



Numerical Investigation on Composite Mono-Leaf Springs Reinforced with Polyurethane/Carbon Nanotubes (PU/CNTs) Nanoweb Interlayers

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Abstract

Composite materials have been widely used in automobile industry to reduce vehicle weight and cut CO₂ emissions. With the rapid advancement of nanotechnology, it is now possible to improve the mechanical performance of these materials more than ever before. In this study, mechanical behavior of carbon fiber/epoxy (CF/EP) composite mono-leaf springs reinforced with polyurethane/carbon nanotubes (PU/CNTs) nanoweb interlayers was investigated numerically. The effect of hybridization in composite leaf springs was revealed. The numerical analyses were carried by using ANSYS Workbench with ACP module. The numerical verification of the finite element model was carried out by comparing numerical results against analytical calculations. Then, the verified FE model was extended to this study. The numerical results showed that the stiffness of the composite wave springs could be increased by 18% with the addition of PU/CNTs nanofibers (CNT content: 5 wt.%) in the interlaminar region without weight and thickness increase. It was also observed that the natural frequency values increased by 8% (CNT content: 5 wt.%) after the addition of these nanofibers.

Keywords: Leaf spring, Composite, Stiffness, Polyurethane, Carbon nanotubes, Interlayers.

1. Introduction

Fiber reinforced composites have been extensively used in automobile, defense and aerospace industries due to their unique advantages such as high strength and stiffness at low weight, good corrosion resistance and fatigue properties [1-3].

Leaf springs are mainly used in suspension systems to absorb shock loads occurred due to road irregularities in heavy and light duty commercial vehicles. They also withstand lateral loads, brake torque, driving torque as well as shock loads. Due to their high elastic strain energy storage capacity, composite materials offer a perfect solution to reduce the overall weight of an automobile without stiffness loss and reduction in load-bearing capacity [4,5]. Therefore, the increased attention has been paid to the replacement of steel leaf springs with composite ones by the researchers. In literature, there are many experimental and numerical studies about composite leaf springs. Recently, Ashwini and Mohan Rao [6] systematically reviewed these studies on this topic.

The use of thermoplastic electrospun nanofibers in the

interlaminar region of composites is one of the most promising techniques due to some unique advantages such as improved delamination resistance (up to 3 times depending on the polymer type and nanofiber areal weight density) with uncompromised in-plane mechanical properties, no additional weight/thickness and unchanged resin viscosity [7-10]. The first commercial suppliers of electrospun nanofiber interlayers are on the market and the transition of these nano interlayers into commercial products has already started. Today, it is possible to obtain different types of thermoplastic nanowebs in the market. The first real-life application of nanointerleaved composites can be seen in a carbon fiber/epoxy fishing rod manufactured by Kilwell Sports Ltd. The bending strength of these fishing rods was almost 100% higher than those of the old-fashioned ones [11]. Further research is needed to understand the effects of nano-interleaving technique for the other possible structural applications.

In this study, for the first time, the effects of PU/CNTs nanoweb interlayers (CNTs content: 1 and 5 wt. %) on the mechanical behavior of carbon fiber/epoxy composite leaf springs were investigated by using ANSYS 16.2 software package. It is aimed to make a

unique contribution to the existing literature and present a new win-win solution to enhance the stiffness and natural frequencies of existing composite leaf springs.

2. Problem definition and analytical calculations

Figure 1 shows the mono-leaf spring considered in this study. The dimensions of the mono-leaf spring were given in Table 1.

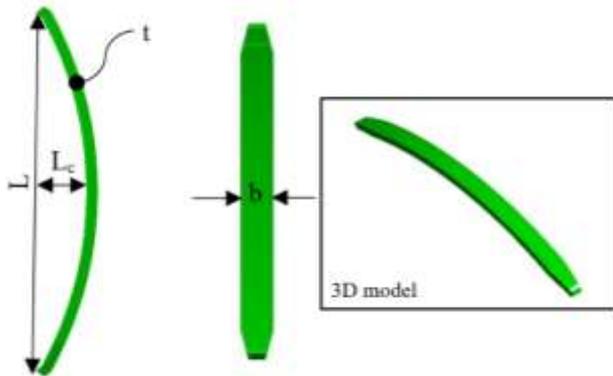


Figure 1. Dimensions and 3D model of the mono-leaf spring.

The maximum displacement of a steel-made mono-leaf spring under the applied load (P) and the stress can be calculated by using Equations (2.1) and (2.2) respectively [12].

$$\delta_{\max} = \frac{3PL^3}{4Ebt^3(3n_m + 2n_g)} \quad (2.1)$$

$$\sigma_{\max} = \frac{3PL}{2n_m bt^2} \quad (2.2)$$

where L , b , t are the length, width and thickness of the mono-leaf spring respectively. n_m and n_g are the number of master leaf and the number of graduated-length leaves, respectively ($n_m=1$ and $n_g=0$ for mono-leaf spring). The elastic modulus and the density of the steel was assumed as 200 GPa and 7850 kg/m³, respectively.

Figure 2 shows the load-displacement characteristics of steel-made leaf spring obtained by using Equations (2.1). The corresponding normal stress values were also shown in Figure 2. The stiffness of the steel-made leaf spring was determined as 749.5 N/mm.

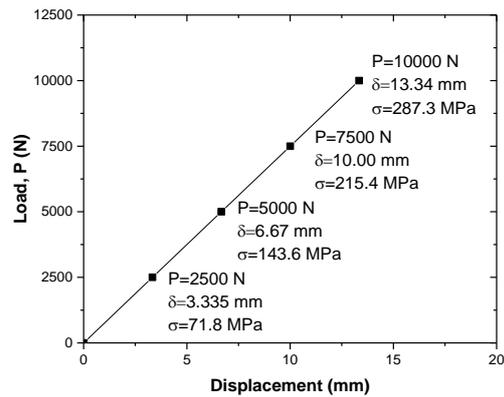


Figure 2. Load-displacement characteristics of steel-made composite leaf spring.

3. Finite element modeling of steel mono-leaf spring and numerical verification

In order to verify the finite element model used in this study, steel-made mono-leaf spring were analyzed by using ANSYS Workbench. The numerical results were compared with the analytical calculations presented in Section 2.

Table 1. Geometrical properties of composite leaf spring.

| Geometry | Dimension (mm) |
|-------------------------|----------------|
| Span length (L_s) | 1300 |
| Thickness (t) | 30 |
| Width at center (b) | 75 |
| Width at both ends | 45 |
| Free camber (L_c) | 142 |

The 3D model of the leaf spring was first created by using Solidworks then imported into ANSYS Workbench to create finite element model. A total of 51040 SOLID 185 elements (having translations in x, y and z directions) were used to create the FE model of leaf spring. The number of nodes was 60480. Through thickness, 20 elements were used in to order to get more accurate results. More refined mesh was used in the center of the leaf spring. Figure 3 shows the FE model of the leaf spring and applied boundary conditions. The both end of the spring were fixed in the z-direction and the force (P) with a magnitude of 10 kN was applied in the z-direction to the center of the mono-leaf spring.

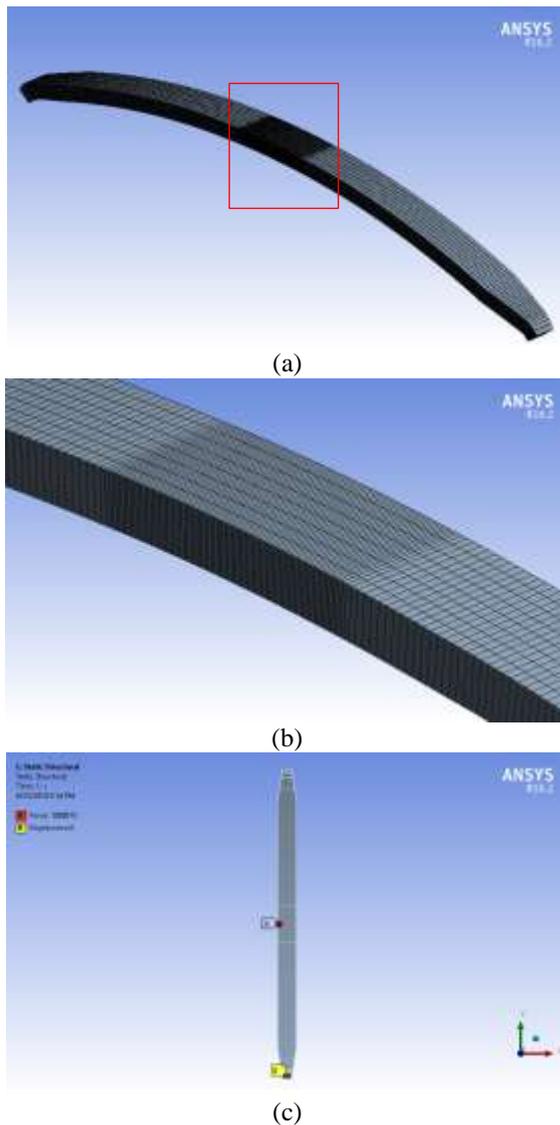


Figure 3. (a) Mesh structure, (b) a detailed view of mesh and (c) applied boundary conditions.

Figure 4(a) shows the directional deformation in the y direction obtained by numerical analyses. The maximum displacement was determined as 12.125 mm. As in the real-case bending test scenario, the both ends of the lead spring moved in the opposite direction of applied force. As can be seen in Figure 4(b-c), the maximum normal stress in the y direction was determined as 264 MPa. As expected, the normal stress in the y-direction took its maximum and minimum values at the top and bottom of the spring, respectively. Because, these points were the farthest points from the neutral axis of the leaf spring.

Table 2 shows the comparison of numerical and analytical results for both deformation and stress values. The presented numerical values were obtained for the leaf spring under 10 kN bending load. As can be seen, the numerical error was lower than 10%. The numerical difference may be caused by the applied boundary

conditions used in the numerical analyses. In the studies by Oztoprak et al. [13] and Sancaktar and Gratton [14], the numerical errors were between 5-7%. The numerical errors were in the acceptable range considering these studies in the literature. Therefore, it could be said that the finite element model was confidently extended to the current study in which the effects of PU/CNTs nanoweb interlayers on the mechanical performance of the composite mono-leaf springs.

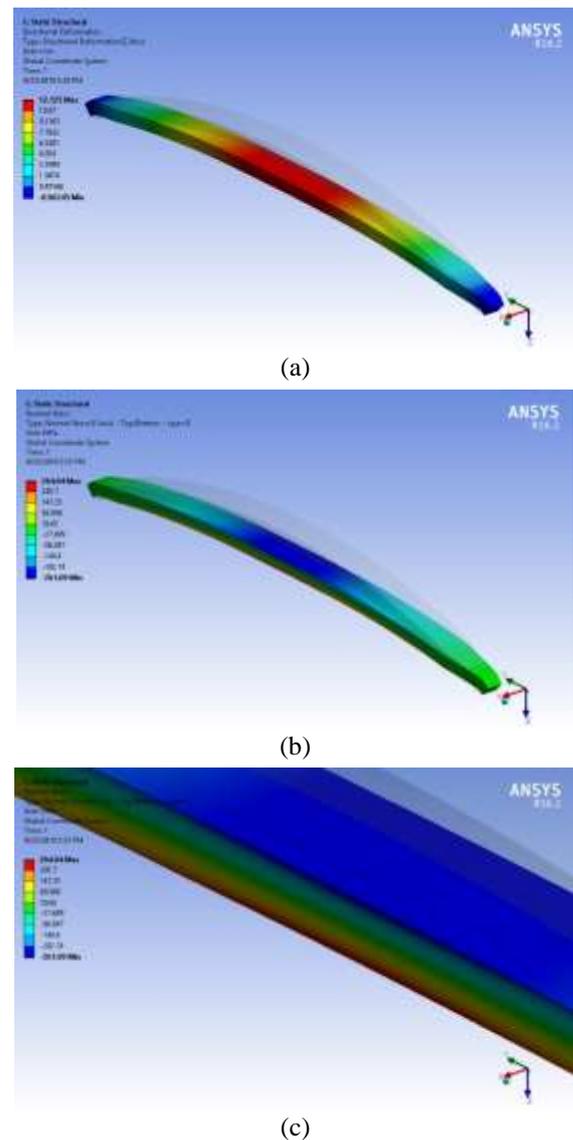


Figure 4. (a) Directional deformation in the z-direction, (b-c) the normal stresses in the y-direction occurred in the leaf spring.

Table 2. Comparison of analytical and numerical results.

| | Analytical | Numerical | % error |
|------------------------|------------|-----------|---------|
| Deflection (mm) | 13.34 | 12.12 | 9.5 |
| Stress (MPa) | 287.3 | 264.0 | 8.4 |

4. Finite element modeling of composite mono-leaf springs with PU/CNTs nanoweb interlayers

Table 3 shows the mechanical properties of CF/EP composites with PU/CNTs nanoweb interlayers in the fiber and transverse directions. Liu et al. [15] stated that the PU/CNTs nanointerlayers had no significant effect on the Poisson's ratio (ν) values of the composites.

Therefore, the Poisson's ratio was (ν) kept constant. The density of the composite material with/without nanoweb interlayers was taken as 1490 kg/m^3 which can be found in ANSYS Workbench. These material data were directly used as material input in ANSYS Workbench.

Table 3. Mechanical properties of CF/EP composites with PU/CNTs nanoweb interlayers in the fiber and transverse directions [15].

| CNTs content (wt%) | E_1 (GPa) | $E_2 = E_3$ (GPa) | $\nu_{12} = \nu_{23} = \nu_{13}$ |
|--------------------|-------------|-------------------|----------------------------------|
| 0 | 115.1 | 9.12 | |
| 1 | 128.1 | 10.15 | 0.311 |
| 5 | 134.9 | 10.68 | |

| CNTs content (wt%) | $G_{12} = G_{13}$ (GPa) | G_{23} (GPa) | $\nu_{12} = \nu_{23} = \nu_{13}$ |
|--------------------|-------------------------|----------------|----------------------------------|
| 0 | 5.67 | 3.48 | |
| 1 | 6.31 | 3.87 | 0.311 |
| 5 | 6.64 | 4.07 | |

The thickness of each carbon fiber/epoxy ply was considered as 0.5 mm. The total number plies were taken as 48. The total thickness of the CF/EP composite leaf springs without nanointerlayers was 24.0 mm. The reason why a thickness of 24.0 mm was considered, will be explained in the following section. In nanoweb interleaved composite leaf springs, the PU/CNT nano interlayers were modeled as additional layers placed between two CF/EP layers. In total, the number of nanointerlayers was 47 (each nanoweb has a thickness of 0.02 mm) in the composite leaf spring. The total thickness of the CF/EP composite leaf springs with PU/CNTs nanointerlayers was 24.94 mm. Figure 5 shows the project schematic used for the numerical analyses of composite leaf springs. After the 3D geometric model was imported to ANSYS Workbench environment (Cell-A), the ply number, ply orientations and material properties were defined by using ACP Pre-module (Cell-B).

Figure 6 shows the fiber direction in the composite leaf spring. Fibers were in the 0° direction going through to the length of the spring. In this figure, green arrows indicate the fiber direction. As in the case of steel-made leaf spring, the SOLID185 element number was 51040

with 60480 nodes. The boundary conditions were also the same used for the analysis of steel-made leaf spring for comparison purposes. Static and modal analyses (Cells C and D) were carried to determine the effects of PU/CNTs nanoweb interlayers on the mechanical performance of composite mono-leaf springs. In modal analysis, only boundary conditions were applied, and no load was acted on the composite leaf spring.

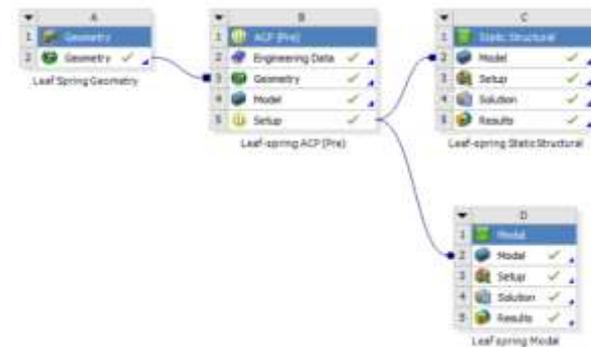


Figure 5. Project schematic of ANSYS Workbench.

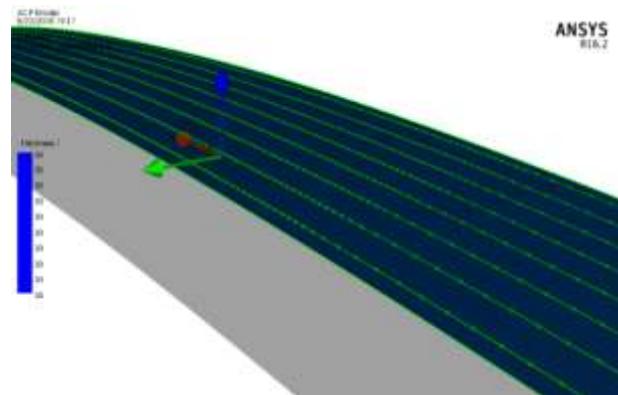


Figure 6. ANSYS ACP-Pre module view.

5. Results and Discussion

5.1 Steel leaf spring vs composite leaf spring

In this section, a 4-wheeler commercial vehicle with a gross weight of 3500 kg was selected for the comparison of steel-made and CF/EP composite leaf springs without PU/CNTs nanointerlayers. The sprung weight of the vehicle was assumed as 3150 kg ($0.9 \times W_{\text{gross}}$). The factor of safety was taken as 1.5. The applied load to each wheel was calculated as 11588 N ($1.5 \times 3150 \times 9.81 / 4$). The minimum required leaf spring stiffness was considered as 200 N/mm. In the case of steel material, the required thickness to maintain this stiffness was calculated as 19.31 mm (approximately 20 mm) using Equation (2.1). The weight of steel leaf spring was determined as 15.29 kg. Figure 7 shows the directional deformation in the z direction. The maximum displacement was determined as 48.98 mm. The corresponding stiffness of steel-made leaf spring was calculated as 236.58 N/mm.

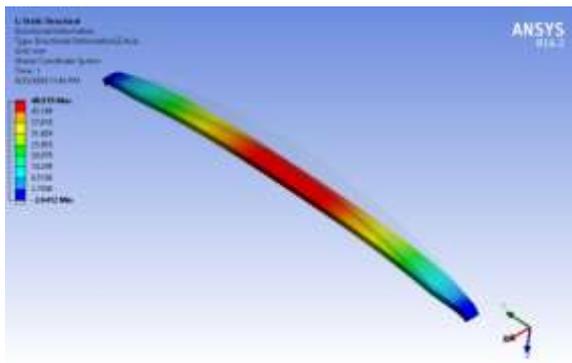
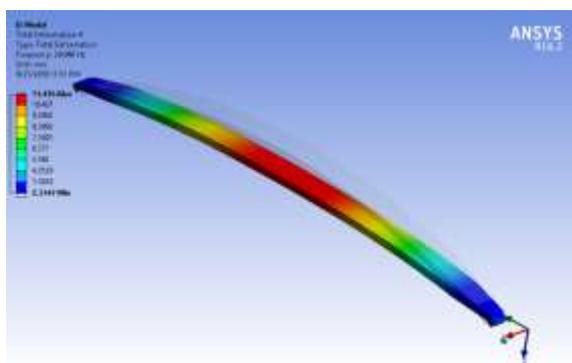
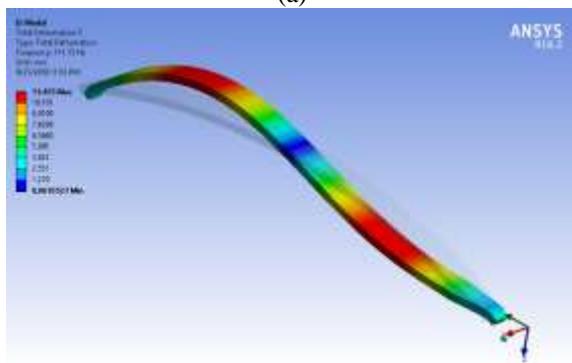


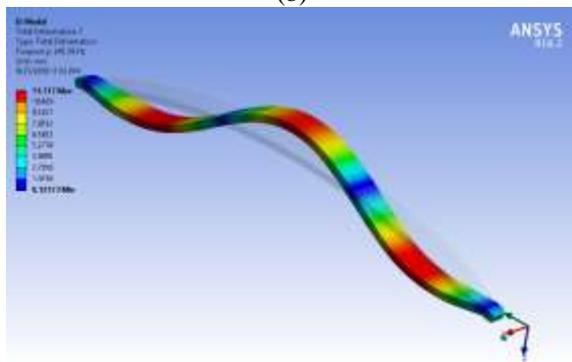
Figure 7. Directional deformation of steel leaf spring in the z-direction ($t=20$ mm, $P=11588$ N).



(a)



(b)



(c)

Figure 8. Mode shapes for steel leaf spring (a) 1st, (b) 2nd and (c) 3rd mode shapes.

Figure 8 shows the first three out-of-plane natural frequency modes of the steel leaf spring. The first, second and third natural frequency values were determined as 28.046, 111.13 and 245.38 Hz, respectively. The frequencies induced by the road surface irregularities is generally less than 20 Hz [12]. The first mode natural frequency of the steel-made leaf spring was higher than this value which ensures the resonant condition was avoided. To obtain the minimum thickness of composite leaf spring which has the same stiffness that of steel-made leaf springs, parametric studies were carried out. Table 4 shows the maximum displacement and stiffness values of the composite leaf spring for different values of thickness. As can be seen, the stiffness values increased with the increase of thickness. In case of 24.0 mm thickness, the stiffness of composite spring (236.38 N/mm) was almost equal to the stiffness of steel leaf spring (236.58 N/mm). The weight of the composite leaf spring was 3.48 kg. This value was almost 4.4 times lower than that of steel-made leaf spring (15.29 kg).

Table 4. Variation of maximum displacement and stiffness values for different composite leaf spring thickness.

| Thickness (mm) | Maximum displacement (mm) | Stiffness (N/mm) |
|----------------|---------------------------|------------------|
| 22.5 | 59.72 | 194.02 |
| 23.0 | 55.84 | 207.50 |
| 23.5 | 52.28 | 221.60 |
| 24.0 | 49.02 | 236.38 |
| 25.0 | 43.26 | 267.86 |
| 30.0 | 24.73 | 468.56 |

Figure 9 shows the first three out-of-plane mode shapes extracted from the modal analysis of CF/EP composite leaf spring. The first, second and third natural frequency values of the CF/EP composite leaf spring were determined as 58.88, 230.64 and 500.6 Hz, respectively. Comparing these values with the natural frequencies of steel-made leaf spring, it could be noticed that the natural frequency values of composite leaf spring were much higher than those of steel-made spring. The out-of-plane natural frequency values were almost two times higher than the steel leaf spring. The frequency values of composite leaf spring were much higher than the frequency value (20 Hz) which could cause resonance.

5.2 Hybridization effect

In this study, the effect of hybridization on the mechanical performance of composite leaf springs were also investigated. For this aim, E-glass fiber/epoxy composite plies were replaced with the carbon fiber/epoxy plies starting from the nearest plies to the

neutral axis. Table 5 shows the mechanical properties of E-glass/epoxy composites. The stiffness values of the composite leaf spring were calculated after the replacement of E-glass fiber/epoxy composites. The thickness of the composite leaf spring was considered as 25 mm in this case. Parametric studies were carried out to determine the highest possible number of E-glass fiber/epoxy plies which provides the stiffness that of equal to the composite stiffness having a 24 mm thickness.

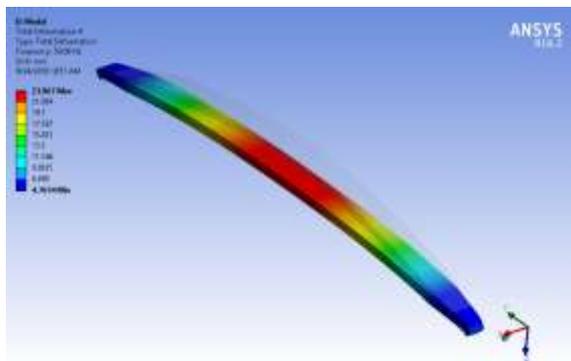
Table 5. Mechanical properties of E-glass /EP composites.

| E_1 (GPa) | $E_2 = E_2$ (GPa) | $G_{12} = G_{13}$ (GPa) | G_{13} (GPa) | ν_{12} |
|----------------|----------------------|----------------------------|-------------------|------------|
| 45.0 | 10.0 | 5.0 | 3.84 | 0.3 |

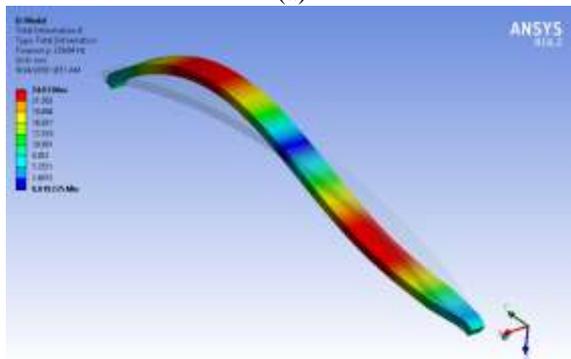
Table 6 shows the hybridization on the stiffness and the weight of the composite leaf spring. The obtained stiffness was almost the same that of 24-mm thick CF/EP composite spring. Although the weight of the spring was increased from 3.48 kg to 4.35 kg after hybridization, the hybridization could reduce part weight 3.5 times compared to a steel leaf spring.

Table 6. Hybridization effect on the stiffness and weight of the composite leaf spring (t=25 mm, Total number of plies=50).

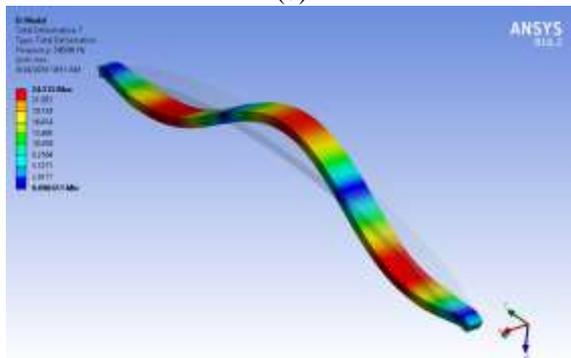
| Number of carbon fabrics | Number of E-glass fabrics | Stiffness (N/mm) | Weight (kg) |
|--------------------------|---------------------------|------------------|-------------|
| 50 | 0 | 267.86 | 3.62 |
| 40 | 10 | 266.51 | 3.87 |
| 30 | 20 | 255.80 | 4.15 |
| 26 | 24 | 247.34 | 4.25 |
| 24 | 26 | 242.07 | 4.30 |
| 22 | 28 | 236.0 | 4.35 |
| 20 | 30 | 228.95 | 4.40 |



(a)



(b)



(c)

Figure 9. Mode shapes for composite leaf spring (a) 1st, (b) 2nd and (c) 3rd mode shapes.

5.3 Effect of PU/CNTs nanoweb interlayers on the stiffness and natural frequencies of composite leaf springs

In this section, the effects of PU/CNTs nanofibers on the mechanical performance of CF/EP composite leaf springs were unrevealed.

Table 7 shows the stiffness of the reference and PU/CNTs nanoweb interleaved CF/EP composite leaf springs at different CNTs concentrations. Figure 10 shows the maximum displacement contours obtained for the nanoweb interleaved composite leaf springs. As can be seen, the incorporation of PU/CNT hybrid nanofibers between the carbon fiber/epoxy plies increased both stiffness and frequency values significantly. This is mainly due to the increased elastic modulus in the fiber direction. The bending stiffness matrix of the composite leaf spring increased after the addition of PU/CNTs nanofibers. The stiffness increased from 236.38 N/mm to 262.88 N/mm after the incorporation of PU/CNT nanofibers with 1 wt% CNT content. This corresponds to an increase by 11 %. Also, with the increase in CNT content, the stiffness values continued to increase. The stiffness was increased from 262.88 to 277.05 N/mm by about 18% in the case of PU/CNTs nanofibers at 5 wt% CNT concentration. It can be also concluded that thinner composite leaf springs could be used in suspension systems to obtain required stiffness by introducing PU/CNTs nanofibers in the interlaminar region. This will provide higher weight reduction comparing to the reference CF/EP composite leaf springs. It is also important to note that the nanofibers in the interlaminar region reduces delamination risk by fiber bridging mechanism and increases the toughness of the composites. Also, as stated in the literature, these

nanofibers have a positive effect on some other mechanical properties such as interlaminar shear strength and impact resistance. It is also noteworthy that the shear modulus of the composites increased after the addition of these nanofibers. The increase in shear modulus will have a positive influence on the mechanical response of nanofiber interleaved composites under torsion in return. As a result, the final product will be much more superior than the traditional composite leaf spring in terms of mechanical performance.

Table 7. Stiffness of CF/EP composite leaf springs with/without PU/CNTs nanoweb interlayers.

| CNTs content (wt%) | Stiffness (N/mm) | 1 st mode (Hz) | 2 nd mode (Hz) | 3 rd mode (Hz) |
|--------------------|------------------|---------------------------|---------------------------|---------------------------|
| 0 | 236.38 | 58.8 | 230.6 | 500.6 |
| 1 | 262.88 | 62.0 | 243.2 | 527.5 |
| 5 | 277.05 | 63.7 | 249.7 | 541.5 |

weight content took the maximum values when the CNTs content was reached to 5% by weight. The natural frequency values increased about 8.2% after the incorporation of these nanofibers as compared to reference CF/EP composite leaf spring. Figure 11 shows the out-of-plane natural frequencies of the CF/EP composites interleaved by PU/CNTs nanoweb interlayers with a 5 wt% CNTs content.

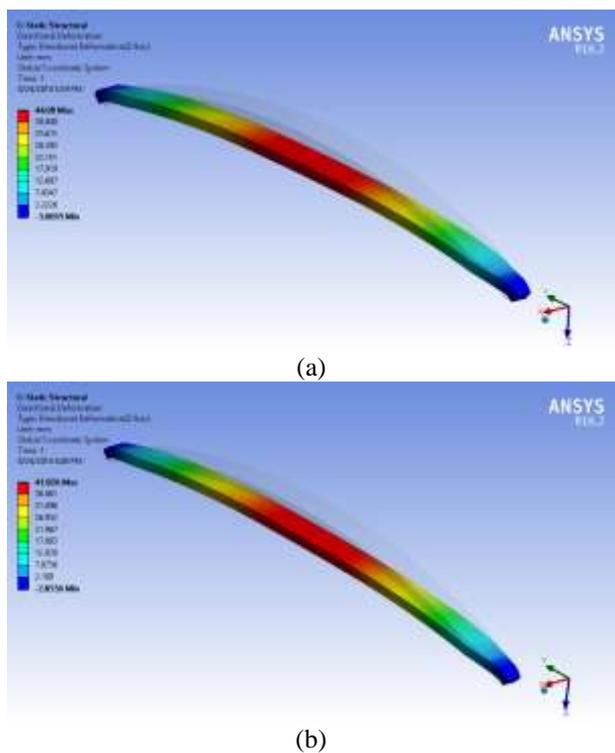


Figure 10. Maximum displacement contour obtained for the composite leaf spring interleaved by PU/CNTs nanofibers at (a) 1 wt% and (b) 5 wt% CNT concentrations.

Table 7 also shows the natural frequency values of CF/EP composite leaf springs with/without PU/CNTs nanofiber. As in the case of stiffness, an increasing tendency was also observed in the natural frequency values after the addition of PU/CNTs nanofibers. The frequency values increased with the increase of CNTs

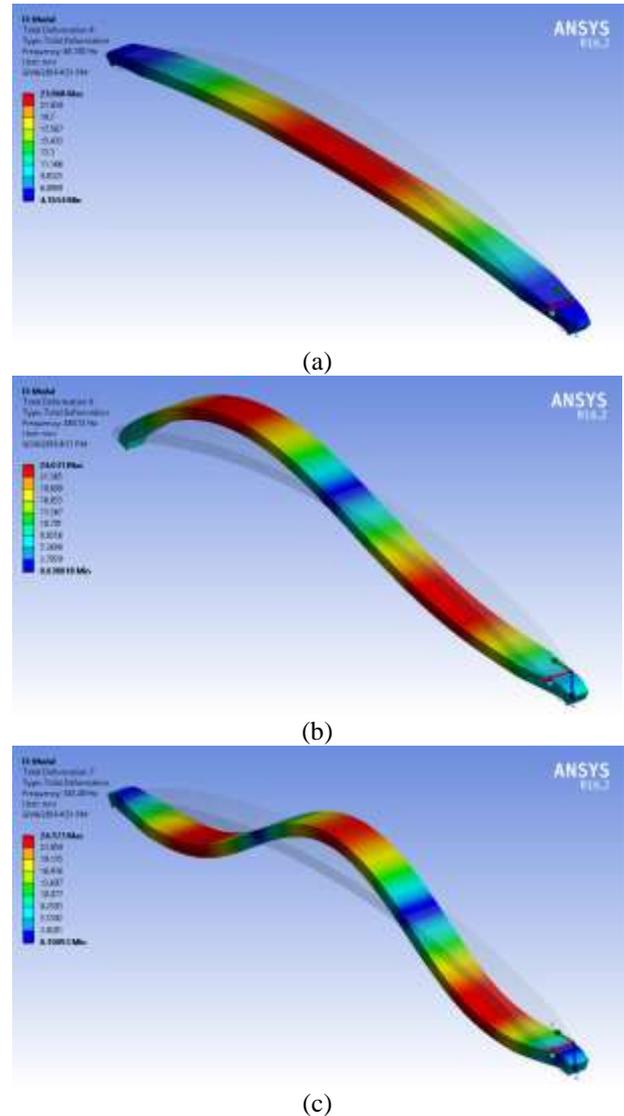


Figure 11. Mode shapes for composite leaf spring interleaved by PU/CNTs nanofibers at 5 wt% CNTs content (a) 1st, (b) 2nd and (c) 3rd mode shapes.

6. Conclusion

In this study, the effects of PU/CNTs nanofibers on the mechanical behavior of carbon fiber/epoxy composite leaf springs were investigated numerically. Numerical analyses were carried out by using ANSYS 16.2 software package. Numerical results were compared with the analytical ones for verification purposes. The numerical results were in good agreement with the



analytical calculations. The main conclusions can be drawn from the present study as follows;

- PU/CNT interleaved composite leaf springs showed higher mechanical performance as compared to reference composite leaf springs without nanointerlayers.
- The stiffness and first mode natural frequencies increased with an increase in the CNTs content (from 1 wt.% to 5 wt.%).
- The stiffness of the composite wave springs could be increased by 18% with the addition of PU/CNTs nanofibers (CNT content: 5 wt.%) in the interlaminar region without weight and thickness increase.
- The natural frequency values increased by 8% after the addition of PU/CNT nanofibers (CNT content: 5 wt.%).
- Hybridization can be used to reduce number carbon/epoxy plies (lower cost) without causing significant reduction in the required stiffness.

Ethics

There are no ethical issues after the publication of this manuscript.

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