Journal of Zhejiang University-SCIENCE A (Applied Physics & Engineering)
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

Finite element analysis on the static and fatigue characteristics of composite multi-leaf spring

Joo-teck Jeffrey KUEH[†], Tarlochan FARIS
(*Department of Mechanical Engineering, Universiti Tenaga Nasional, Selangor 43000, Malaysia*)
[†]E-mail: tjeffrey@uniten.edu.my

Received Aug. 10, 2011; Revision accepted Oct. 21, 2011; Crosschecked Feb. 7, 2012

Abstract: This paper investigated the static and fatigue behaviors of steel and composite multi-leaf spring using the ANSYS V12 software. The dimensions of an existing conventional leaf spring of a light commercial vehicle were used. The same dimensions were used to design composite multi-leaf spring for the two materials, E-glass fiber/epoxy and E-glass fiber/vinyl ester, which are of great interest to the transportation industry. Main consideration was given to the effects of material composition and its fiber orientation on the static and fatigue behaviors of leaf spring. The design constraints were bending stresses, deflection and fatigue life. Compared to the steel leaf spring, the designed composite spring has much lower bending stresses and deflections and higher fatigue life cycles.

Key words: Leaf spring, Composites, Finite element, Stress, Deflection, Fatigue
doi:10.1631/jzus.A1100212 **Document code:** A **CLC number:** TB302

1 Introduction

To meet the needs for sustainable development, significant increase in the demand for lighter, more fuel efficient, reduced design-testing iterations, and satisfactory reliability level has promoted the adoption of optimum materials and components design in the transportation industry (Beardmore and Johnson, 1986; Al-Qureshi, 2001; Mahdi *et al*., 2006; Zheng *et al*., 2011). Beardmore (1986) studied the application of composite structures in automobile. Morris (1986) investigated the application of composites in rear suspension systems. Yu and Kim (1988) designed an optimized double tapered beam for automotive suspension leaf spring. Rajendran and Vijayarangan (2001) presented an artificial genetics approach for the design optimization of composite leaf spring. Rahman and Kowser (2010) studied the inelastic deformations of stainless steel leaf springs using experimental and nonlinear analysis.

The suspension leaf spring is one of the potential components for weight reduction in automobiles (Lukin *et al*., 1989) as the leaf spring accounts for 10%–20% of the unsprung weight (Tanabe *et al*., 1982). The reduction in unsprung weight can improve the riding quality and increase fuel efficiency significantly. Since fiber reinforced plastics (FRPs) composite material has a high elastic strain energy storage capacity (Kumar and Sabapathy, 2007), it is possible to use FRP material to replace the conventional multi-leaf steel spring in order to achieve weight reduction without any reduction of the load carrying capacity (Vijayarangan *et al*., 1999). Therefore, the present work is directed towards the design of optimized leaf spring where better stiffness and durability represent the real advantages in the use of composite leaf spring.

2 Specifications of leaf spring

2.1 Existing steel leaf spring

Design parameters of the existing seven-leaf spring include: total length 1150 mm, arc height at axle seat (camber), 175 mm; spring rate, 20 N/mm; number of full length leaves, 2; number of graduated

---

leaves, 5; width of the leaves, 34 mm; thickness of the leaves, 5.5 mm; full bump loading, 3250 N; and spring weight 13.5 kg (Kumar and Sabapathy, 2007). Since this spring is symmetrical, only half is consider for the analysis to save computational cost and time.

Experimental results including stresses and deflection of steel leaf spring under full bump loading were obtained from Kumar (2007). Analytical analysis was performed using the Society of Automotive Engineers standard design formulas for leaf spring (SAE, 1980). A finite element analysis was performed on the above mentioned leaf spring using the ANSYS V12. The finite element model (FEM) for the leaf spring was 3D. The model was restricted to the right half only because the spring was symmetric. The spring body was modeled using SOLID 45. The contact between leaves was emulated by interface elements CONTACT 174 and TARGET 170. An average coefficient of friction 0.03 was taken between the surfaces. The axle seat was assumed to be fixed and full bump loading was applied at the eye end. The maximum normal stress, σ_{11} from finite element analysis is compared with the experimental and analytical results to verify the drawn model. There is a good correlation for the results in all three methods. Experimental, analytical and FEM results are listed in Table 1.

2.2 Composite leaf spring

The theoretical design details of composite mono-leaf spring have been explained in previous studies. Basically, the design can be categorized into: (I) Constant thickness, constant width design; (II) Constant thickness, varying width design; and (III) Varying width, varying thickness design.

Table 1 Experimental, analytical and FEM analysis of steel leaf spring

Parameter	Load (N)	Maximum stress (MPa)	Maximum deflection (mm)	Maximum stiffness (N/mm)
Experiment*	3250	680.05	155.00	20.96
SAE formulations	3250	982.05	133.03	24.43
FEM	3250	946.88	168.63	19.27

* Kumar and Sabapathy (2007)

However, the conventional steel leaf spring is not easily replaceable with mono-leaf spring due to its catastrophic failure. Hence, in this work, the composite multi-leaf spring is investigated for its load carrying capacity, stiffness, and fatigue life to replace the conventional leaf spring. Fig. 1 shows flow chart for static and fatigue analysis of composite leaf spring.

2.3 Properties of composite materials

Two materials which are of greatest interest to transportation industry, E-glass fiber/epoxy and E-glass fiber/vinyl ester were taken into consideration for its practicality in the use of composite leaf spring design. The material, termed UNI-ELT5500 in the database (DOE-MSU, 2010), is comprised of E-glass fiber fabrics. Plates of this material were fabricated by a resin transfer molding (RTM), and processed with epoxy and vinyl ester matrix to an average fiber volume of 0.59. The mechanical and fatigue properties of the materials can be found in (DOE-MSE, 2010) and are summarized in Table 2 and Fig. 2.

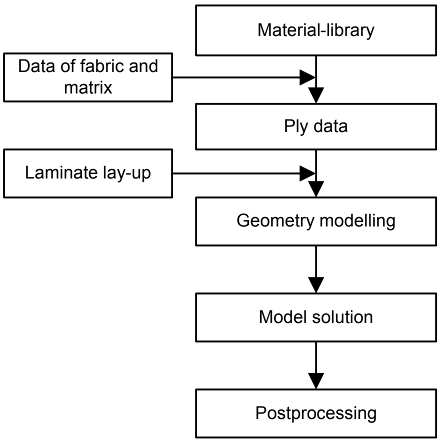

Fig. 1 Flow chart of the static and fatigue procedure

Table 2 Mechanical properties for E-glass/epoxy and E-glass/vinyl ester (DOE-MSU, 2010)

Designation and material	E_X (GPa)	E_Y (GPa)	E_Z (GPa)	υ_{XY}	υ_{YZ}	υ_{ZX}	σ_t (MPa)	σ_c (MPa)
UNI-ELT5500-EP1 (E-glass/epoxy)	45.7	15.9	15.9	0.27	0.094	0.094	1203.67	703.25
UNI-ELT5500-VE4 (E-glass/vinyl ester)	43.7	15.2	15.2	0.28	0.097	0.097	1092.50	702.98

E_X, E_Y, and E_Z is the modulus along X, Y, Z direction, respectively; υ_{XY}, υ_{YZ}, and υ_{ZX} is the Poisson's ratio along XY, YZ, and ZX direction, respectively; σ_t it the ultimate tensile strength; and σ_c is the ultimate compression strength

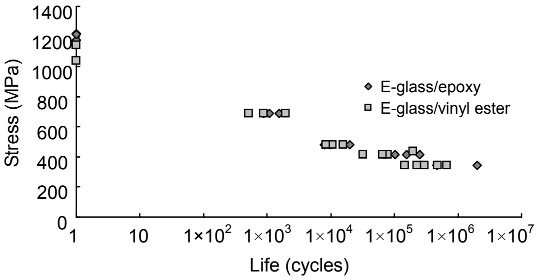

Fig. 2 Fatigue behavior of unidirectional E-glass fiber/epoxy and E-glass fiber/vinyl ester (DOE-MSU, 2010)

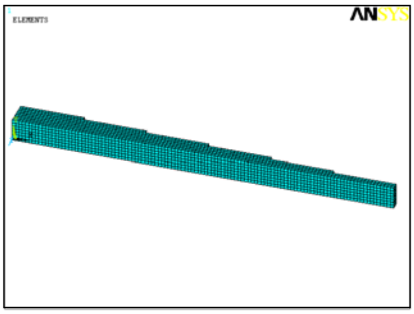

Fig. 3 FEM of composite leaf spring

3 3D finite element analysis

The differences in performance of E-glass/epoxy and E-glass/vinyl ester were studied using 3D FEM, built by ANSYS 12V. A 3D eight-Node Layered Structural Solid Element 46 was used for the solid mesh. 3D eight-Node Surface-to-Surface Contact 174 and 3D Target Segment 170 were used to represent contact and sliding between adjacent of leaves. These analyses were performed iteratively at different element lengths until the solution obtained appropriate accuracy. As shown in Fig. 3, the *X*, *Y*, and *Z* coordinates represent the applied load, transverse, and thickness direction, respectively for the composite leaf spring. The model contained 8365 eight-node solid elements for a total of 7504 nodes and each layer was modeled through the thickness by one element. Boundary conditions were imposed on the axle seat of the spring, which are X=0, Y=0, and Z=0. From Kumar and Sabapathy (2007), the theoretical static load to flatten the leaf spring is 3250 N. They applied the same load to their experimental fatigue lab test. Therefore, it is assumed that a load of 3250 N needs to be applied to the composite leaf spring if it is fully flattened. Therefore, a full bump of 3250 N was applied at the free end of the spring in this study. Convergence of the stresses was observed, as the mesh size was successively refined.

Later, a stress-life approach was adopted for a fatigue analysis. The stress state of each node in '.rst' file from the transient analysis should be read to be defined in fatigue analysis. Another input for this fatigue FEM analysis is the Fatigue S-N curves of E-glass/epoxy and E-glass/vinyl ester from DOE-MSE (2010). Fatigue analyses were implemented to study the fatigue life cycles and stress sensitivity of the composite leaf spring design.

4 Results and discussion

4.1 Static results

Vertical vibration and impacts are buffered by variations in spring deflection so that the potential energy is stored in the spring as strain energy and then released slowly. According to Kumar and Sabapathy (2007), the stored elastic strain energy in a leaf spring varies directly with the squared maximum allowable stress and inversely with the modulus of elasticity both in the longitudinal and transverse directions. This relationship can be represented as

$$S=\frac{1}{2}\frac{\sigma_{\mathrm{t}}^{2}}{\rho E}, \tag{1}$$

where S is the strain energy, σ_{t} is the allowable stress, E is the modulus of elasticity, and ρ is the density. Since the composites in the direction of fibers have good characteristic for storing strain energy, the unidirectional lay-up along the longitudinal direction of the spring is selected to evaluate the performance of E-glass/epoxy and E-glass/vinyl ester with conventional steel leaf spring.

The leaf spring is normally analyzed under bending loading condition and the normal stresses are important. FEM results of the maximum deflection and maximum stress of different materials are listed in Table 3. Figs. 4 and 5 show the variation of displacement and longitudinal stress of FEM results for steel, E-glass/epoxy and E-glass/vinyl ester leaf spring, respectively. The longitudinal compression strength of E-glass/epoxy and E-glass/vinyl ester is less than its longitudinal tensile strength, so failure criterion stress is the longitudinal compression stress. Table 3 shows that the maximum longitudinal compression stresses for unidirectional E-glass/epoxy and E-glass/vinyl ester are approximately 223.58 and 223.52 MPa, respectively. At the same loading, the stress developed in the steel leaf spring is approximately 946.88 MPa. The compression strength of both composites is about 703 MPa and the yielding strength of the steel is 1175 MPa. The safety factor in steel spring is 1.24 while in the composites these are 3.14 and 3.15 for E-glass/epoxy and E-glass/vinyl ester, respectively. The deflections of spring under full bump loading are 42.67 and 44.54 mm, respectively (Table 3), which are less than the value of steel leaf spring 168.63 mm, which show 74.80% and 73.69% increases in stiffness, respectively. Fig. 6 shows the longitudinal stress along length for steel, E-glass/epoxy, and E-glass/vinyl ester leaf spring.

Table 3 Comparison results of deflection and stresses for three different materials

Material	Maximum deflection (mm)	Maximum tensile stress (MPa)	Maximum compressive stress (MPa)
Steel	168.63	946.88	941.79
E-glass/epoxy (unidirectional)	42.67	210.28	223.58
E-glass/vinyl ester (unidirectional)	44.54	210.30	223.52

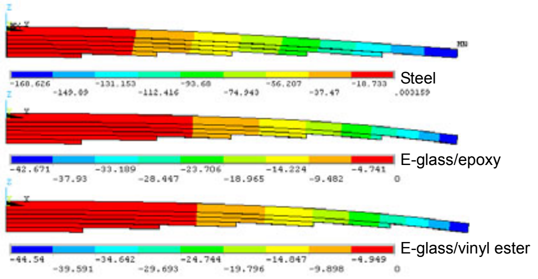

Fig. 4 Variation of displacement of FEM results for steel, E-glass/epoxy and E-glass/vinyl ester leaf spring, respectively (unit: mm)

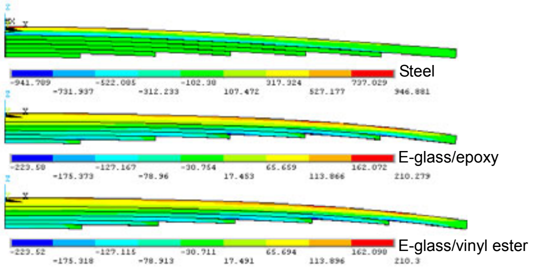

Fig. 5 Variation of longitudinal stress of FEM results for steel, E-glass/epoxy and E-glass/vinyl ester leaf spring, respectively (unit: MPa)

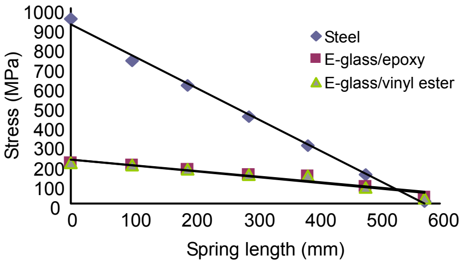

Fig. 6 Longitudinal stress along length for steel, E-glass/epoxy and E-glass/vinyl ester leaf spring

4.2 Fatigue results

In material science, fatigue is the progressive structural damage that occurs when a material is subjected to cyclic loading. It is important to determine the critical locations due to fatigue damage in the practical composite leaf spring. From the static FEM results, the stress distribution in the elements showed that high stress occurred at the outmost surface and the bottom contact between the leaves. Therefore, Nodes 929, 987, 1007, 1026, and 930 were identified to be the critical nodes along the spring longitudinal direction and depicted in Fig. 7.

In this fatigue analysis, the leaf spring is modeled with an alternating load of 1625 N and a mean stress of zero. Table 4 lists the effective stress produced by the combination of both loading on the critical nodes. It is observed that the stress of the steel leaf spring is approximately 3 times larger compared to E-glass/epoxy and E-glass/vinyl ester leaf spring. This is closely related to the bending stresses created when they are exposed to fatigue loading. Composite fatigue performance is generally very good when compared with conventional metallic materials. With composites, it is possible to get fatigue life of approximately twice as long compared to the conventional steel leaf spring. Although E-glass/epoxy and E-glass/vinyl ester have about the same static mechanical properties, their fatigue performances are totally different when subject to fatigue loading. Fatigue failure tends to result from the gradual accumulation of minor and localized damages. The fatigue behavior of composites is affected by the resin toughness, its resistance to micro cracking, voids, and defects. Resin toughness can be hard to measure, but is broadly indicated by its ultimate strain to failure. As shown in Fig. 8, ultimate failure for vinyl ester occurs at the strain of about 4.5%, whereas for epoxy is 7%

(SP Systems Guide to Composites, 2011). This indicates that micro cracking will occur at a lower strain value for vinyl ester compared to epoxy. Due to poor bonding strength and susceptibility to damage in fatigue, loose bundle fibers tend to occur in E-glass/vinyl ester leaf spring. Undoubtedly, epoxy is still a better choice of matrix resin for composite leaf spring although vinyl ester is cheaper in terms of cost.

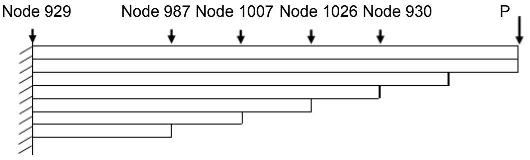

Fig. 7 Critical nodes along the spring longitudinal direction

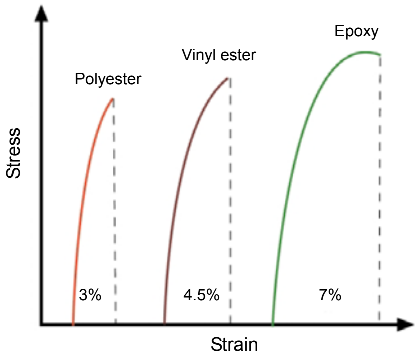

Fig. 8 Typical resin stress/strain curves (post-cured for 5 h@80 °C) (SP Systems Guide to Composites, 2011)

Table 5 Variation in deflection, maximum tensile stress and maximum compressive stress for different orientation composite leaf spring

Material (E-glass/epoxy)	Maximum deflection (mm)	Maximum tensile stress (MPa)	Maximum compressive stress (MPa)
$[0_5]$	42.671	210.279	223.580
$[90_5]$	107.319	208.259	222.522
$[30_5]$	108.220	215.582	230.551
$[45_5]$	124.037	216.044	235.645
[0/0/45/−45/0]	53.185	270.125	279.200
[0/45/−45/90/0]	61.380	304.161	334.642

4.3 Effects of fiber orientation

The sensitivity of fiber orientation towards the spring strength and fatigue life is studied in this section. The possibility of attaining different strength and stiffness composite leaf spring through different lay-up and fiber orientation is further investigated. Analysis is performed for E-glass/epoxy of fiber orientation $[0_5]$, $[90_5]$, $[45_5]$, [0/0/45/−45/0], and [0/45/−45/90/0]. Table 5 lists the deflection, maximum tensile stress, and maximum compressive stress. Table 6 lists the effective stress produced by the combination of both loading on the critical nodes for different fiber orientation. All different lay-ups composite leaf spring showed similar deflection trends. These deflections increased considerably while the fiber direction approached 45° and decreased slightly when the direction changed from 45° to 90°. On increasing the percentage of non-axial fibers, the static tensile strength and stiffness were reduced since fewer fibers were available to support the mean applied load. Although the deflection and maximum stress were larger, if the fibers were not oriented in 0°, the increase was not significant. From the fatigue analysis, the fatigue life for all the fiber orientation is more than 1×10^6. This showed that the fiber orientation did not significantly affect the fatigue behavior of the material as well. Stiffness and strength are two main parameters in the design of

Table 6 Alternating stress on the critical nodes for different fiber orientation

Material	Alternating stress					Cycles to failure
	Node 929	Node 987	Node 1007	Node 1026	Node 930	
$[0_5]$	138.47	168.45	194.30	201.01	4.44	>1 000 000
$[90_5]$	235.23	160.23	206.54	215.63	7.86	>1 000 000
$[30_5]$	240.25	163.29	198.66	201.22	8.02	>1 000 000
$[45_5]$	244.47	164.51	194.99	207.55	8.27	>1 000 000
[0/0/45/−45/0]	188.47	235.54	272.32	275.89	6.41	>1 000 000
[0/45/−45/90/0]	204.99	260.13	299.90	300.53	6.45	>1 000 000

Table 4 Alternating stress on the critical nodes

Material	Effective stress					Cycles to failure
	Node 929	Node 987	Node 1007	Node 1026	Node 930	
Steel	415.41	523.12	580.26	605.78	13.25	256 700
E-glass/epoxy (unidirectional)	138.47	168.45	194.30	201.01	4.44	>1 000 000
E-glass/vinyl ester (unidirectional)	138.74	168.27	194.14	200.89	4.52	500 000

composite leaf spring. Different vehicle types and applications required different specifications. Since the static and fatigue behaviors of composite leaf spring were not affected significantly by the fiber orientation, it is possible to design different stiffness and strength leaf composite through proper lay-up arrangement without the change of geometry (changes of geometry and material typically apply in the conventional steel leaf spring design to obtain different stiffness and strength values).

5 Conclusions

In this paper, multi-leaf steel and composite springs were analyzed using ANSYS. Their static and fatigue performances were obtained. It was shown that static and fatigue performances were improved significantly when conventional steel leaf spring was replaced by either E-glass/epoxy or E-glass/vinyl ester. The maximum bending stresses in composite leaf spring are much lower than that of steel spring. The fatigue life of E-glass/epoxy or E-glass/vinyl ester composite leaf spring was proven to be 2 and 4 times higher than that of steel multi-leaf spring. When a comparison was made between E-glass/epoxy and E-glass/vinyl ester leaf spring, it was found that the fatigue performance of E-glass/epoxy composite leaf spring was better than that of vinyl ester. Finally, it was proven that different strength and stiffness composite spring was attainable through the arrangement of fiber lay-up and orientation.

References

Al-Qureshi, H.A., 2001. Automobile leaf springs from composite materials. *Journal of Materials Processing Technology*, **118**(1-3):58-61. [doi:10.1016/S0924-0136(01)00863-9]

Beardmore, P., 1986. Composite structures for automobiles. *Composite Structures*, **5**(3):163-176. [doi:10.1016/0263-8223(86)90001-2]

Beardmore, P., Johnson, C.F., 1986. The potential for composites in structural automotive applications. *Composites Science and Technology*, **26**(4):251-281. [doi:10.1016/0266-3538(86)90002-3]

DOE-MSU, 2010. Wind Turbine Blade Composite Material Fatigue Database. Department of Chemical Engineering, Montana State University at Bozman, Montan 59717, USA. [doi:10.2172/578635]

Kumar, M.S., Sabapathy, V., 2007. Analytical and experimental studies on fatigue life prediction of steel and composites multi-leaf spring for light passenger vehicles using life data analysis. *Materials Science*, **13**(2):141-146.

Lukin, P., Gasparyants, G., Rodionov, V., 1989. Automobile Chassis-Design and Calculations. MIR Publisher, Moscow.

Mahdi, E., Alkoles, O.M.S., Hamouda, A.M.S., Sahari, B.B., Yonus, R., Goudah, G., 2006. Light composite elliptic springs for vehicle suspension. *Composite Structures*, **75**(1-4):24-28. [doi:10.1016/j.compstruct.2006.04.082]

Morris, C.J., 1986. Composite integrated rear suspension. *Composite Structures*, **5**(3):233-242. [doi:10.1016/0263-8223(86)90005-X]

Rahman, M.A., Kowser, M.A., 2010. Inelastic deformations of stainless steel leaf springs-experiment and nonlinear analysis. *Meccanica*, **45**(4):503-518. [doi:10.1007/s11012-009-9270-7]

Rajendran, I., Vijayarangan, S., 2001. Optimal design of a composite leaf spring using genetic algorithms. *Computers and Structures*, **79**(11):1121-1129. [doi:10.1016/S0045-7949(00)00174-7]

SAE, 1980. Manual on Design and Application of Leaf Springs, SAE HS 788. Society of Automotive Engineers, Warrendale, PA.

SP Systems Guide to Composites, 2011. Technical Report No. GTC-1-1098. St Cross Business Park, Newport, Isle of Wight, England.

Tanabe, K., Seino, T., Kajio, Y., 1982. Characteristics of Carbon/Glass Fiber Reinforced Plastic Leaf Spring. SAE 820403, p.1628-1634. [doi:10.4271/820403]

Vijayarangan, S., Alagappan, V., Rajedran, I., 1999. Design optimization of leaf springs using genetic algorithms. *Journal of the Institution of Engineers (India): Mechanical Engineering Division*, **79**:135-139.

Yu, W.J., Kim, H.C., 1988. Double tapered FRP beam for automotive suspension leaf spring. *Composite Structures*, **9**(4):279-300. [doi:10.1016/0263-8223(88)90049-9]

Zheng, Y.H., Xue, K., Huang, Z.G., 2011. Finite Element Analysis of Composite Leaf Spring. The 6th International Conference on Computer Science & Education, SuperStar Virgo, Singapore, p.316-319. [doi:10.1109/ICCSE.2011.6028643]