

# Failure Analysis of Inner Suspension Spring of Railway Engine: A Case Study

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**Abstract**—Springs are subjected to cyclic load and failures are not uncommon. However, the high rate of failure of the specific spring in the composite assembly calls for the investigation. WAG-9 type electric locomotives, of Indian Railways' fleet, used for Goods train hauling and maintained at Ajani Electro loco shade, of central railway has the history of frequent failure of the middle axle primary inner suspension spring. The study of failures revealed that, this specific components fails at a much higher rate between first to third coil from the top end. Though the exact time and instance of failure cannot be ascertained as it does not halt the loco and it is noticed only when the loco comes for maintenance. This paper discusses the FE analysis of the same. This paper discusses the details of FE analysis of arrangement for the loading on straight and curved path.

**Index Terms**—Helical springs, spring deflection, load & stress calculation, FE analysis.

## I. INTRODUCTION

WAG-9 is an electric locomotive engine of Indian railways used to haul specially goods train and is maintained by Ajani Loco shed, Nagpur India. The Loco has six axles in two sets of three frontal and rear wheels as shown in figure 1.

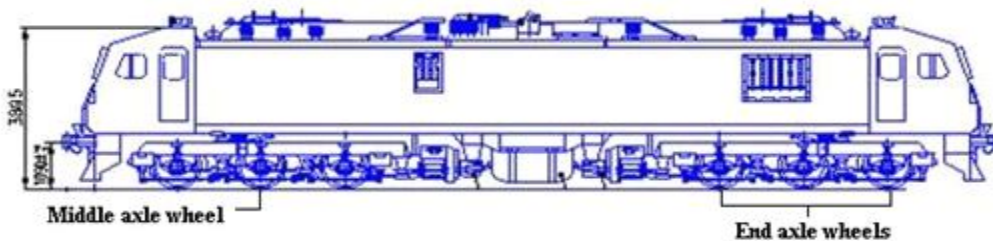


Figure1.Side view of Indian locomotive class wag-9

Each of the wheels has two suspension springs called primary springs. The total numbers of primary spring are 24. The figure 2 shows the arrangement on end axles and figure 3 shows the arrangement on middle axle. The primary springs of the middle axle wheels on each of frontal and rear side has a concentric inner spring called primary inner springs as shown in figure 4.

### A. Observations

The maintenance record <sup>[1]</sup> at loco shade indicates that there is very high rate of failure of primary inner spring. For instance in 2009-10 the primary inner spring was replaced on 51 instances as against 8 instances of middle axle primary outer spring. Following are the observations on failed spring:

- The spring usually breaks between first to third coils.
- Failure initiates at the inner radii of spring which progresses and shears the spring into two pieces. (Refer figure 5).
- The scratches on the damper confirm the deformation of assembly by about 25mm more than the stationary condition indicating higher loads while running. (Refer figure 6).



Figure 2. Actual photo of End axle wheel set with Primary spring



Figure 3. Actual photo of Middle axle wheel set with Composite spring



Figure 4. Actual photo of Middle axle composite spring (Primary Inner & outer spring)



Figure 5. Failed middle axle inner spring



Figure 6. Rubbing marks over inclined damper on end axle

## II. SPECIFICATION OF SUSPENSION SPRING

There are two types of suspension spring used in WAG-9 railway engine, primary and secondary suspension spring. These are the helical spring used to absorb shock and vibration coming on the wheels of locomotive. The technical specifications of each spring<sup>[2]</sup> are shown in table I.

TABLE I.  
TECHNICAL SPECIFICATION OF SPRING SET

Particulars	Unit	Middle Axle Outer Spring	Middle Axle Inner Spring	End Axle spring
Free length ( $L_f$ )	mm	258.6	252.4	238.8
Outer diameter ( $D_o$ )	mm	212	104	221
Mean diameter ( $D_m$ )	mm	180.5	87.5	185
Coil diameter ( $d$ )	mm	31.5	16.5	36
No. of active coil ( $n$ )	-	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 <sup>2</sup>	78500	78500	78500
stiffness ( $k$ )	N/mm	470	144	868

### A. CASE-I: Load analysis for loco moving on straight path

The overall load of about 123 tonne of loco is acted over the suspension springs on all wheel set. The schematic diagram of figure7 shows the load distribution over the all suspension spring.

Using various load acted upon the axle assembly when loco is moving on straight path are as given below.

- 1) Total weight of loco = 123 T
- 2) Unsprung mass per wheel set = 3.984 T
- 3) Total unsprung mass = 23.904 T
- 4) Net load on all axles = 99.096 T
- 5) This net load is distributed over each of frontal and rear wheel sets through front and rear wheel frames.

Thus net load distributed on each frame = 49.548 T

6) At first this load of 49.548 T is acted over each middle axle primary outer spring as the height of this spring higher than all the spring which is 2mm more than middle axle inner spring and 20 mm more than end axle springs. Then the load is acted on middle axle inner spring. After 18 mm deflection of middle axle spring (inner & outer); the load is distributed over end axle springs.

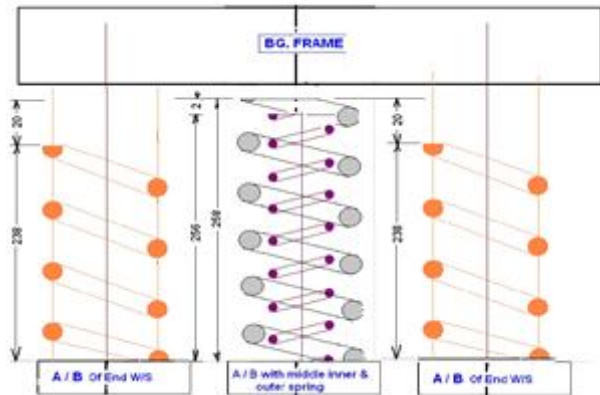


Figure 7. Load distribution on all spring

Following assumptions were made for simplification.

- i) The rails are smooth and there are no geometrical irregularities.
- ii) The loading is static.
- iii) Impact load during operation are neglected.
- iv) All other kind of load than mentioned in calculations is neglected.

Using Wahl's factor, shear stress and other design parameters were calculated<sup>[3]</sup> for the case of loading on straight path and are shown in table II

TABLE II.  
ANALYTICAL RESULTS OF ALL SPRINGS FOR THE LOCO AT STRAIGHT PATH

Particulars	Unit	Middle Axle Outer Spring	Middle Axle Inner Spring	End Axle Spring
Spring Index (C)	-	5.73	5.3	5.14
Wahl's Factor (K)	-	1.27	1.29	1.30
Deflection ( $\delta$ )	mm	66.6	64.6	46.6
Load (W)	N	31268.7	9351.46	40451.38
Shear stress ( $\tau$ )	N/mm <sup>2</sup>	583	598.6	530.98
Tensile Strength ( $\sigma_u$ )	N/mm <sup>2</sup>	1550 – 1720		

### B. CASE-II: Load analysis for loco moving on the curved path

To negotiate curves on the railway track, only the middle axles are given the free play of about 16 mm in a lateral direction perpendicular to the direction of motion. It should be noted that the axle do not turn about the loco but there is a sliding of the middle axle which helps in negotiating the curve.

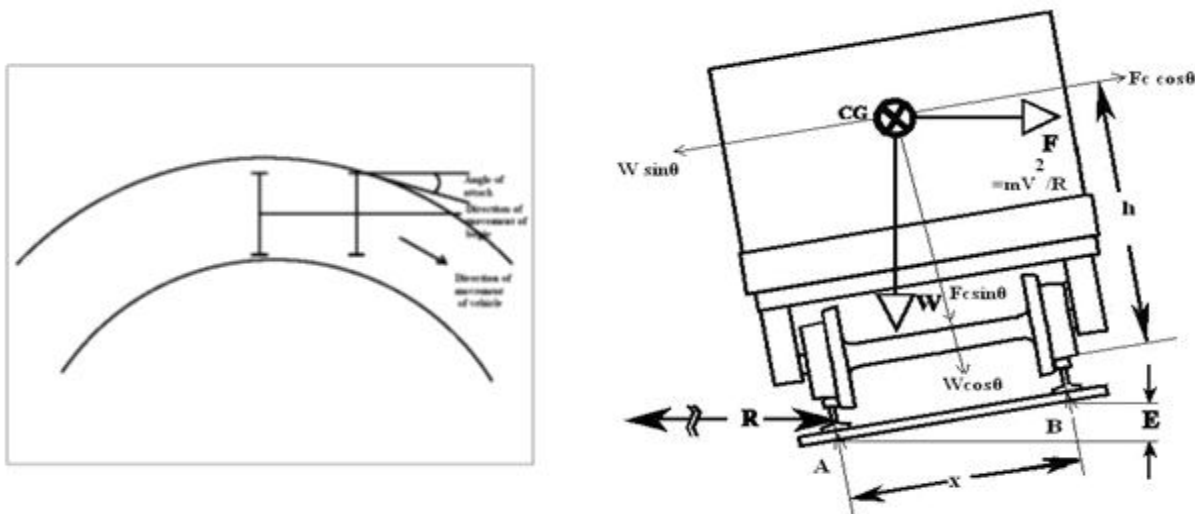


Figure 8. Loco at radius of curvature

While moving on the curved path the loco is subjected to additional lateral load because of centrifugal force which causes the lateral load on the spring with its bending moment maximum at the top end. The figure 8 shows the load when the loco is moving on curved path [4]. Following are the details for calculation of the load [5].

- 1) The loco speed is 80 km/hr.
- 2) The radius of curvature is 292 m, which is the minimum recommended radius.
- 3) The banking angle is 6°.
- 4) Diameter of wheel is 1016 mm
- 5) Angular velocity of wheel is 43.74 rad/s
- 6) Angular velocity of precession is 0.076 rad/s
- 7) Moment of Inertia of wheel is 514.06 kg-m<sup>2</sup>
- 8) Gyroscopic couple is 1720.46 N-m
- 9) Reaction at gyroscopic couple (calculated)

$$R_{GB} = 1026.53 \text{ N} \uparrow, R_{GA} = 1026.53 \text{ N} \downarrow$$

10) Reaction at outer rail

$$R_B = 564.47 \text{ KN}$$

Reaction at inner rail

$$R_A = 449.85 \text{ KN}$$

Table III shows the load and stresses on middle axle wheel set by calculation.

TABLE III.  
ANALYTICAL RESULTS OF ALL SPRINGS FOR LOCO AT CURVED PATH

Particulars	Unit	Middle Axle Outer Spring	Middle Axle Inner Spring	End Axle Spring
Load (W)	N	35250	10512	47740
Deflection (δ)	mm	75	73	55
Shear Stress (τ)	(N/mm <sup>2</sup> )	659.71	672.96	626.97

### III. FE ANALYSIS OF MIDDLE AXLE SPRING

Using the technical specification of spring the FE analysis was carried out in Ansys 12.0. A higher order 3-D, 10-node element having three degrees of freedom at each node: translations in the nodal x, y, and z directions SOLID187 was used [6].

The analysis was carried out for both the above mentioned loading cases. For the analysis purpose the plate with higher rigidity was mounted on the top and below the spring for axial loading and fixing up the displacement. At first the inner spring is analyzed by considering the load calculated above. The deflection and maximum shear stresses are obtained which will compare with the results calculated. But the loads are often shared by the concentric or composite spring; therefore it is necessary to analyze it to check the strength of spring. The figure 9 depicts the loading and boundary condition for each of the cases. The FE analysis of composite spring at straight path is shown in figure 10 and at curved path is shown in figure 11. The comparison of analytical and FE analysis of composite spring for both cases is shown in table IV. From the above analysis shear stress in the middle axle inner spring for the straight path is 748.89 N/mm<sup>2</sup> which is comparatively high considering the allowable shear stress of 860 N/mm<sup>2</sup>. For the case of turning this increases to 870.06 N/mm<sup>2</sup>. 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. It should be noted that a modification shown in figure 12 has been made to the existing design. A shim of 5 mm has been added at the end axle spring to increase the height, decreasing the difference between the middle and end axle spring heights. The load and shear stress calculation for with this modification are shown in table V. The load shared by middle axle springs is reduced because the end axle springs are loaded earlier than the original design. This modification has significantly reduced the failure as this lead to decrease in pre-stressing of middle axle springs. Further this would also mean utilizing the end axle springs to their capacity as the stress on them is increased from current level of 530.98 N/mm<sup>2</sup> to 545.66 N/mm<sup>2</sup> which is within allowable limit. This “equal stress in all springs approach” shall yield better life for each of the spring. However, higher height of spring are not advisable as they tend to shift CG of loco because of increase stiffness of spring assembly and this creates problems in joining loco with bogies.

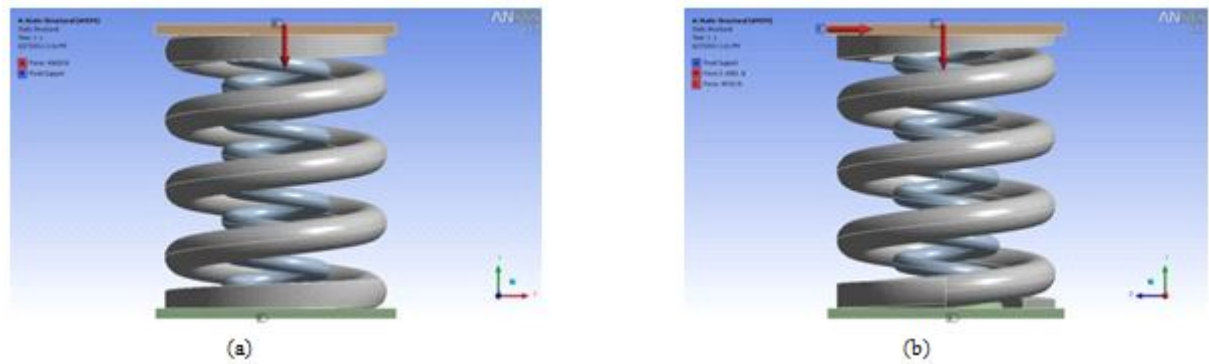


Figure 9. Loading & boundary condition for (a) Composite spring at straight path & (b) composite spring at curvature

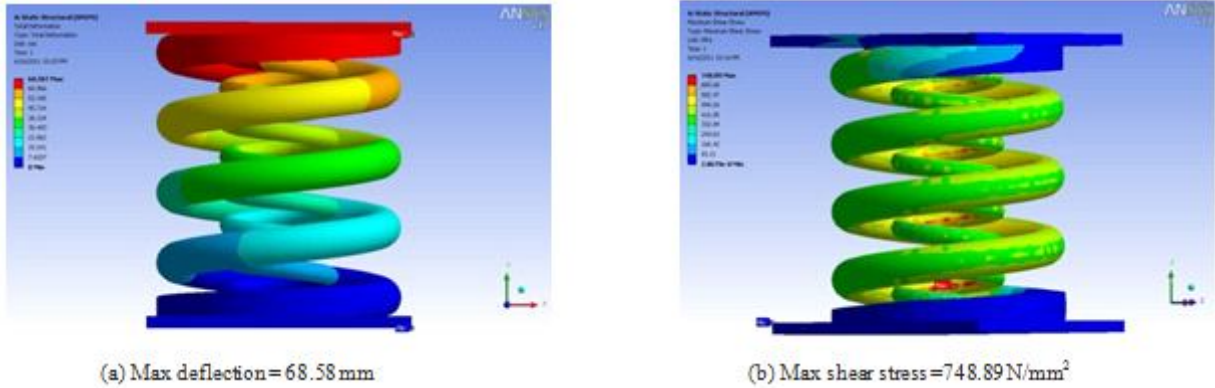


Figure10. FE Analysis of composite spring when loco at straight path

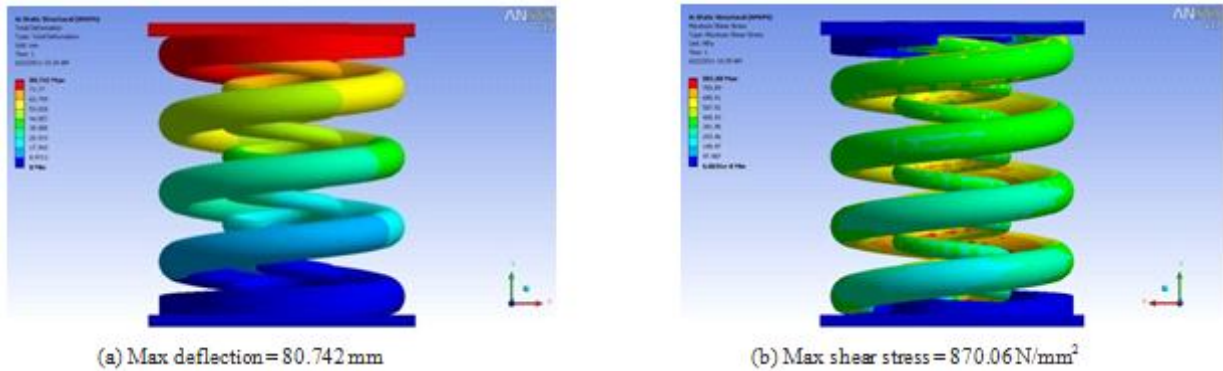


Figure 11. FE Analysis of composite spring when loco at curved path

TABLE IV.  
COMPARISON OF ANALYTICAL AND FE ANALYSIS OF COMPOSITE SPRING WHEN THE LOCO AT STRAIGHT PATH AND CURVED PATH

Spring	Condition	Load	Analytical Analysis			FE Analysis (ANSYS)	
			Deflection (mm)	Shear stress (N/mm <sup>2</sup> )		Deflection (mm)	Max Shear stress (N/mm <sup>2</sup> )
				Inner spring	Outer spring		
Composite spring	At straight path	40620.16	66.6	598.36	583	68.58	748.89
Composite spring	Max Axial load at curved path (due to banking)	45762	75	672.96	659.71	76.939	841.52
Composite spring	a. Axial & b. Lateral load at curved path (due to banking)	a. 45762 & b.6981.52	Analytical formula for lateral load of spring is not available.			80.742	870.06

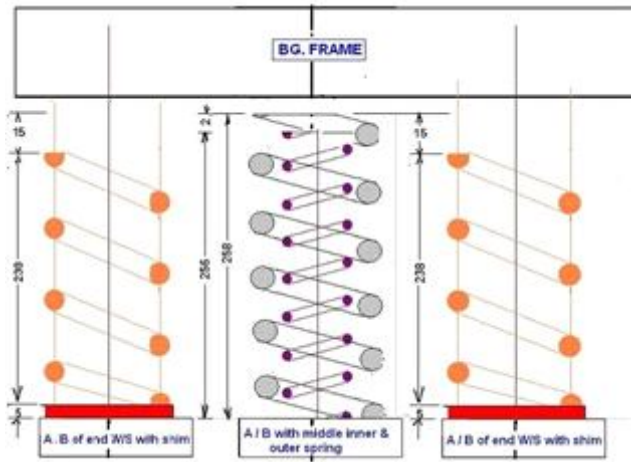


Figure 12. Distribution of load on all spring by adding shim at end axle spring

TABLE V.

ANALYTICAL RESULTS OF ALL SPRINGS AFTER ADDING SHIM AT END AXLE SPRING

Particulars	Unit	Middle Axle Outer Spring	Middle Axle Inner Spring	End Axle Spring
Load(W)	N	29414.175	8779.29	41569.94
Deflection( $\delta$ )	mm	62.91	60.91	52.91
Shear Stress( $\tau$ )	(N/mm <sup>2</sup> )	550.21	561.75	545.66

CONCLUSIONS

From the analytical and FE analysis it is clear that the spring under consideration has shear stresses sufficient to bear while the loco is moving on the straight path. However while traveling on the curved path the shear stress are higher making the design critical. Further the loco has to travel on the rails which have the joints and local irregularities which bring the impact loads.

It should be noted that the middle axle does not have lateral damping and it has a free play of 16 mm to slide to negotiate curvatures. While negotiating with this curvature, the middle axle springs are subjected to lateral loading causing the highest moment and shear stresses at the top end of springs. The FE analysis suggests the maximum shear stress of about 870.74 N/mm<sup>2</sup> while moving on the critical curvatures at the prescribed speed of 80 km/hr. This is almost same as that of allowable maximum shear stress of 860 N/mm<sup>2</sup>. Further actual working conditions also have additional loads due to jerks and impact in all three directions making the loading further complex. Hence the actual stresses are much more than calculated. Therefore the bending stress due to lateral loading may initiate a failure which is further enhance and aggregated because of stress concentration at the failure region and nature of loading and once there is significant development of this crack the shearing occurs almost instantaneously. An observation on the failed spring confirms this failure by crack initiating followed by shear failure. Hence it is suggested that (i) the spring should have some damping for lateral loads that the spring is subjected to while negotiating the curvatures. (ii) The initial stresses in the middle axle spring can be reduced by increasing the length of end axle springs but limiting by shift in C.G. of loco.

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