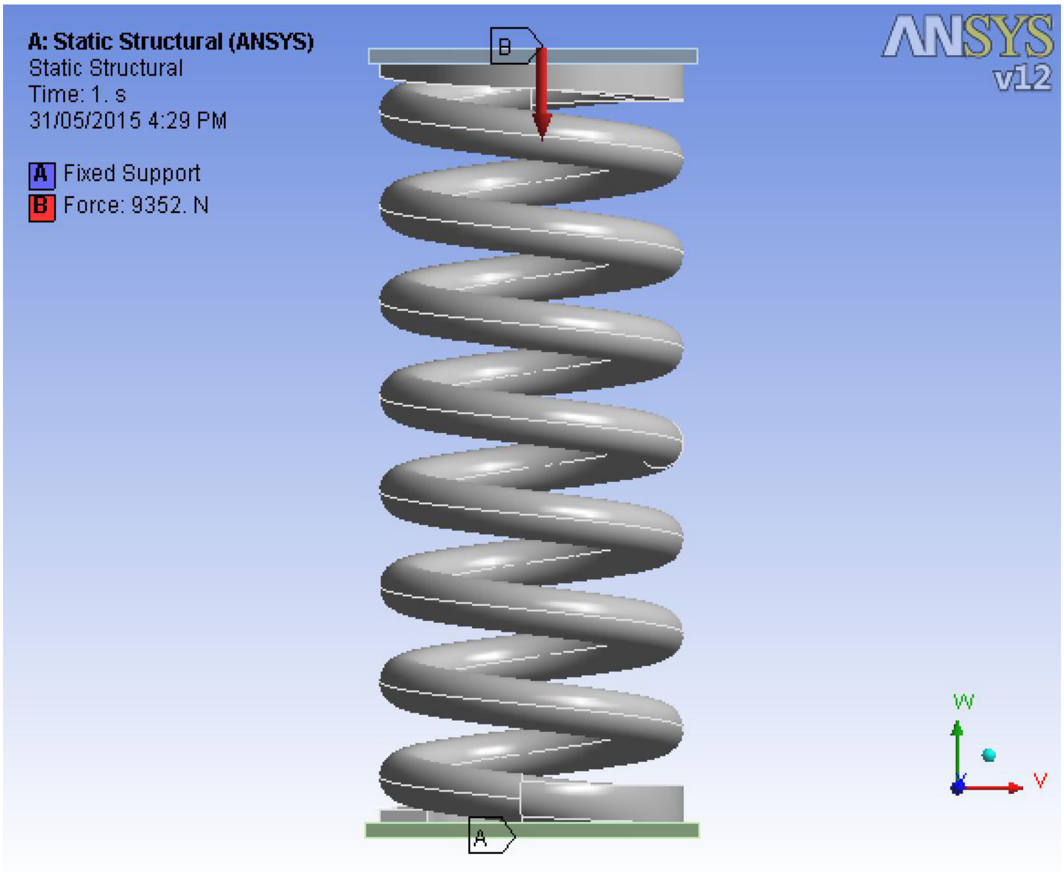


(b)

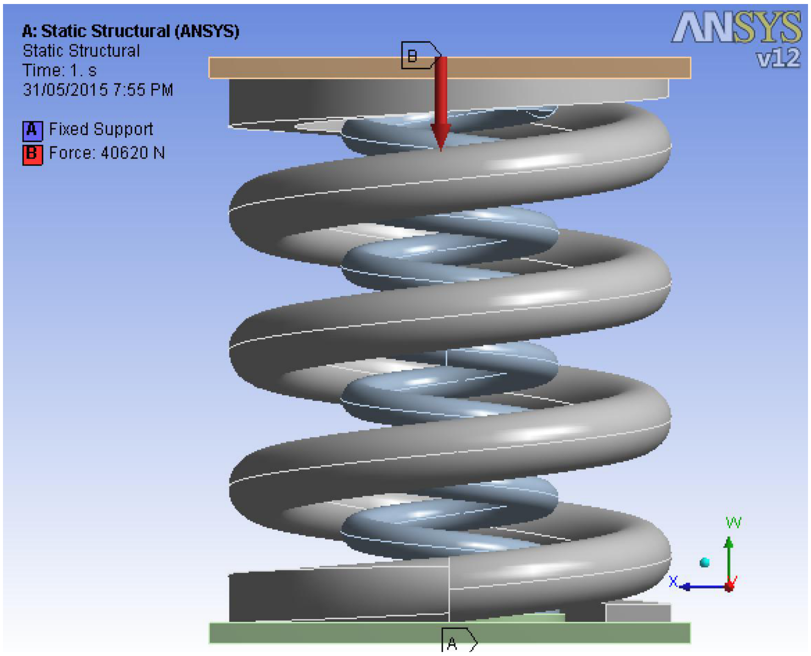


(c)

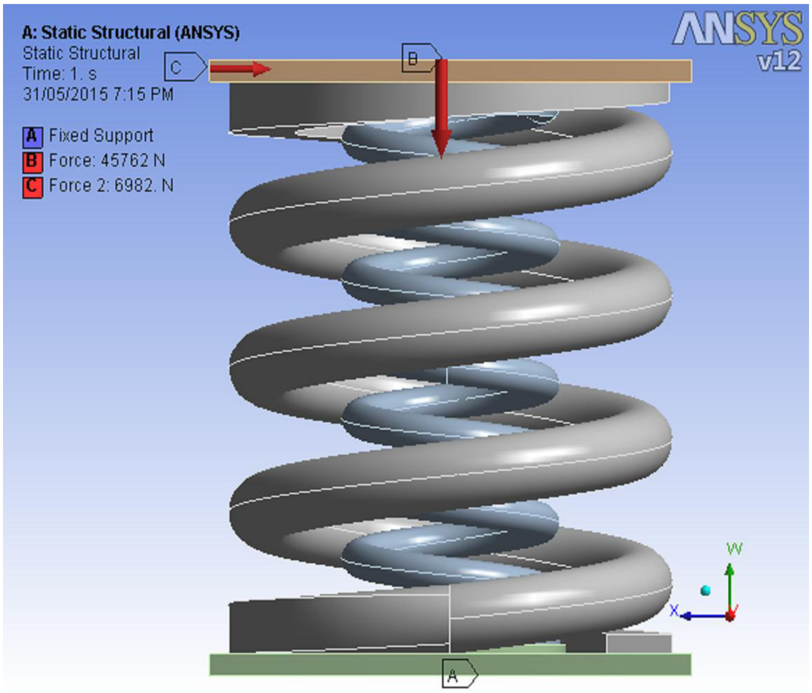
Figure 6: (a) Solid187 tetrahedral element (b) Mesh model of inner suspension spring (c) Mesh model of composite spring



(a) Middle axle inner spring at straight track



(b) Middle axle composite spring at straight track



(c) Middle axle composite spring at curved track

Figure 7: Boundary condition for middle axle inner spring and composite spring at straight and curved track

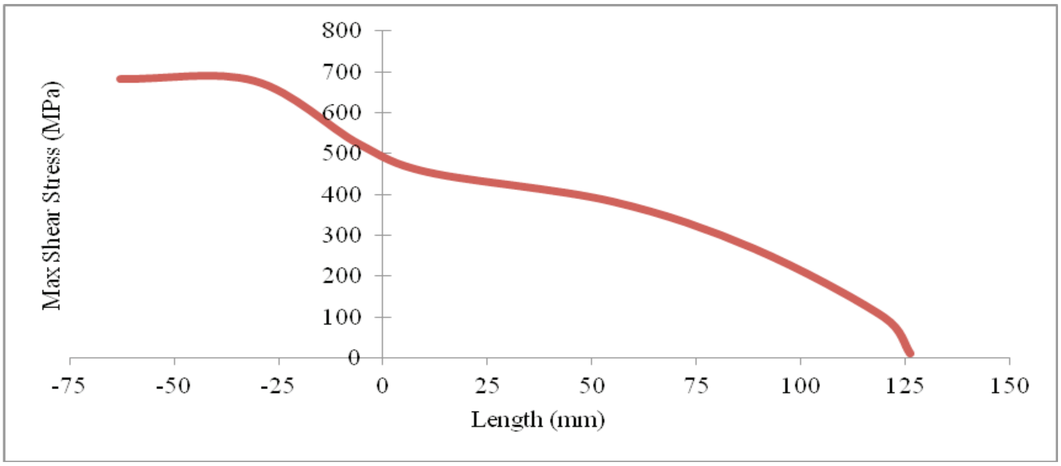


Figure 8: Elemental Shear stress along length of Central axle inner spring

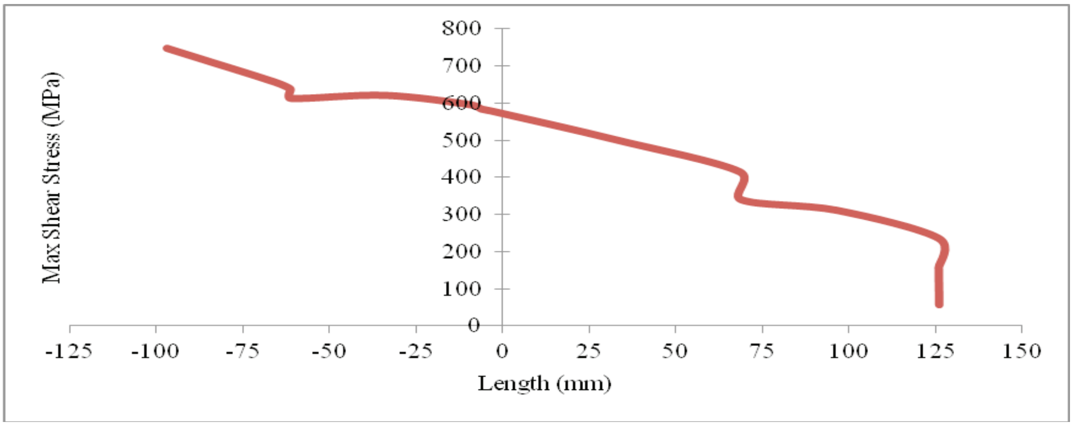


Figure 9: Elemental Shear stress along length of composite spring for axial loading only

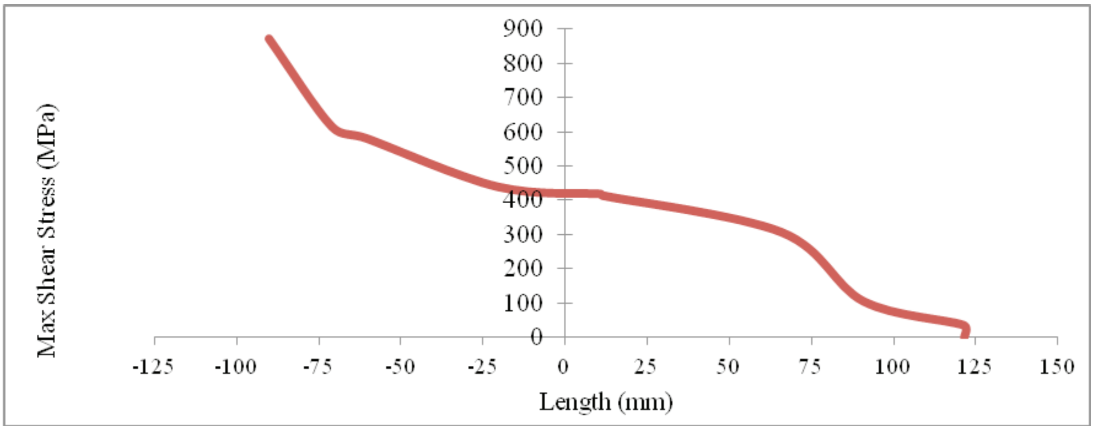


Figure 10: Elemental shear stress along length of composite spring for axial and lateral loading

5. Results and Discussion

The material requires the proper chemical contents to have a better strength for finite or infinite life. Improper contents can affect the ultimate strength which may not bear load for which it has been designed. The analysis reveals the less percentage of vanadium may responsible for failure of spring from first to third coil as the strength of material already being reduced.

According to Shabana et al. (2008) cant excess is the amount of super-elevation that needs to be reduced so that the current vehicle speed will be equal to the balance speed. On the other hand, cant deficiency is the amount of the super-elevation that is needed to be increased so that the vehicle current speed will be equal to the balance speed. In the case of cant deficiency, the vehicle has high lateral forces that can cause undesirable motion on the higher rail. These lateral forces, if high enough, will fail springs and produce a wheel climb that can lead to a vehicle derailment.

The analytical and FE analysis is observed that the stresses are comparatively increased at curvature due to effect of lateral force. As the central axle is free to move laterally, it has a free play of 16 mm lateral deflection and the stresses induced at the top of spring is much higher because of lateral force due to central axle is near to the limiting stress. From analysis shear stress in the central axle inner spring for axial loading is 748.89 N/mm^2 which is comparatively high considering the allowable shear stress of 860 N/mm^2. For the case of turning this stress increases to 870.06 N/mm^2.This high value attribute to fact that the middle axle spring are having more length and hence these are stressed before the load is distributed over all spring, it causes pre-stressing. It could be reduced if the end axle springs have more height.

The FE analysis is also shows the region of high stresses at about one and half coil at which the failure is known to happen frequently. Hence analysis proves that the spring is heavily loaded and on some instances like vehicle moving on curvature, it crosses the ultimate shear stress. Further the actual loading condition would have the additional load as gap in track, alignment errors, jumping of wheel, breaking loads etc. All these factor shall contribute to increase in the load and hence the stress.

The damper support to absorb the extra load or impact comes on the spring. Due absence of lateral dampers at the central axle spring, the spring is subjected to lateral loading and this develops a very high stress initiating the crack which acts as the starting point for shear failure, leading to final shearing of spring due to crack propagation.

6. Conclusion

The experimental spectroscopy analysis has been carried out which reveals the chemical composition of material for first three specimens are improper and responsible for failure of spring due to improper strength for the defined loading condition. On the other hand, the analytical and FE analysis reveals that remaining two spring specimens are failed only due to design incompetency and not due to material defect as the designed stresses are reaches to the limiting condition for axial loading and crosses the limit for the combination of axial and lateral loading. The elemental stress results shows maximum stresses are occurred at second to third coil at which the real failures are occurred. The above values are near shear stress region and hence the design is critical.

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