OPTIMIZAREA PROIECTĂRII ARCURILOR CU FOI COMPOZITE FOLOSIND METODOLOGIA SUPRAFEȚEI DE RĂSPUNS

OPTIMIZATION OF COMPOSITE LEAF SPRING DESIGN USING RESPONSE SURFACE METHODOLOGY

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The advancement in fiber composite technology puts back many dense materials by high strength to density ratio. Many attempts have been made with glass/carbon fiber for suspension system; still, not much has been done in the direction of optimization of the design of the leaf spring. This paper reports the work in which a new glass/carbon fiber composite material was made and tested under Tsai–Wu failure stress criteria. The Response Surface Methodology (RSM) was applied to identify the optimal composite leaf spring's design with less stress-strain and deflection. The mechanical properties of the optimal geometry glass/carbon fiber composite leaf spring were experimentally evaluated and compared with the conventional leaf spring.

Keywords: *Optimization; leaf spring; Composite; Suspension; Fiber Reinforced Plastic (FRP)*

1. Introduction

Automotive industries need tremendous amount of metal, alloys for producing different parts of the vehicle. The replacement of metals have been a distant dream but due to rapid development in glass, polymers, ceramics, synthetic fibers etc., proved as the turning point [1]. To meet the needs of natural resources conservation, automobile manufacturers have been making efforts to reduce the weight of vehicles as recent years. The interest in reducing the weight of automobile parts has necessitated the use of better material, design and manufacturing processes [2]. The suspension leaf spring is one of the prospective elements for weight reduction in automobiles which is mainly used to absorb shock loads in automobiles; it carries lateral loads, brake torque, driving torque in addition to absorbing shock [3]. Various studies have been conducted on the application of composite materials for the automobile suspension system [4, 5]. Composite materials have high elastic strain energy, storage capacity and strength to weight ratio compared with metals [6]. The Glass Fiber Reinforced Polymer (GFRP) composite contains polymer granules and glass fiber has been proved to be effective in lowering the cracking risk induced by restrained drying shrinkage. It is mainly attributable to the glass fiber's volume fraction and significantly lowering the capillary water absorption. Therefore, the determination of these volume fractions as well as the corresponding particle size and distribution seems advisable and essential in order to optimize its use [7]. Al-Qureshi [8] developed the GFRP single leaf spring having constant width and stress due to the parabolic tape of the thickness of the spring and showed it to be very effective with low flexural stress, high nominal shear stress and substantial weight saving. The static tensile strength and modulus of glass/epoxy tapered composites are slightly enhanced by the addition of nanoclay [9].The presence of nanoclay in the matrix increases the ultimate strength and decreases the strain to failure. Nanoclay suppresses the fatigue damage growth in terms of damage index and crack growth rate over the whole fatigue life except the early stage of loading.Numerous methods for optimizing design variables of Carbon Fiber Reinforced Polymer (CFRP) composite spring are developed to reduce the weight of automotive coil springs [10]. The analytical calculation shows that the CFRP springs can be calculated like a homogeneous body with constant Young's modulus providing a good

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approximation. Optimization in the construction of simple composite structures can be done by using the Euler – Bernoulli beam theory [11]. Kong et al [12] analyzed the performance of parabolic leaf spring on various roads and stated that the rural area rough road condition with highest damage to the parabolic leaf spring followed by curvature and smooth highway road. Also it was inferred that the actual loading was different for simulation models which resulted in fatigue failure. Meijaard [13] inferred that the imperfections in the size of order and the thickness of a leaf-spring could considerably reduce its in-plane stiffness, as the stiffness for the perfectly flat and straight leaf-spring is the highest. Brouwer et al [14] studied the torsion of the leaf-springs which accounts for a major part of the overall stiffness in the displaced configuration. Therefore, the constrained warping becomes important for small length/weight ratio. The torsion contribution to the compliance has a peak at length/weight being about 1.75, which is independent of displacement. The static analysis, fatigue analysis, modal and shock analysis have been performed using analytical, numerical and experimental approaches on steel as well as composite leaf spring by many researchers. It has been observed that the E-Glass/Epoxy composite leaf spring with more strain energy, lesser stresses, weight, noise, vibration, harshness characteristic and increasing in fatigue life, which provides comfort ride compared with the conventional mono and multi steel leaf spring [15]. Even though many experimental approaches claimed that the optimization of leaf spring design is influenced by various parameters, there is still a need for investigation. Traditional optimization method operates on a mathematical abstraction of the real design problem.These methods usually give only a local optimum. While traditional techniques are of little value here, new non-traditional techniques such as Response Surface Methodology (RSM) give a global optimum. RSM has become a common practice in engineering problems, and it has been used extensively in characterization of the problems, in which the input variables influence performance over the output variables. RSM provides quantitative measurements of possible interactions between factors, which are difficult to obtain using other optimization techniques [16]. In this study, the stress-strain and deflection analyses were conducted on hybrid fiber reinforced composite leaf spring with various geometries and compositions of glass/carbon. The mechanical properties of the optimal design suggested by RSM were evaluated and compared with the conventional leaf spring.

2. Materials and Methods

2.1. Materials

The CFRP and GFRP of 600gsm bidirectional mats were cut into layers and arranged in the ratio of 1:1, 1:2, and 1:3 for various dimensions with the combination of epoxy LY556 resin and hardener HY951 in the ratio of 10:1 by weight. The glass/carbon/epoxy composite material with bidirectional fibers has good characteristics for storing strain energy with the Young's modulus of 23000N/mm^2. The layup was selected to fabricate the longitudinal unidirectional composite leaf spring. Wax coating was applied on the top surface of the die because it was helpful in the removal of leaf from the die and to get good surface finish. In between the layers, the mixture of resin was poured and rolled out by rollers to remove the entrapped air bubbles. The curing time for the set-up was allowed around 24 hours at room temperature. After curing, the leaf was removed from the die and trimmed by grinding process as per the required dimensions. The stress, strain, and deflection were experimentally obtained for these composite leaf springs using universal testing machine (ASTM D2343 – 09) and the data were collected through Data acquisition (DAQ) system. It was assumed that the maximum static loading on the spring was about 4000N without considering the eye point [17]. For comparison, the conventional steel leaf spring with the dimension of 900 mm length, 60mm width, and 10mm thickness were considered.

2.2. Design Constraints

According to Yu and Kim [18], the flexural rigidity is an important parameter in the leafspring design, and it should increase from the two ends of the spring to its centre. This idea gives different types of design possibilities like constant cross-section design, constant width with varying thickness design, and constant thickness with varying width design. The constant cross-section design is selected due to its capability for mass production, and to accommodate continuous reinforcement of fibers. The stress constraint is an inequality constraint to guarantee that the maximum applied stress in the spring is not greater than the material strength. In this work, the Tsai–Wu [19] theory has been selected as failure criterion to evaluate the stress constraint because it is a simple, versatile, analytical criterion and includes interaction among the stress components (Equation 1). F_i,F_{ij} are the material strength parameters and σ_i, σ_j are the stresses on ith and jth planes.

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j \leq 1 \qquad (1)$$

2.3 Optimization Method

RSM is deals with the responses influenced by multi-variables. This method significantly reduces the number of trials that are required to respond to a model [20]. This study includes the responses based on the

Table 1

Input level of influencing factors

S.No	*Variable*	*Factors*	*Units*	*levels*	
				Low	*High*
1.	A	Width	mm	20	80
2.	B	Thickness	mm	5	40
3.	C	Layer ratio	-	1	3

Table 2

Analytical table of responses for the independent variables

S.No.	**Width**	**Thickness**	**Layer Ratio**	**Stress**	**Strain**	**Deflection**
1	80	40	3	72.5	0.003	0.89
2	50	22.5	2	244.4	0.011	5.36
3	50	22.5	3	366.7	0.016	8.04
4	80	22.5	2	152.8	0.007	3.35
5	20	5	3	18562.5	0.807	-
6	50	22.5	2	244.4	0.011	5.36
7	50	22.5	1	122.2	0.005	2.68
8	20	40	1	96.7	0.004	1.19
9	80	5	3	4640.6	0.202	-
10	50	22.5	2	244.4	0.011	5.36
11	50	40	2	77.3	0.003	0.95
12	20	5	1	6187.5	0.269	-
13	50	22.5	2	244.4	0.011	5.36
14	50	5	2	4950.0	0.215	-
15	80	40	1	24.2	0.001	0.30
16	20	40	3	290.0	0.013	3.58
17	50	22.5	2	244.4	0.011	5.36
18	50	22.5	2	244.4	0.011	5.36
19	80	5	1	1546.9	0.067	-
20	20	22.5	2	611.1	0.027	13.40

combinations, estimating the coefficients, fitting the experimental data, predicting the response and checking the adequacy of the fitted models [21]. The responses are stress, strain, and deflection which are obtained for the influencing factors shown in Table.1. For this Design of Experiment (DOE), the RSM L_{20} array was conducted using MINITAB 16.

3. Response Surface Methodology

3.1. Experimental Analysis

Based on the constructed design table, the composite parabolic leaf springs were fabricated for the length of 900mm. The experiments were conducted with the composite leaf springs and the results are tabulated in Table 2. Few failure cases were inferred for the leaf spring with thickness of 5mm and the failure was due to its insufficient energy storage capacity.

3.2. Checking of Data and Adequacy of Models

The normality of the data was assessed by means of the normal probability plot. The normal probability plot for the responses disclosed that the residuals fell in a straight line, which showed the errors being distributed normally [22]. The independence of the data was tested, by plotting a graph between the residuals and the run order for the responses as shown in Figure 1 (a-c). From the figures, we observed all the run residues lay on or between the levels.

3.3 Estimated Regression Coefficients

The uncoded regression equation of the stress, strain, and deflection were estimated in the form of mathematical models as shown in Equations 2-4.The stress and strain were highly influenced by composition layer ratio compared with the other factors but the deflection was quite influenced by thickness also. The adequacy of the

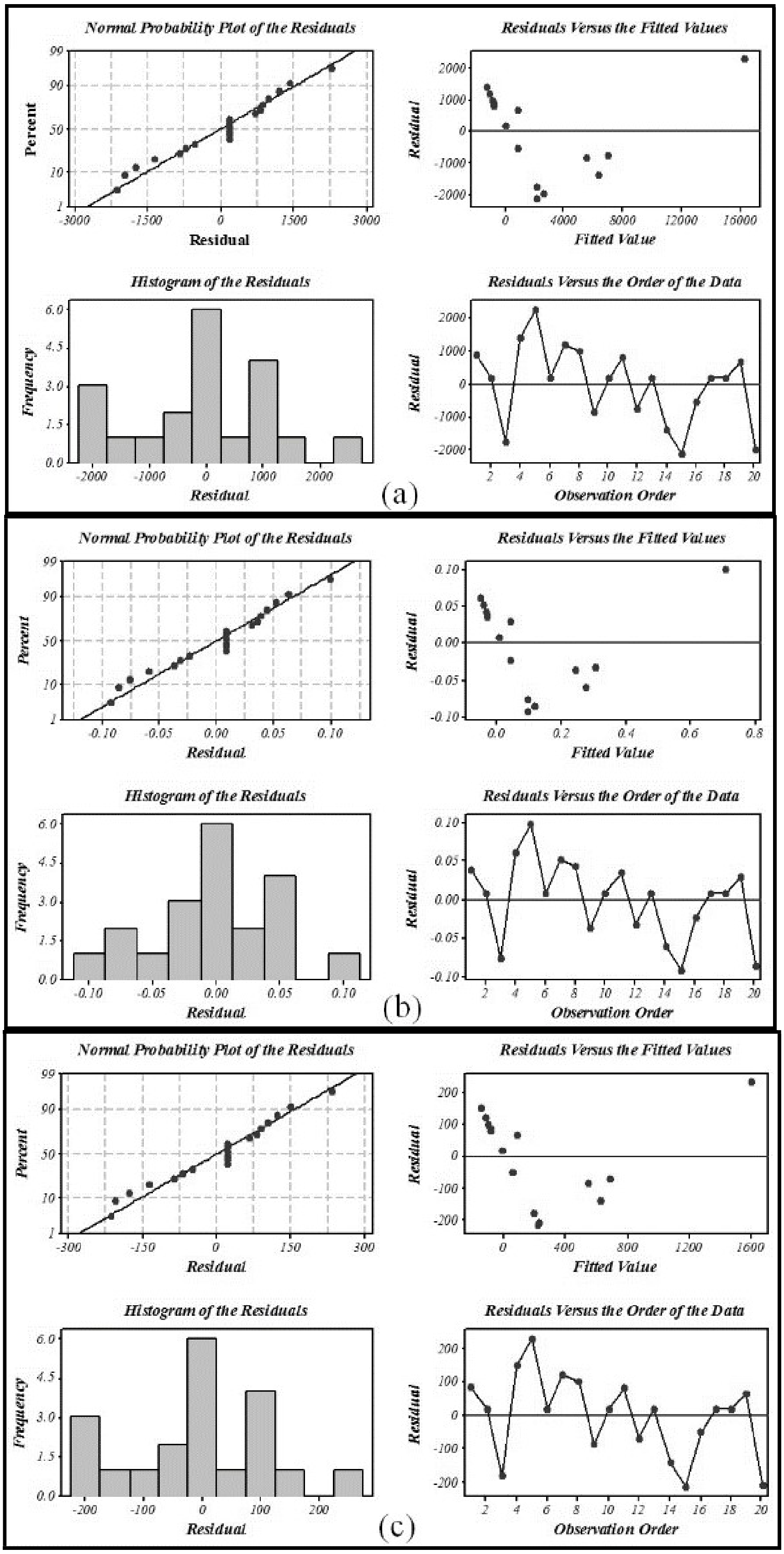

Fig. 1 - Residual plots for (a) stress (b) strain and (c) deflection

responses are tabulated in Table 3 with R^2 and $R^2_{(adj)}$ values. These values indicate the fitness of data model and support the prediction capacity of the model. In all the models, the R^2 values were good and above 90% which was indicative of the fitness in predicting responses.The values of the $R^2_{(adj)}$ coefficient were also high, which indicated the high significance of the model.

$$Stress = 8747.15 - 150.56 * A - 603.51 * B + 4149.78 * C + 0.67 * A * A + 8.93 * B * B + 464.18 * C * C + 4.35 * A * B - 39.28 * A * C - 108.77 * B * C \quad (2)$$

$$Strain = 0.379479 - 0.006576 * A - 0.026178 * B + 0.181491 * C + 0.000029 * A * A + 0.000387 * B * B + 0.019955 * C * C + 0.000189 * A * B - 0.001708 * A * C - 0.004729 * B * C \quad (3)$$

$$Deflection = 874.893 - 14.067 * A - 62.535 * B + 393.517 * C + 0.058 * A * A + 0.941 * B * B + 48.940 * C * C + 0.435 * A * B - 3.822 * A * C - 10.878 * B * C \quad (4)$$

Table 3

Adequacy of the models

S. No.	Response	Std. Deviation	R^2	$R^2_{(adj)}$
1.	Stress	1638	93.5%	87.3%
2.	Strain	0.07112	92.5%	85.7%
3.	Deflection	167.2	92.1%	85.0%

Table 4

ANOVA for the responses

Response	Source	DF	Seq SS	Adj SS	Adj MS	F	P
Stress	Regression	9	328770561	328770561	36530062	13.62	0
	Residual Error	10	26817157	26817157	2681716		
	Total	19	355587718				
Strain	Regression	9	0.621189	0.621189	0.069021	13.65	0
	Residual Error	10	0.050577	0.050577	0.005058		
	Total	19	0.671766				
Deflection	Regression	9	3266895	3266895	362988	12.98	0
	Residual Error	10	279624	279624	27962		
	Total	19	3546519				

3.4 Analysis of Variance (ANOVA)

The ANOVA for the stress, strain, and deflection was done and the results are tabulated in Table 4. It was inferred that the p values were smaller than 0.05 for all the responses and it confirmed that the developed model had 95 % confidence level. Simultaneously, the P values were less compared with the F values of each response. Therefore, it revealed that the developed models were adequate and the predicted values were in good agreement with the measured data.

3.5. Effects of Factors on Responses

The influences of factors on stress, strain, and deflection were analyzed by contour plots as shown in Figures 2 (a-c) respectively. Figure 2 (a) reveals that the low stress is experienced with larger dimensions and high glass layer mixture but rise in layer ratio leads to severe deflection. The thickness is the maximum influencing factor on all the responses compared with width and layer ratio. The similar patterns of the influencing factors are noticed between the responses due to loading relations.

3.6 Optimization

The optimal configuration of factors for the responses is identified from Figure 3. It reveals 48.37mm of width, 15mm of thickness and 1:1 layer ratio are optimal factors which can provide 233.78N/mm^2 of stress and minimum strain of 0.01 for the deflection 14.39mm. This configuration was experimentally evaluated and its results were 289.3N/mm^2 of stress, 0.02 of strain for the

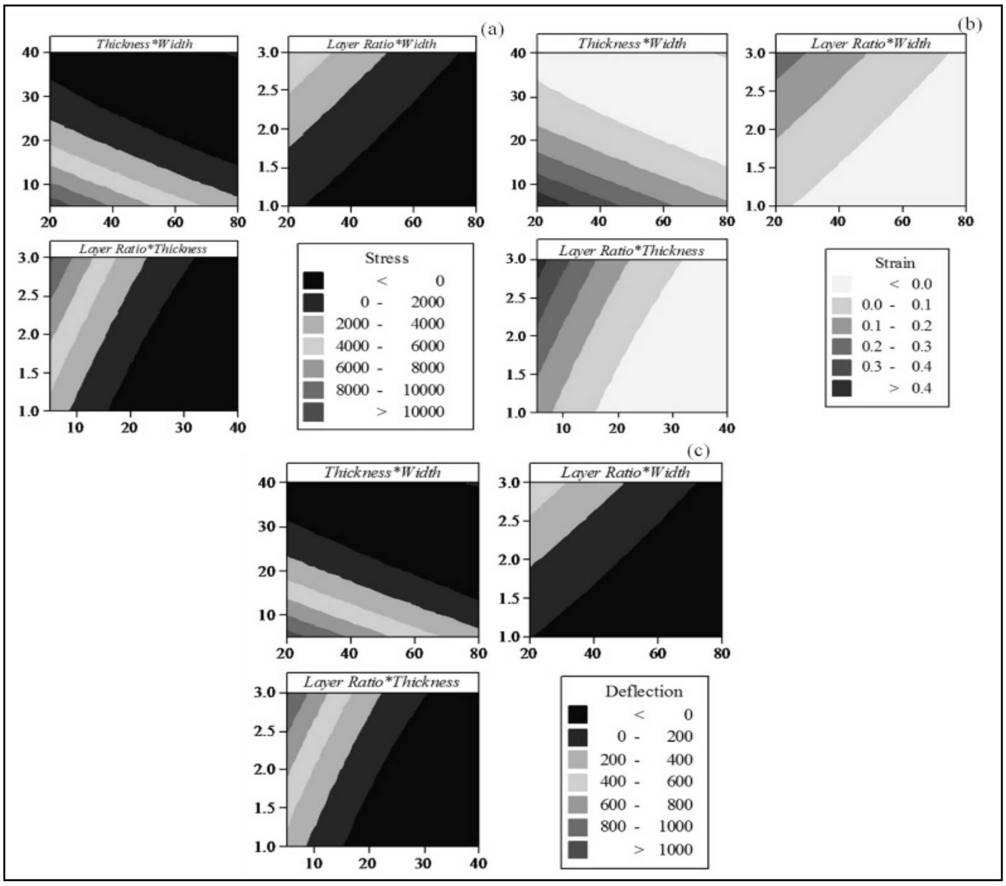

Fig. 2 - Contour plots for (a) stress (b) strain and (c) deflection.

deflection of 15.7mm which was identified to be the optimal for the composite leaf spring with the desirability of 88.68%. The weight of the optimal composite leaf spring was measured to be about 744g which was about 31% less compared with the conventional steel leaf spring.

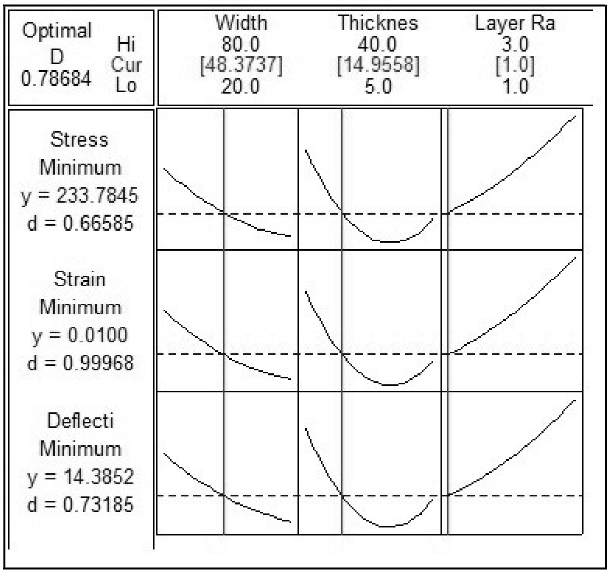

Fig. 3 - Optimal configurations for optimal responses.

4. Results and discussions

4.1 Low Impact Loading Analysis

The optimal composite leaf spring and the conventional steel leaf spring were tested using the fabricated low velocity impact test rig with the load carrying fixture of 400N. The fixture was made to fall from a drop height of 1000mm for 50 trials. The deflection of the leaf spring was measured using LVDT and the data were recorded by DAQ system. The results of the composite and the conventional steel leaf springs were compared and are graphically represented in Figure 4. It reveals that the composite leaf spring can deflect better compared with the conventional leaf spring but the ductility of the conventional leaf spring remains high. The first natural frequency of the composite leaf spring will be higher than that of the steel since the enhanced resistance is offered by the composite leaf spring at the beginning, which is due to the high energy storage capacity of the carbon fibres in the material [23].

4.2 Cyclic Loading Analysis

The cyclic loading capacities of the optimal composite leaf spring and the conventional steel leaf spring were tested using the cyclic loading assembly embedded universal testing machine. The load was applied from 1 to 500N at the centre of the leaf spring with the frequency of 63 cycles

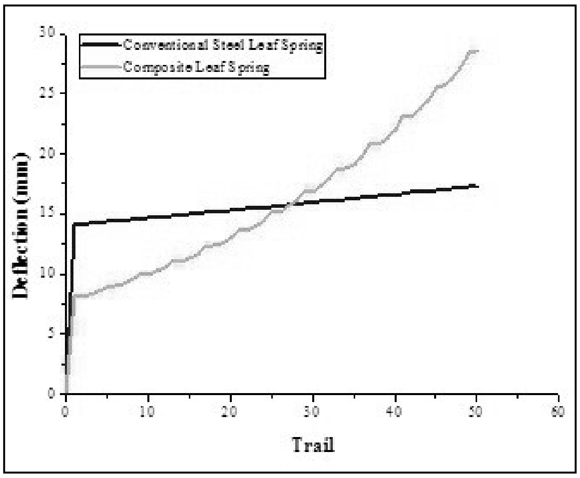

Fig. 4 - Deflection of leaf springs under low impact loading.

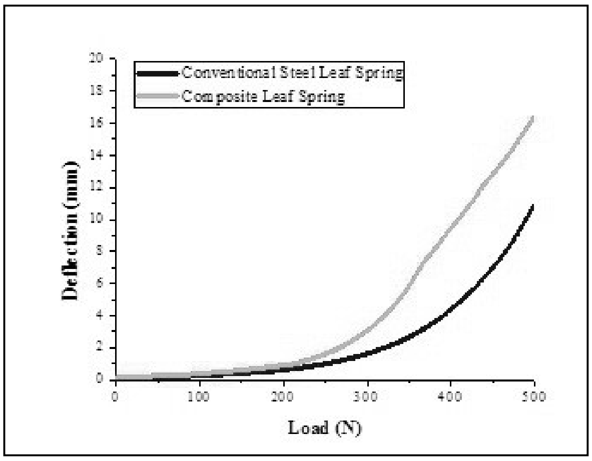

Fig. 5 - Deflection of leaf springs under cyclic loading.

per minute. The deflection of the leaf springs was measured using LVDT and the data were recorded by DAQ system. The load-deflection curves for the leaf springs are plotted in Figure 5. It is observed that the composite leaf spring deflects highly after 300N compared with the conventional leaf spring and it is due to the higher stiffness index of the composite leaf spring. Therefore, the composite leaf spring is more suitable for light weight automotives.

4.3 Fatigue Life Analysis

The fatigue life of the composite as well as the conventional leaf springs was separately measured using bending fatigue machine. The effect of notching was eliminated and the responses were collected through DAQ system. The stress-strain curve and S-N curve were drawn as shown in Figures 6 (a) and (b) respectively to find the fatigue limit of the materials. The crack propagation is survived and the fracto-graphs of the failure zone were studied. The stress-strain curve exposes that the composite leaf spring experiences low strain and stress compared with the conventional leaf spring but it fails before attaining the maximum stress, which is equal to the conventional leaf spring's maximum stress. The conventional leaf spring has the ability to withstand above 800MPa but the composite leaf spring fails at 632MPa. From the S-N curve, it is observed that the composite leaf spring has the ability to pass 22,000 cycles and the conventional leaf spring has gone through 34,000 cycles. This result agrees with the stress-strain curve result. The crack propagates at the centre of the composite leaf spring; it is examined using Scanning Electron Microscope (SEM) with the magnification of 500X. SEM images for different stages of crack propagation show the cup and cone formation and failure nodes of the composite leaf spring.

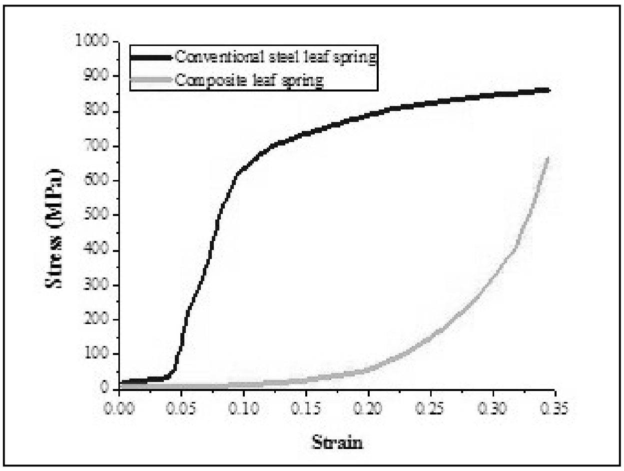

Fig. 6 (a) - Stress-strain curve of leaf springs.

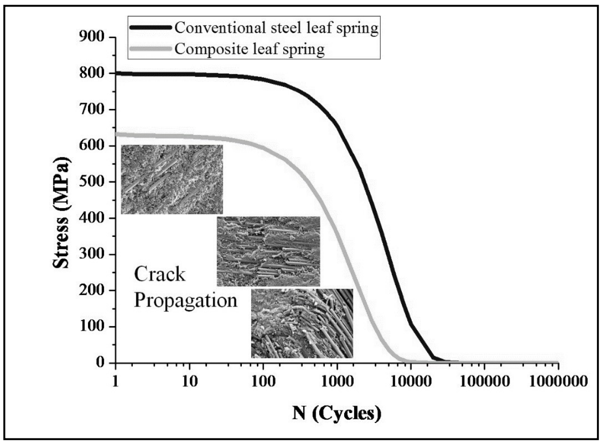

Fig. 6 (b) - S-N curve of leaf springs.

Weibull life distribution model was selected to find the reliability of the life of the leaf springs. The reliability of Weibull distribution is given by Equation (5).

$$R_t = 1 - e^{(-x/\theta)^b} \quad (5)$$

Where, x is the life, b is the Weibull slope index, and θ is the characteristic life; the parameters of the Weibull distribution were calculated using probability plotting [24]. The reliability of the composite leaf spring was 83.9%, which was 6.6% less compared the conventional leaf spring.

5. Conclusions

- The optimal glass/carbon/epoxy fibre composite leaf spring has been identified with 48.37mm of width, 15mm of thickness, and 1:1 layer ratio using RSM, which has 31% less weight compared with the conventional steel leaf spring.
- The enhanced resistance to stress has been offered by the composite leaf spring at the beginning of loading which is due to the high energy storage capacity of the carbon fibres in it.
- The presence of glass fibre in the composite leaf spring has increased the stiffness compared with the conventional leaf spring, which makes it more suitable for light weight automotives.
- The different stages of crack propagation show the cup and cone formation and failure nodes of the composite leaf spring, confirming its brittle nature.
- The reliability of the composite leaf spring has been found to be 6.6% less compared ~~to~~ with the conventional leaf spring which possesses less strain and better weight to strength ratio.

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