Design Optimization of SGCI Insert Embedded in Pre Stressed Concrete Sleeper

Srihari Palli, and Azad Duppala

***Abstract*---**One of the most spectacular developments railway tracks went through since the beginning of the railways can be seen in the improvement of their fastening systems. The pre-stressed concrete sleepers in a railway track use Spheroidal Graphite Cast Iron (SGCI) inserts together with Elastic Rail Clip and rubber/elastomeric pad to hold the rails. Fastener suppliers are rising to meet the challenges in a variety of ways. One such a way is to economize the design of the SGCI insert by reducing its weight. As there are four SGCI inserts embedded in a normal single/mono-block pre-stressed concrete sleeper, reducing the weight of the insert is necessary both from the economical point of view and the design point of view.

This work is concentrated on optimizing the design of the insert, considering various geometric parameters used in its design by reducing its volume which is in direct proportion to its weight. The best feasible/optimum solutions are obtained for reduced weight of the insert. Stress analysis of the insert under its operating conditions for different load cases has been done. Parametric model of the insert has been built to carry on the design optimization of the SGCI insert model using ANSYS, considering the geometric parameters as design variables and volume as the objective. On the basis of the algorithmic optimization carried out using ANSYS , it has been found that the weight of the insert can be reduced from 1.51 Kg to 1.38 Kg for the worst state of stresses occurring in the most effective load condition keeping the maximum induced stresses within the permissible limit. The optimum design set obtained has been compared with that of the neural network optimization that has been carried out.

***Keywords*--**Design Optimization, Fastening system, Rail Insert, Parametric Model

I. INTRODUCTION

THE combination of rails, fitted on sleepers with a suitable fastening system and resting on ballast and subgrade is called the railway track or permanent way [2]. The name permanent way is given to distinguish the final layout of track from the temporary tracks that are laid for conveyance of earth and materials during construction works.

The most important function of fastening systems is to provide strong and flexible connection between rail and its supporting structure that can be sleeper or slab. Two types of fastening systems are used to secure the rails to the sleepers, indirect fixation and direct fixation [1]. The "indirect fixation" fastening uses a steel tie plate beneath the rail and a tie pad between the plate and the tie.

The tie plates are through bolted to the ties/sleepers. The "direct fixation" fastening eliminates the tie plate Concrete shoulders cast into the sleeper providing lateral support to the clips.

Bolts, threaded into stainless steel inserts cast into the sleepers are used to secure the clips to the sleeper/tie. The direct fixation clips are less rigid than those used in the indirect fixation.

The Inserts/Iron Shoulders are manufactured from pearlitic malleable iron (M.C.I. Inserts) and spheroidal graphite iron (S.G.C.I. Inserts). Pre-stressed concrete sleepers use SGCI inserts together with Elastic Rail Clip and rubber/elastomeric pad to hold the rails [3], [7]. An illustration of a SGCI insert in a direct fixation system is shown in Fig. 1. The shank/shaft part of the insert is embedded into the sleeper before the sleeper is casted with concrete. The top part of the insert resting on the sleeper surface is a combination of the tapered part called the shoulder and semi cylindrical part with a cylindrical hole in it called the centre-leg [4].

Two elastic rail clips are provided on both sides of the rail and hold the flange side of the rail with the SGCI insert. The elastic liners are used between the rail flange and SGCI insert, and together with ERC they reduce the dynamic loads on the insert. A rubber/elastomeric pad is placed between the rail and concrete sleeper, and reduce the dynamic loads acting on the surface of the rail. As there are four SGCI inserts embedded in a normal single/mono-block pre-stressed concrete sleeper, reducing the weight of the insert is necessary both from the economical point of view and the design point of view. The present work is concentrated on optimizing the design of this insert, considering various geometric parameters used in its design by reducing its volume which is in direct proportion to its weight.

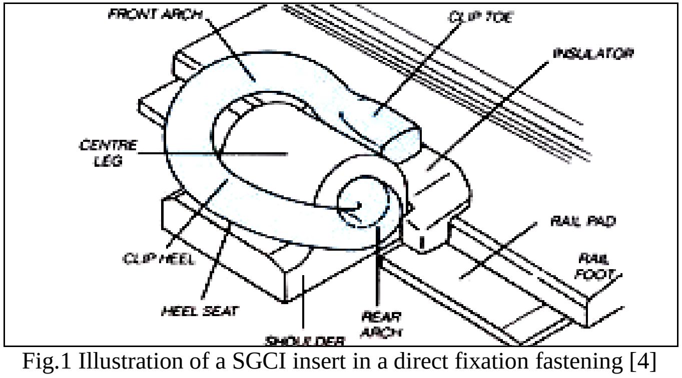

Fig.1 Illustration of a SGCI insert in a direct fixation fastening [4]

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II. MODELING OF THE RAIL INSERT

The insert considered is a SGCI insert which is used in the concrete sleepers in Indian Permanent way. The insert is modeled parametrically in ANSYS to run the optimization with ease and efficiency [6]. Key dimensions which are used in designing the insert are taken as parameters. These geometric parameters are the independent quantities that are varied in order to achieve the optimum design.

The shaft cross section of the insert comprises of a set of ellipses and these ellipses are guided by arcs. Hence major and minor axes of the base ellipse and the guiding smaller ellipse are taken as the parameters ('a' and 'b', 'c' and 'd' respectively), the vertical distance between the base ellipse and the smaller ellipse is taken as another parameter ('h'). The top most part of the shaft has another smaller ellipse with a variable minor axis and is considered as another parameter ('e'). The length ('l') of the shoulder of the insert which is projected outside the sleeper and the thickness ('t') of the centre leg are also taken as geometric parameters and shown in Fig.3.

A. *Modeling the shaft of the insert*

The shaft of the insert is embedded in the concrete sleeper, its cross section is of an ellipse and its profile is designed as a curved surface to increase its contact area. As there is no direct command to create an ellipse in ANSYS, the ellipse is created through a set of key points satisfying the basic ellipse equation [5].

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$$

The key points are input in polar co-ordinate form i.e., (a cosθ, b sinθ). These key points are joined through a smooth curve (spline). Using the symmetry these smooth curves are reflected about Y-Z and X-Y planes to complete the ellipse.

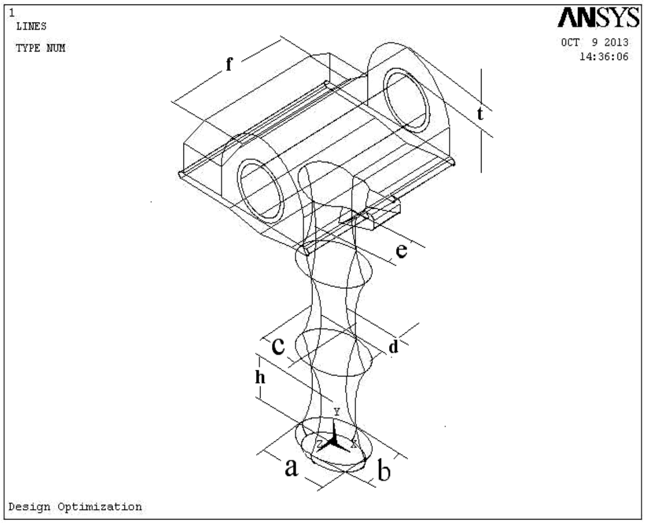

Fig. 2 SGCI Rail Insert with geometrical parameters Modeled using Parametric Modeling

Similarly the guiding smaller ellipse is also created and line arc guiding the profile of the shaft through the specific key points of the larger and smaller ellipses is created. Now, areas and volumes are created through the splines and arcs using modeling commands used in the MACRO written for modeling of the insert.

B. *Modeling the shoulder and centre leg of the insert:*

The shoulder of the rail insert lies on the surface of the sleeper on which the elastic rail clip rests. The shoulder is modeled by tapered lines and its length is taken a geometric parameter. The centre leg of the insert is a half cylinder and is modeled as a semicircle extruded throughout the length of the shoulder. The thickness of the centre leg is taken as a geometric parameter. The diameter of the hole (22mm) depends on the cross-section of the elastic rail clip and is a fixed parameter.

Boolean Operations were used to combine various parts i.e. shaft, shoulder, and centre leg into a single volume. As, the behavior of the SGCI rail insert on a whole has to be studied for optimization, free meshing with tetrahedral elements has been used for the FE model of the rail insert. Solid45, 3D structural solid element type was used for FE modeling. The total number of elements were 13895 and nodes were 3704. The FE model of the insert is shown in Fig.3.

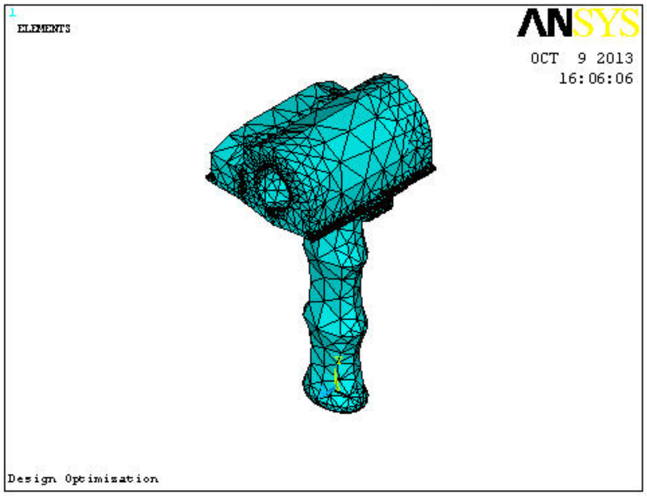

Fig.3 FE Model of the Rail Insert

III. STRESS ANALYSIS OF RAIL INSERT UNDER OPERATING CONDITIONS

The elastic rail clip contacts the insert at locations I and C as shown in Fig.4. The forces F_I and F_C will be acting at these locations, in addition to these forces a horizontal force F_h ($F_h = F_y - \mu \times F_z$) also acts on the insert coefficient of friction μ between rail and rubber pad or between rubber pad and concrete may be assumed as 0.4 (a conservative estimate). The force F_h can be safely assumed to be equally distributed along the length of the insert as shown in the Fig.4. For analysis of stresses on the insert, six different load cases have been considered as per the RDSO (Research Division & Standards Organization for Indian Railways) specifications and are explained below. The six load cases are further simplified into three effective load cases to arrive at the worst state of stress conditions. The insert in different stages of the optimization procedure is subjected to forces from these three load cases.

A. Load case 1:

Only vertical load of 15000 kg acts on the rail in this case. According to RDSO specifications it gives the force analysis on the insert in this case gives the loads as

$F_I = 28760$ N, $F_C = 17980$ N, $F_h = 0$.

The force F_I acts at the inside upper surface in the insert hole and has been taken as uniformly distributed. The force F_C acts on a small elliptical area made due to contact between ERC (Elastic Rail Clip) and face of the insert shoulder at point C. The principal stresses in different parts of the insert vary from 2.09E 7 N/m^2 (compressive) to 11.3E 7 N/m^2 (tensile). The Vonmises (S-Equivalent) stresses in the insert vary from 11.133E 3 N/m^2 (tensile) to 17.3 E 7 N/m^2 (tensile). When embedded in the sleeper block the principal stresses vary from 1.93E 7 N/m^2 (compressive) to 9.09E 7 N/m^2 (tensile). The principal stresses in the concrete block vary from 18.5576E 4 N/m^2 (tensile) to 2.17E 7 N/m^2 (tensile).

B. Load case 2:

The toe load has been increased to 1500 kg in addition the elastomeric pad is missing (frictional coefficient $\mu = 0$), force analysis on the insert gives

$F_I = 39200$ N, $F_C = 24500$ N, $F_h = 68600$ N.

The lateral load F_h acts just above the projected part of the insert on which the rail rests through the elastic liner. The principal stresses in different parts of the insert vary from 58.6E 7 N/m^2 (compressive) to 609.8E 7 N/m^2 (tensile). The Vonmises (S-Equivalent) stresses in the insert vary from 42.091E 3 N/m^2 (tensile) to 604.0 E 7 N/m^2 (tensile). When embedded in the sleeper block the principal stresses vary from 8.63E 7 N/m^2 (compressive) to 48.9E 7 N/m^2 (tensile). The principal stresses in the concrete block vary from 0.124E 7 N/m^2 (compressive) to 10.5E 7 N/m^2 (tensile).

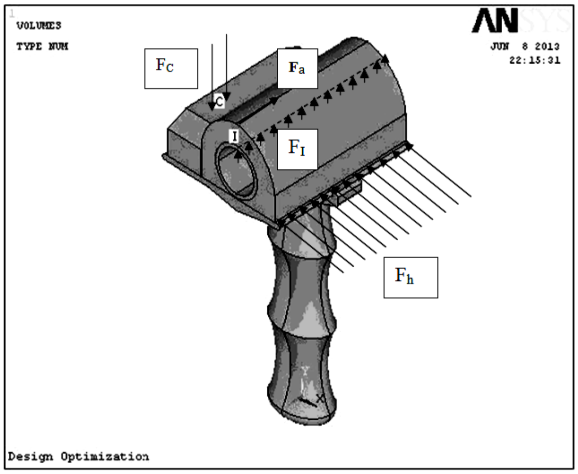

Fig. 4 Different Forces acting on the Rail Insert

C. Load case 3:

The force acting in the axial direction of the 22 mm hole in the insert at the centre leg part to account for the hammer striking force, along with forces

$F_I = 39200$ N, $F_C = 24500$ N, $F_h = 0$.

The axial force accounting for the hammer force (F_a) = 14700 N is assumed to be acting at the top most node of the centre-leg part of the insert as shown in Fig. 4.

The principal stresses in different parts of the insert vary from 26.1E 7 N/m^2 (compressive) to 195.0E 7 N/m^2 (tensile). The Vonmises (S-Equivalent) stresses in the insert vary from 15.638E 3 N/m^2 (tensile) to 183.0 E 7 N/m^2 (tensile). When embedded in the sleeper block the principal stresses vary from 4E 7 N/m^2 (compressive) to 20E 7 N/m^2 (tensile). The principal stresses in the concrete block vary from 45.8620E 4 N/m^2 (compressive) to 4.92E 7 N/m^2 (tensile).

IV. DESIGN OPTIMIZATION OF RAIL INSERT

Design optimization is a technique that seeks to determine an optimum design. By "optimum design," means the one design that meets all specified requirements but with a minimum expense of certain factors such as weight, surface area, volume, stress, cost, etc. In other words, the optimum design is usually one that is as effective as possible. In ANSYS, Design optimization is a technique available to obtain the optimum design. Actually, any ANSYS item that can be expressed in terms of parameters can be subjected to design optimization.

The ANSYS program offers two optimization methods to accommodate a wide range of optimization problems. The subproblem approximation method is an advanced zero-order method that can be efficiently applied to most engineering problems. The first order method is based on design sensitivities and is more suitable for problems that require high accuracy.

A single criterion optimization of the SGCI insert has been carried out for individual load cases using the Design Optimization tool in ANSYS. The model is built parametrically and explained in the macro file. Assumptions considered for this optimization process are:

- The insert alone is considered and its base is fixed to account for the maximum stress condition.
- To make the maximum utility of insert material, the state variable is taken as a fraction which is defined as ratio of minimum tensile strength of the insert material to factor of safety times the Vonmises stress (S-Eq). Optimization has been carried out for maximum Vonmises stress and Total Vonmises stress condition occurring in the insert.
- The limits of the design parameters considered as design variables for optimization process are taken to be within the limits of the topology of the insert.

A. Design Variables

Geometrical parameters considered as design variables for optimization are explained below. The original values of each of these geometrical parameters are presented in Table I. For all the optimization processes carried out for all the three load cases considering both the maximum Vonmises stress as well as the total Vonmises stress the limits for the design variables are taken as per the topology requirement of the insert.

a -----Major axis of the base ellipse
b ------Minor axis of the base ellipse
c ------Major axis of the small guiding ellipse
d ------Minor axis of the small guiding ellipse

e ------Minor axis of the small guiding ellipse at the top part of the shaft
h ------Vertical distance between base and small ellipses
f-------Length of the shoulder part
t ------- Thickness at the centre-leg above the hole.

TABLE I
LIMITS AND VALUES OF DESIGN VARIABLES

Design Variable Name	Minimum Limit (m)	Maximum Limit (m)	Original Value (m)
a	0.015	0.02	0.0175
b	0.01	0.015	0.0125
c	0.01	0.015	0.012
d	0.005	0.009	0.007
e	0.007	0.012	0.012
h	0.015	0.023	0.02
f	0.055	0.062	0.05868
t	0.009	0.012	0.0105

B. State Variables

State Variable taken here is a fraction defined as a parameter for different types of stresses as:

$$\text{Fraction (Fr)} = \frac{\text{Minimum Tensile strength of SGCI}}{(1.2 * \text{Maximum Vonmises stress})}$$

$$\rightarrow \text{Fraction (Fr)} = \frac{500E\,10}{[1.2 * (S - Eq)_{\max}]}$$

Maximum Vonmises stress (S -Eq) $_{\max}$ is extracted from the post processing results data. Minimum tensile strength of SGCI is taken as 500E 10 N/m^2 (IS code 1865:1991) [8].

$$\text{Fraction (Fr1)} = \frac{\text{Minimum Tensile strength of SGCI}}{(1.2 * \text{Total Vonmises stress})}$$

$$\rightarrow \text{Fraction (Fr1)} = \frac{500E\,10}{[1.2 * (S - Eq)_{total}]}$$

Total Vonmises stress (S -Eq) $_{\text{total}}$ is extracted by summing up each element's S-Eq and accepting it as a parameter from the results data. For the State variable i.e. for the fraction, a maximum limit has been used which is approximately taken as 60% of the original value.

C. Objective Function

The objective of the optimization process is to minimize the weight of the insert, since there is no direct option to extract weight from the post processing results data volume of the insert is extracted from the results data as the volume is in direct proportion to the weight. Hence volume is taken as the objective parameter for the design optimization processes. The density of the Spheroidal Graphite Cast Iron (SGCI) material is taken as 7800 kg/m^3.

For the Objective the convergence tolerance for all the load cases is taken as 1E-09.

V. RESULTS OBTAINED IN ANSYS DESIGN OPTIMIZATION

The design sets have been obtained in the optimization for different load cases considering maximum Vonmises stress as well as total Vonmises stress. It has been found that for load case 2 considering total von-Mises Stress in which the worst state of stresses occur the weight of the insert has been reduced from 1.511 kg to 1.378 kg as shown in Table II. From Fig. 5 to Fig.9 the variations of design variables, state variables and objective with each design set are shown.

TABLE II
OPTIMUM VALUES OF GEOMETRIC PARAMETERS FOR REDUCED WEIGHT OF THE INSERT

PARAMETER NAME	PARAMETER TYPE	DESIGN SETS OBTAINED BY OPTIMIZATION USING ANSYS					
		SET 1	SET 2	SET 3	SET 4	*SET 5*	SET 6
Fr1	(SV)	> 1.99	> 1.567	> 1.754	1.54	1.436	1.482
a	(DV)	1.75E-02	1.7214E-02	1.6830E-02	1.5832E-02	1.5412E-02	1.5386E-02
b (DV)	(DV)	1.25E-02	1.2345E-02	1.1461E-02	1.1236E-02	1.1137E-02	1.11092E-02
c (DV)	(DV)	1.20E-02	1.2318E-02	1.0952E-02	1.0834E-02	1.0624E-02	1.0724E-02
d (DV)	(DV)	7.00E-03	7.2400E-03	6.6270E-03	6.3820E-03	6.2510E-03	6.2538E-03
e (DV)	(DV)	1.00E-02	9.8720E-03	9.7401E-03	9.7540E-03	9.3262E-03	9.1672E-03
h (DV)	(DV)	2.00E-02	2.1630E-02	1.8630E-02	1.8261E-02	1.7683E-02	1.8164E-02
f (DV)	(DV)	5.868E-02	5.9027E-02	5.7162E-02	5.7346E-02	5.7164E-02	5.7189E-02
t (DV)	(DV)	1.05E-02	1.1600E-02	9.8351E-03	9.6411E-03	9.8341E-03	9.5436E-03
Volume (m^3)	(Objective)	1.9367E-04	2.0104E-04	1.8234E-04	1.7918E-04	1.7667 E-04	1.7715E-04
Weight (Kg)		1.5106	1.56811	1.4225	1.3976	1.37802	1.38177
**SEq (N/m^2)		2.09224E+12	2.6586E+12	2.3753E+12	2.70562E+12	2.90157E+12	2.81151E+12

* ---------- Optimum Design Set
**SEq ------------ Vonmises(Equivalent) Stress
\> ---------- In Feasible Set

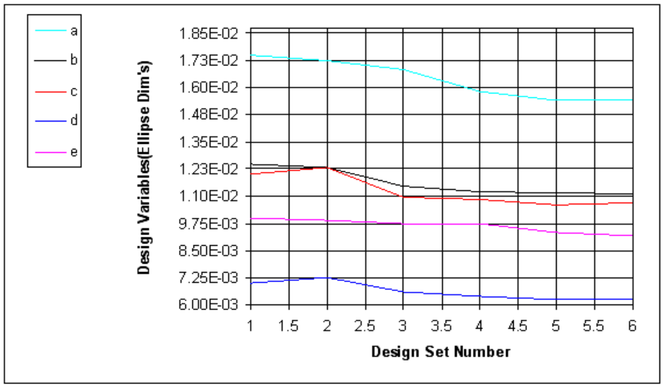

Fig. 5 Design variables of ellipses (Vs) Design set number for Load case 2 considering $(S\text{-}Eq)_{total}$

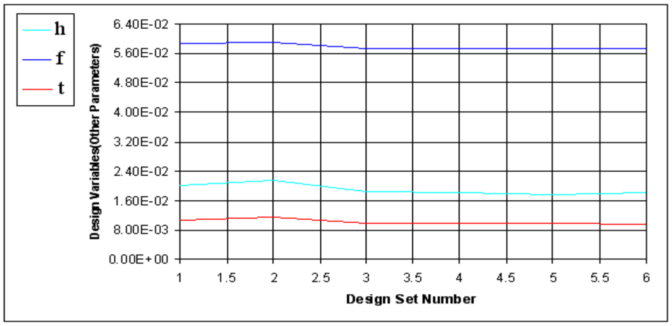

Fig. 6 Design variables of other parameters (Vs) Design set number for Load case 2 considering $(S\text{-}Eq)_{total}$

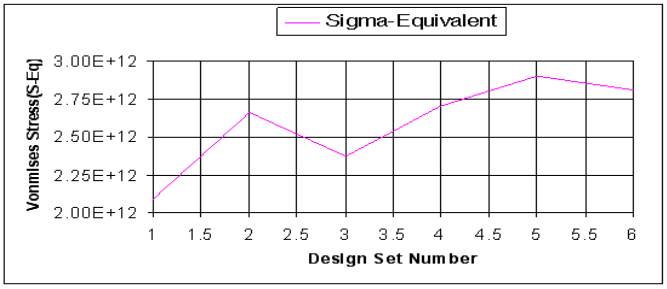

Fig. 7 Total Vonmises stress$(S\text{-}Eq)_{total}$ (Vs) Design set number for Load case 2

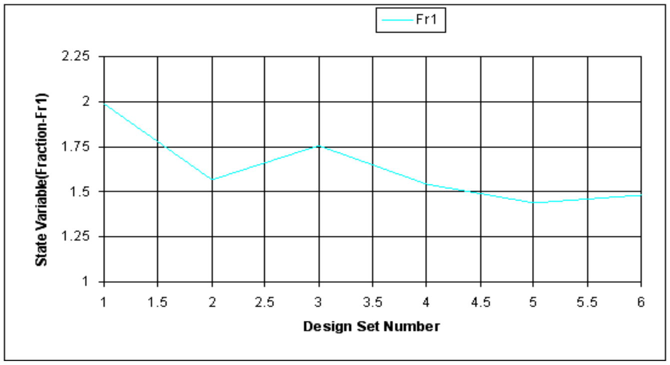

Fig. 8 State Variable (Fraction-Fr1) (Vs) Design set number for Load case 2 considering $(S\text{-}Eq)_{total}$

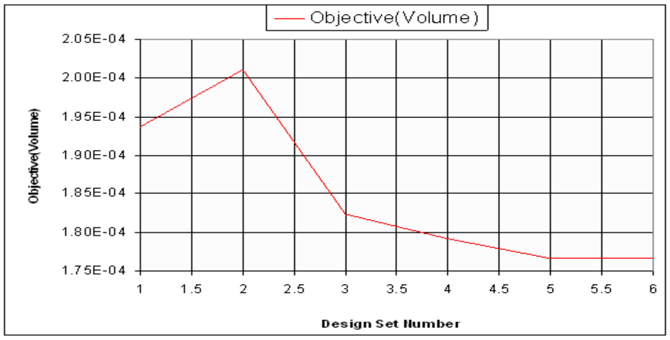

Fig. 9 Objective-Volume (Vs) Design set number for Load case 2 considering $(S\text{-}Eq)_{total}$

By varying each individual design variable (geometric parameter) and keeping all other design variables fixed, volume of the insert has been found. Using these values of parameters and variation of each individual parameter with the volume has been plotted in Fig.10.

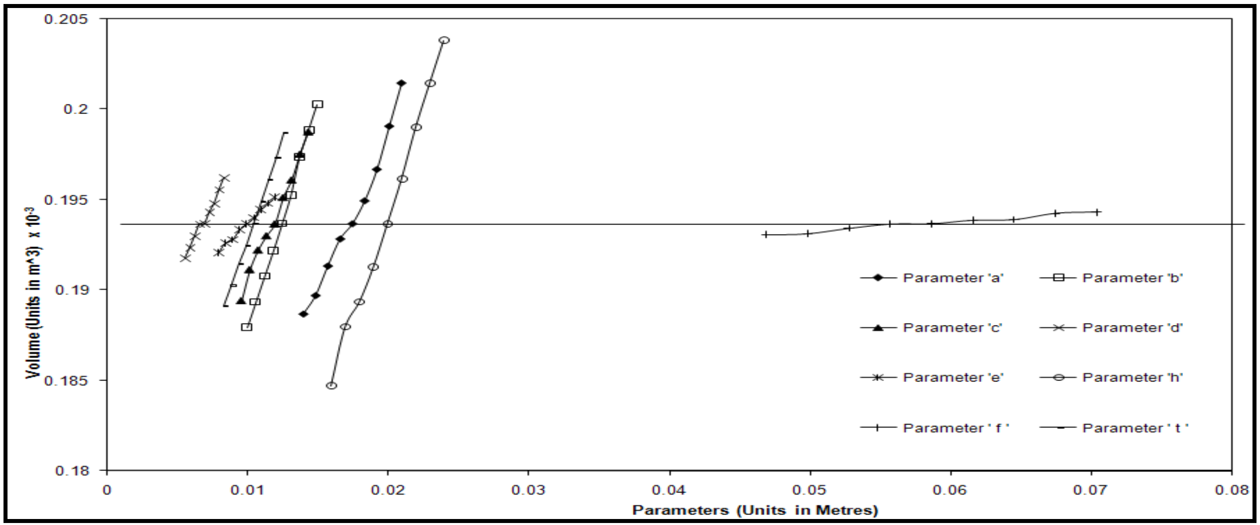

Fig. 10 Volume Vs Parameters

A. Results Obtained in stress Analysis of Insert before and after optimization for the three Load cases.

1. For the first load case the maximum von-Mises (S-Equivalent) stress in the insert has been found as 17.3E 7 N/m^2 (tensile). After optimization the maximum von-Mises (S-Equivalent) stress in the insert has been found as 81.821E 10 N/m^2 (tensile) and is far lesser than the tensile strength of the insert material (500E 10 N/m^2).
2. For the first load case the maximum von-Mises (S-Equivalent) stress in the insert has been found as 604.0E 7 N/m^2 (tensile). After optimization the maximum von-Mises (S-Equivalent) stress in the insert has been found as 281.151E 10 N/m^2 (tensile) and is far lesser than the tensile strength of the insert material (500E 10 N/m^2).
3. For the first load case the maximum von-Mises (S-Equivalent) stress in the insert has been found as 183.0E 7 N/m^2 (tensile). After optimization the maximum von-Mises (S-Equivalent) stress in the insert has been found as 223.15E 7 N/m^2 (tensile) and is far lesser than the tensile strength of the insert material (500E 10 N/m^2).

B. Results obtained in Single criterion Design Optimization of insert

1. When considering maximum von-Mises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.35108 Kg for load case 1, whereas considering total von-Mises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.36102 Kg.
2. When considering maximum von-Mises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.3863 Kg for load case 2, whereas considering total von-Mises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.37802 Kg.
3. When considering maximum vonMises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.3602 Kg for load case 3, whereas considering total von-Mises stress condition the weight of the insert has been reduced from 1.5106 Kg to 1.3503 Kg.

VI. NEURAL NETWORK MODEL FOR OPTIMIZATION

Using the data from the above plots from Fig.5 to Fig.9 in a neural network model, the values of each individual parameter by reducing the volume of the insert i.e. by reducing its weight at an interval of 100 gm have been obtained and are shown in Table III. Neural network model is developed using the neural planner program for estimating the parameters [9]. The program implements the back propagation algorithm. The configuration of each model with the obtained individual geometric parameter has been subjected to all the three load cases for stress analysis. Comparison of target volume and weight achieved with neural network has been shown in Table IV.

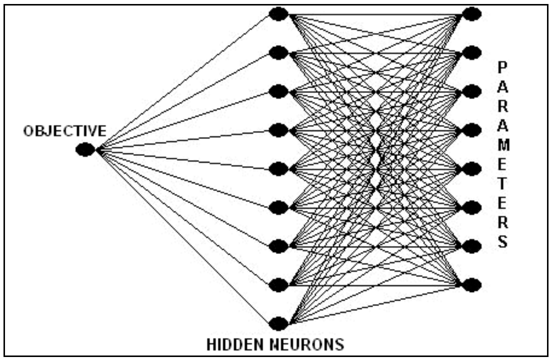

Fig. 11 Schematic diagram of Neural Network Model

TABLE III
VALUES OF VARIOUS PARAMETERS OBTAINED THROUGH NEURAL NETWORK

Weight of the SGCI Insert (Kg)	Volume(E-03) (m^3)	Design Variables (m)							
		a	b	c	d	e	h	f	t
1.5106	0.19367	0.0175	0.0125	0.012	0.007	0.01	0.02	0.05868	0.0105
1.4106	0.18089	0.0169682	0.012281	0.011576	0.006818	0.01001	0.019024	0.058511	0.010464
1.3106	0.16807	0.0168559	0.012204	0.011487	0.006769	0.010014	0.018785	0.058238	0.010403
1.2106	0.15525	0.0168416	0.012133	0.011505	0.006744	0.010025	0.01876	0.058056	0.010392
1.1106	0.14243	0.0169144	0.012011	0.011611	0.006724	0.010051	0.018852	0.057696	0.010415

TABLE IV
COMPARISON TABLE OF THE VOLUME OBTAINED THROUGH ANSYS AND THE VOLUME GIVEN BY NEURAL NETWORK.

Target Volume of the insert given by Neural Network (m^3)	Volume of the insert calculated in ANSYS (m^3)	Target Weight of the insert given by Neural Network (Kg)	Weight of the insert calculated in ANSYS (Kg)	Percentage reduction in Weight/Volume for Neural Network
0.18089E -03	0.18945E -03	1.4106	1.4777	4.518
0.16807E -03	0.18775E -03	1.3106	1.4644	10.45
0.15525E -03	0.18752E -03	1.2106	1.4630	17.22
0.14243E -03	0.187497E -03	1.1106	1.4624	24.05
0.12961E -03	0.19186E -03	1.0106	1.4965	32.44

VII. CONCLUSIONS

Design evaluation of SGCI insert used on concrete sleepers by the Indian Railways has been carried out. The stress analysis of the insert under its operating conditions for different effective load cases has been carried out. The best feasible/optimum solutions have been obtained for reducing the weight of the SGCI insert. On the basis of this study it can be concluded that

1. The influence of each individual design variable on the weight of the insert has been found and it can be concluded that the design variable ‘h’ defining the height of the shaft/shank of the insert is most critical to the weight of the insert, i.e. slight reduction in the value of ‘h’ results in a significant reduction the weight of the insert. Subsequently, design variables ‘a’ and ‘b’, the major and minor axes of the base ellipse are more critical to the weight of the insert as compared to other design variables.
2. On the basis of the algorithmic optimization carried out using ANSYS, it has been found that the weight of the insert can be reduced from 1.51 Kg to 1.38 Kg for the worst state of stresses occurring in the most effective load condition i.e. load case 2, keeping the maximum induced stresses within the permissible limit. Hence the optimized weight of the SGCI insert has been found to be 1.38 Kg.
3. The limited parametric optimization carried out using the neural network indicates that the target weight could not necessarily be achieved by using the obtained design variable values from the neural network. Hence parametric optimization by neural network as formulated cannot be recommended for achieving the desired results.
4. The studies conducted clearly indicate that reduction in weight of the SGCI insert is a distinct possibility, without compromising on the enhanced factors of safety associated with its functioning under normal operating conditions. This aspect needs further studies collaborated by experimental work before a configuration can be adopted for mass production, leading to enormous savings for the Indian Railways.

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