Failure Analysis of the Longitudinal Composite Leaf Spring

Lubin Wang · Zhenyu Wang

Abstract This paper describes the common structure of the longitudinal composite leaf spring as well as the stress of different parts. Combined with force analysis, various failure modes may occur in the middle and end parts of the composite leaf spring. Attention should be paid to the stress concentration in the clamping area in the middle of the leaf spring, caused by U-bolt pre-tightening. At the end of the composite leaf spring, enough bolt hole-edge distances shall be ensured and attention should also be paid to the stress concentration caused by the bolt. In spring design, the static stiffness of the composite leaf spring can be appropriately increased to ensure the suspension has sufficient offset frequency. At the same time, attention should be paid to the glass transition temperature (Tg point) value of the resin, which is suggested to be higher than 80 °C.

Keywords Composite material ·
Longitudinal leaf spring · Failure analysis

Introduction

The leaf spring is the most widely used elastic element in the automotive suspension. The most commonly used leaf springs on the Chinese market are steel leaf springs. Steel leaf springs have the advantages of simple structure, reliable operation and easy processing. However, at the same time, steel leaf springs have the disadvantages of heavy structure, high stiffness and poor comfort. Traditional leaf springs are no longer able to meet the industry needs.

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Reducing the weight of a car has special significance to its development. In order to improve the performance of leaf springs, reduce their weights and improve comfort, researchers have conducted a lot of research on the material and the structure of leaf springs [1]. They have developed composite leaf springs that use plastic instead of steel [2, 3]. Compared with traditional steel leaf springs, composite leaf springs' weight is only 30–40% of steel leaf springs of the same type [4]. Composite leaf springs inherit the advantages of simple structure and reliable operation of steel leaf springs. At the same time, it has the characteristics of large elastic strain, high specific strain energy, long fatigue life, and good safety fracture performance. At present, composite leaf springs outside China have gone into mass production and been put into practical use by companies, such as GM, Ford, Daimler, Chrysler, Iveco, and International Truck. Compared with traditional metal materials, composite materials have the advantages of high strength, large specific modulus, light weight, corrosion resistance, good shock absorption performance, excellent impact resistance performance, long service life, good noise reduction performance and excellent designability [5–7].

Composite Leaf Spring Structure

The typical structure and installation environment of composite leaf springs are shown in Fig. 1. There are two types of composite leaf spring: transverse composite leaf spring and longitudinal composite leaf spring. The transverse composite leaf spring is generally installed on the vehicle with an independent suspension. The two ends of the spring body transfer loads through the lap joint. The

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Fig. 1 Typical composite leaf spring
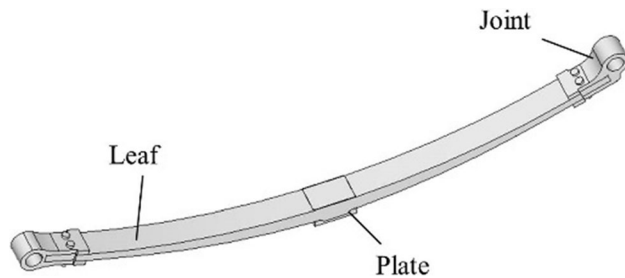

Fig. 2 Eye-end composite leaf spring

Fig. 3 Sliding composite leaf spring

service condition of such spring is relatively good, and there is no need to specially design the joint. The longitudinal composite leaf spring is generally installed on the vehicle with a non-independent suspension. The service condition is relatively harsh, and a joint with reliable performance needs to be designed.

According to the type of connection with the vehicle body, longitudinal composite leaf springs can be divided into eye-end leaf springs and sliding leaf springs.

The common structure of the eye-end leaf spring is shown in Fig. 2. Both ends of the leaf spring are metal eye joints, the leaf spring body and the eye joints are connected by bolts. Two metal plates are attached to the middle of the leaf spring body for eliminating the stress concentration when the U-bolt is clamped.

The structure of the sliding leaf spring is shown in Fig. 3. The middle structure of the sliding leaf spring is basically as same as that of the eye-end leaf spring. On both ends of the leaf spring are gaskets and hooks, usually made of metal. The gaskets are mainly responsible for the force transmission between the spring body and the support, and the hooks can prevent the leaf spring from leaving the suspension. The spring body, gaskets and hooks are connected by bolts.

For spring body design, the main concerns are its material utilization, fiber volume content and manufacturability. After the structure design is completed, the calculation model of the composite leaf spring should be established based on the mechanics of materials. Geometric parameters of the spring body shall be determined according to the mounting environment and the design stiffness of the composite leaf spring. In structural optimization, the finite element method shall be applied to
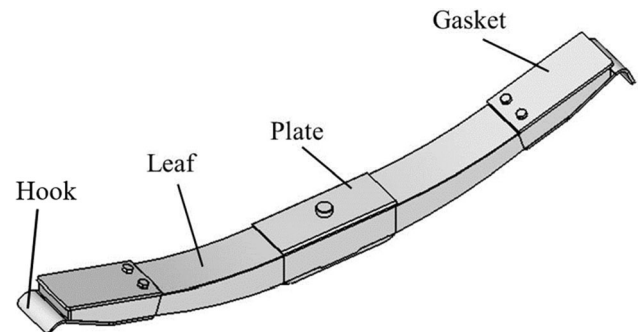
Table 1 General working conditions of the leaf spring

Stiffness matching	Free stiffness
	Clamping stiffness
Load condition	Vertical
	Steering
	Braking
	Fatigue

analyze and evaluate the design solution. Finally a test shall be carried out to verify whether the structural performance meets the requirements.

Failure Analysis of the Composite Leaf Spring

Condition Analysis

Currently, most composite leaf springs are replacements of metal leaf springs, and their working conditions are basically same as those of metal springs. General working conditions are shown in Table 1.

Considering the spring's working temperature, mechanical properties, structure, technique, low toxicity, low irritation and reasonable price, the glass fiber used for the composite leaf spring is generally the E fiber; the choice of resin is usually epoxy or PU [8, 9]. Due to the characteristics of the composite material itself, the junction and connection between the spring body and the support need to be checked.

The middle of the composite leaf spring is connected to the axle by two U-bolts. In addition, the ends of the leaf spring are linked with bolts. These parts also need to be checked. Working conditions of the composite leaf spring are shown in Table 2.

Stiffness Check

Stiffness of the leaf spring directly affects the stability and comfort of the vehicle. It is the key performance parameter of the leaf spring. In each subsystem of the vehicle, the different arrangements, types and performance parameters of the suspension system will affect the overall performance of the vehicle. The damping and elastic components in the suspension system have the greatest influence. It has been proven by theoretical research and experience that the natural frequency of the suspension system is one of the main parameters affecting the ride comfort of the vehicle, which is determined by the suspension stiffness.

The mass distribution coefficient of the modern automobile is approximately equal to 1. In this way, there is no vibration connection between the front axle and the rear axle. At this point, the vibration frequencies of the front and rear parts of the vehicle can be expressed by using the following formula:

$$n_1 = \frac{1}{2\pi}\sqrt{\frac{K_1}{m_1}}, \ n_2 = \frac{1}{2\pi}\sqrt{\frac{K_2}{m_2}} \quad \text{(Eq 1)}$$

where K_1 and K_2 are the stiffness of the front and rear suspensions, while m_1 and m_2 are the sprung mass of the front and rear suspensions, respectively. The relationship between suspension static deflection, suspension stiffness and sprung mass is as follows:

$$f_{c1} = \frac{m_1 g}{K_1}, \ f_{c2} = \frac{m_2 g}{K_2} \quad \text{(Eq 2)}$$

Through substitution for the formula, the following can be obtained:

$$n_1 \approx \frac{5}{\sqrt{f_{c1}}}, \ n_2 \approx \frac{5}{\sqrt{f_{c2}}} \quad \text{(Eq 3)}$$

Thus, it can be seen that the static deflection of the

suspension is directly related to the offset frequency of the body vibration. Increasing the static deflection of the automobile suspension, that is, reducing the stiffness of the suspension, can reduce the natural frequency of the vehicle. However, reducing the vibration frequency can significantly decrease the acceleration of the vehicle body, and therefore increases the comfort of the vehicle.

Figure 4 shows the stiffness curve of the composite leaf spring and the benchmark steel leaf spring (four-piece leaf spring). It can be seen from the curve that the system damping of the steel leaf spring was greater than that of the composite one. Damping of the steel leaf spring was mainly caused by the friction between the spring pieces. The composite leaf spring had only one piece, and therefore there was no friction between spring pieces. Figure 5 compares the dynamic stiffness of 8 composite leaf springs with that of 8 steel leaf springs. Through comparison of the two figures, it was discovered that when the static stiffness of the steel leaf spring was about 10% less than that of the composite leaf spring, the dynamic stiffness of the steel leaf spring was about 10% higher than that of the composite leaf spring.

Generally, increasing static deflection means reducing suspension stiffness, which can improve the ride comfort of a vehicle [10]. However, when the suspension stiffness is reduced, the high-frequency vibration displacement of the non-suspension mass will be increased, which may cause the wheel to leave the ground and significant change of the front wheel orientation at the same time. In the event of emergency braking, the vehicle bends forward seriously, and in the event of turning, due to insufficient suspension stiffness, the car body will roll seriously, which is unfavorable to comfort and stability. Therefore, for the stiffness design of the composite leaf spring, it is suggested that the stiffness value be higher than the target value of the steel leaf spring by 10–20%.

Table 2 Working conditions of the composite leaf spring

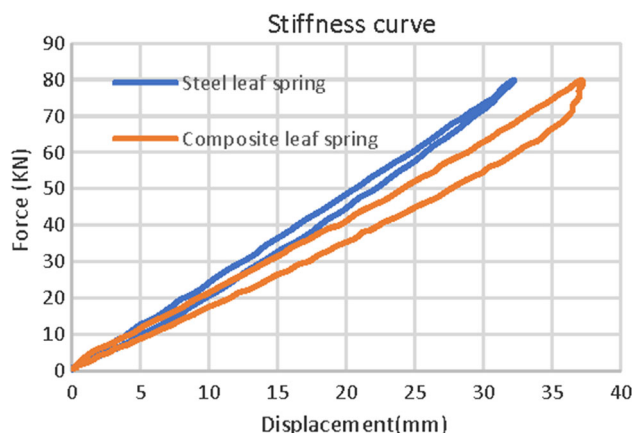| Stiffness matching	Free stiffness
	Clamping stiffness
Load condition	Vertical
	Steering
	Braking
	Fatigue
	U-bolt pre-tightening
	Hook

Fig. 4 Static stiffness of the composite leaf spring and the steel leaf spring

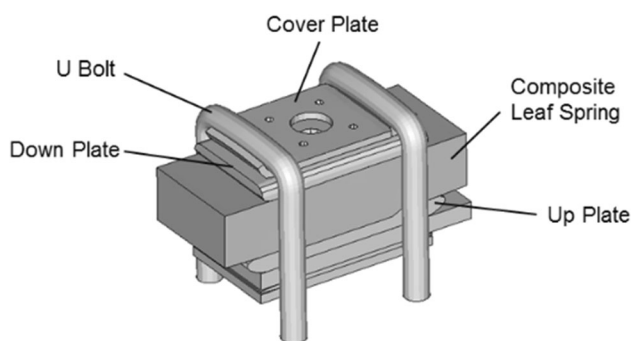Fig. 5 Dynamic stiffness of the composite leaf spring and the steel leaf spring

Table 3 Standard bolt torques

Bolt diameter M (mm)	Bolt grade strength		
	6.9 Ma (Nm)	8.8 Ma (Nm)	10.9 Ma (Nm)
M16	155	210	310
M18	215	300	430
M20	305	425	610
M22	415	580	820
M24	530	730	1050
M27	780	1100	1550
M30	1050	1450	2100
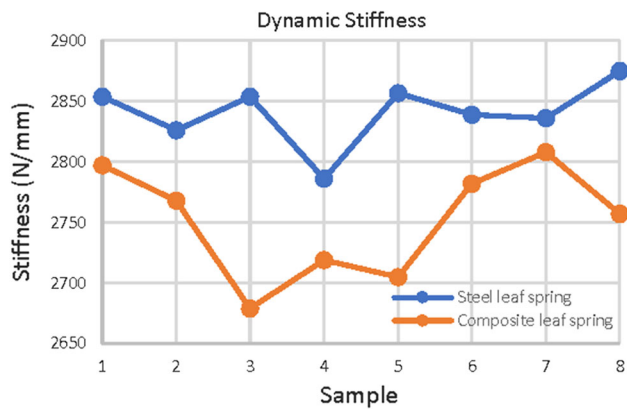
Fig. 6 Assembly structure of the middle of the spring

Stress Analysis

The longitudinal composite leaf spring is subject to the vertical, lateral, and longitudinal forces acting on the automobile chassis. The force acts on each part of the leaf spring differently. Clamping regions of U-bolts are mainly affected by bolt pre-tightening forces. Figure 6 is the clamping structure diagram of the U-bolt in the middle of the leaf spring. The structure is composed of the U-bolt, the spring body, the cover plate, the up plate and the down plate. The spring body is made of composite materials, while other parts are metal. Different U-bolts are selected according to different vehicle loads. Bolts with different grades and diameters have different torques. Standard bolt torques are shown in Table 3.

Figure 7 shows the stress distribution of various parts in the leaf spring after U-bolt pre-tightening. Under bolt pre-tightening deformation, local stress concentration occurred at the four angles where the cover plate and bolts contact. The cover plate and the up plate mainly fix the spring and scatter bolt stress. With the help of the cover plate and the up plate, the stress concentration on the spring body will be significantly reduced.
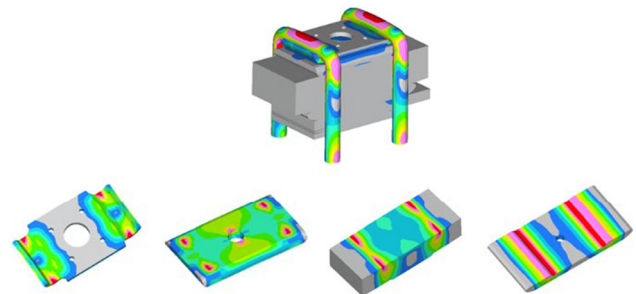

Fig. 7 Stress distribution of bolt pre-tightening

Figure 8 shows the stress distribution at the ends of the composite leaf spring under general working conditions (vertical, braking and steering). Under the three general working conditions, metal gaskets and hooks all showed stress concentration near the bolt hole. Stress concentration was mainly caused by bolt pre-tightening forces. Stress concentration at the bolt hole of the spring body was not obvious; the main stress occurred in the transition zone between the hook and the spring body.

The composite materials are anisotropic materials. The fiber direction can bear relatively heavy loads, while the vertical fiber direction's load-bearing performance is much worse. Displacement needs to be monitored while the strength is checked, especially lateral displacement.

Table 4 compares the lateral displacement of two composite leaf springs reinforced by glass fibers and the benchmark metal leaf springs. No. 1 is an eye-end leaf spring, while No. 2 is a sliding leaf spring. Compared with the metal leaf springs, the lateral displacement of the composite leaf springs was much larger, and the displacement ratio was about 2.7. This was mainly due to the material characteristics; the elastic modulus of the glass fiber is normally about 40–45 Gpa, while the elastic modulus of spring steel is about 206 Gpa. Large lateral displacement equals low lateral stiffness. In actual situations, attention must be paid to the forces at the ends of the leaf spring, especially the sliding spring. The chances of

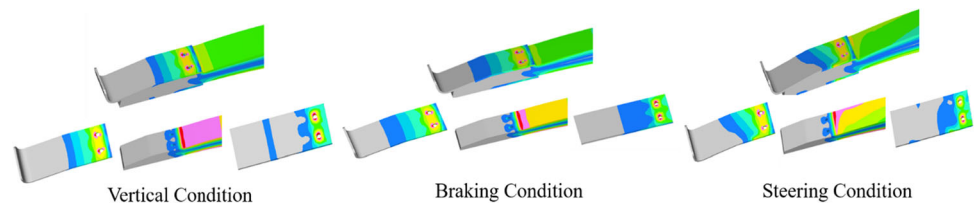**Fig. 8** Analysis results of spring ends under general working conditions

Vertical Condition   Braking Condition   Steering Condition

Table 4 Lateral displacement of different leaf springs

| No. | Vertical stiffness (N/mm) | Lateral force (KN) | Lateral displacement | | |
			Steel leaf spring (mm)	Composite leaf spring (mm)	Ratio
1	160	18	3.2	8.7	2.7
2	2650	27.5	2.1	5.7	2.7

friction between the end sides of the leaf spring and the support will be greatly increased. In theory, increasing vertical stiffness helps increase lateral stiffness, but too much vertical stiffness will affect vehicle comfort. At present, springs 1 and 2 are at the stage of user experience, and no problems have been found for the time being. The lateral displacement problem needs continuous attention and further research.

Failure Mode and Analysis

Generally, the bench test (also known as standard test), the system bench test and the road test are required to verify the feasibility of the leaf spring. The bench test is a three-point bending test of the uniaxial leaf spring to examine the stiffness and fatigue performance of a single leaf spring. The system bench test is a biaxial or triaxial linkage test to evaluate the performance of multi-axial leaf springs. The main purpose of the road test is to evaluate the performance of the leaf spring under various extreme road conditions. The bench test equipment is shown in Fig. 9.

Based on analysis of forces on the composite leaf spring, the leaf spring failure can be divided into two types according to the failure object: the spring body failure and the failure of metal connected to the spring body. According to the failure positions happened in the spring, the failures can be seen in the following places: the U-bolt clamping area in the middle of the spring, the friction area between the leaf spring and the vehicle support, and the connection area between them.

Figure 10 shows the failure status of the U-bolt clamping region of the spring. Such failure is mainly caused by stress concentration. Picture a shows the spring body surface cut by the up plate; picture b shows the surface layer in the center of the spring body caused by uneven bolt pre-tightening force; picture c shows the fracture of the up plate

(a) Bench test

(b) System bench test

(c) Road test

Fig. 9 General tests of the leaf spring

Fig. 10 Failure picture of the middle of the leaf spring

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caused by its insufficient fatigue performance; picture d shows the white color on the spring body surface mainly caused by stress concentration.

The stress concentration of the leaf spring is primary attributed to the uneven stress distribution and excessive stress on the spring body surface. Since the central part of the spring is clamped by two U-bolts, it is recommended that soft materials be added in the middle for transition buffer first, as shown in Fig. 11. Then connect the middle with the up and down plates.

Lamination failures usually occur at the ends of the leaf spring, and its common failure mode is that the interlamination stress exceeds the material limit, leading to the crack spreading to the middle of the spring.

The spring body is made of glass fibers and resin, and resin is the matrix material and the glass fibers are reinforcement materials. The resin is used to fix and protect the fibers, and transfer external loads to the fibers and transfer the loads among the fibers. At the same time, buckling is avoided and the stability of the fibers is maintained. As a result of the material properties, temperature resistance of resin is much worse compared with that of steel.

The working temperature range of the composite leaf spring can be tested in the system bench test. As shown in Fig. 12, three temperature measurement points were set on the left and right sides of the spring, respectively. On each side, one of them was located at the end of the spring, and the other two were located near the bolt hole on the sides of the spring, close to the gasket. The temperature measurement points were all located on the spring body. LT1, LT2, RT1 and RT2 are infrared data, and LT5 and RT5 are thermocouple data. Figure 13 shows the temperature variation trend (ambient temperature 27 °C) at each temperature measurement point within 2 h. It can be seen from the figure that the data of the temperature measurement point on the right side are significantly higher than that on left side. This is because in the system bench test, the left side of the support is connected to a rod, and in the test, the motion displacement on the left side of the spring was less than that on the right. That is, the fiction between the spring and the support on the left is less than that on the right. Within 60 min, the temperature of each temperature measurement point showed a rising trend. Without any
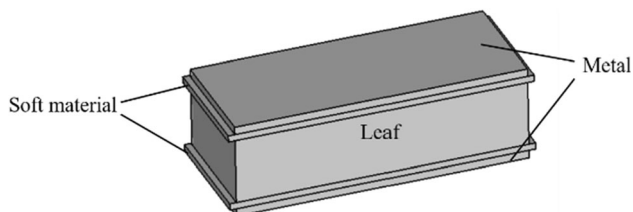
cooling measures, the ends of the spring body reached 140 °C in 60 min. At 80 min, the temperature of RT5 reached the highest point of 180 °C, and then the temperature slowly declined and stabilized. At 120 min, the temperature was around 160 °C. At LT5, the temperature peaked at 90 °C in 60 min, and declined from 90 to 60 °C from 60 to 100 min, and then stabilized. The temperatures at RT2 and LT2 were higher than those at RT1 and LT1. This is because RT2 and LT2 were closer to the friction surface than RT1 and LT1.

The commonly used Tg point of epoxy resin is about 120–160 °C, while the Tg point of polyurethane resin is even lower, about 80–120 °C. When the working temperature of the spring exceeds the Tg point of the resin, the binding force between the resin and the fiber will decrease rapidly, and the binding surfaces between them will sepa-
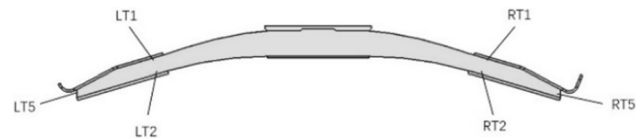

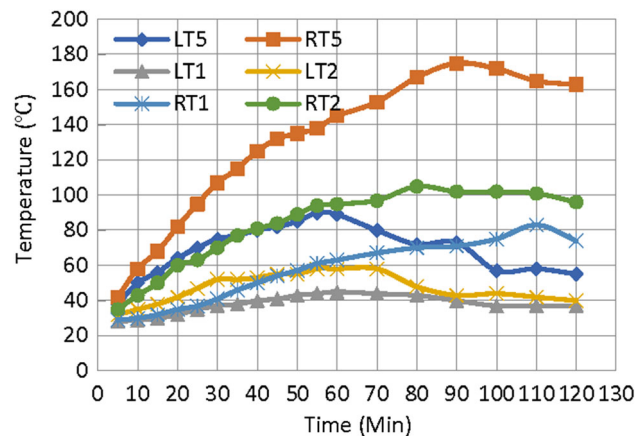**Fig. 12** Temperature measurement points of the spring

Fig. 13 Temperature variation trend at each measurement point

Fig. 11 Recommended structure for the middle of the composite leaf spring

Fig. 14 Failure of the leaf spring end

rate, resulting in a lamination failure of the spring. Figure 14 shows the picture of a spring end failure in the system bench test without any cooling measures. At 60 min, a tiny crack started to appear at the right spring end, which led to stiffness decrease in the right side of the spring. The stiffness of the leaf and right sides was not the same. During the vertical loading, the displacement on the right side of the spring increased instantly while the displacement on the left side decreased relatively, resulting in more severe friction on the right side. This is why the temperature on the left side dropped after 60 min. As the test continued, the temperature on the right side of the spring continued to rise, and the binding surfaces of the resin and the fibers of the spring body gradually separated. Finally, the interlamination stress at the spring end exceeded the limit value of the material, and the crack expanded from the end to the middle of the spring. According to the curve in Fig. 13, it can be concluded that obvious cracks appeared on the spring body within 30 min after the spring body temperature exceeded the Tg point, and its performance also declined significantly.

To ensure that the composite leaf spring can be used safely on an actual vehicle, it is necessary to keep the spring's working temperature lower than the Tg point. The eye-end leaf spring mainly transfers the force between the spring body and the support through its eyes. The friction between the eyes and the support is mainly rotational friction, and the heat generated by rotational friction is far less than that by sliding friction.

Fig. 15 Actual measurement temperature of the leaf spring

To check the actual working temperature of the spring in practical use, 6 points were selected for the clamping area and the friction area of the spring, as shown in Fig. 15. Three temperature test papers of different intervals were attached to each point. Since the spring support of the vehicle was bilaterally symmetrical, the temperatures only needed to be measured on one side. In order to try to ensure the measured data were the actual temperatures, Shenzhen of China ($-$ 113° 46′–114° 37′ E, 22° 27′–22° 52′ N) with lower latitude was selected as the test location and the test was conducted in summer, with an average temperature of 31 °C, for 3 months. According to the measurement on actual vehicles, the highest temperature at the spring end was about 60 °C, and the highest temperature in the middle of the spring was about 80 °C. The high temperature at the spring end was mainly caused by the friction between the spring and the support, while the high temperature in the middle area was mainly caused by the exhaust of the brake drum. Therefore, for the sliding leaf spring, resin with a Tg point as high as possible shall be selected, and a Tg point higher than 80 °C is preferable.

Bolt connection is usually adopted between the spring body and the metal gasket, and the bolt hole of the spring body is generally made through post-processing. Composite material bolt connection failures are caused by many factors. The layer structure, the pre-tightening force, connection form, the width–diameter ratio, the end distance and the load application form have a great influence on bolt connection strength of the composite material [11]. Their effects on the composite bolt strength have been verified by large numbers of experiments and numerical simulations. The influence of these factors on failures of bolt connection is transformed into analysis of stress concentration around the bolt hole. Stress concentration is the main factor that affects the bolt joint. Generally, stress makes the tensile strength of the connection laminate only 20–30% of its actual value. The bolt joint shape has a great influence on stress distribution. Improper design can result in shearing or a net cross-section tensile failure, which only requires a fraction of the normal stress. At the same time, the composite bolt joint connected to the bolt will lead to the redistribution of stress concentration, so whether the bolt joint is symmetrical or not has a great impact on loads. If the joint is not symmetrical, eccentric load will easily occur and the eccentric distance of the joint will be increased, thus canceling the effect of local strengthening.

The influence of the laminate structure on the composite material bolt connection failure is mainly determined by the performance of the composite laminate. There can be many kinds of lamination sequence. Therefore, the interlamination stress changes, significantly affecting the mechanical properties of the laminate. So, in lamination design, stacking the same layers shall be avoided to the
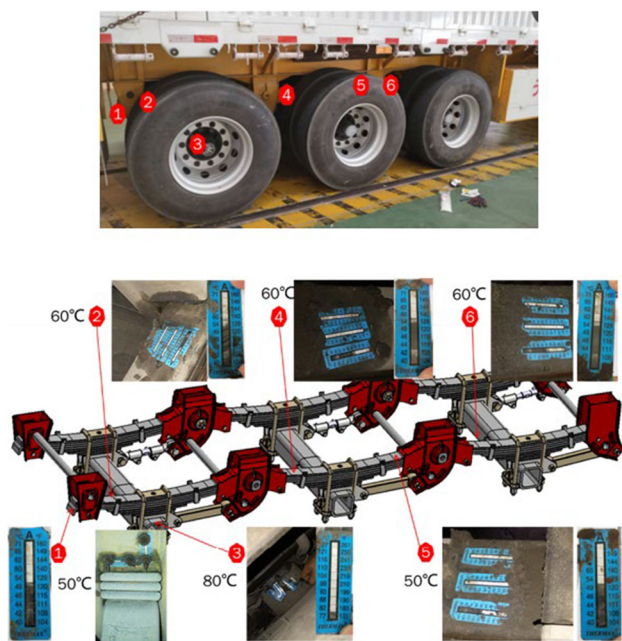
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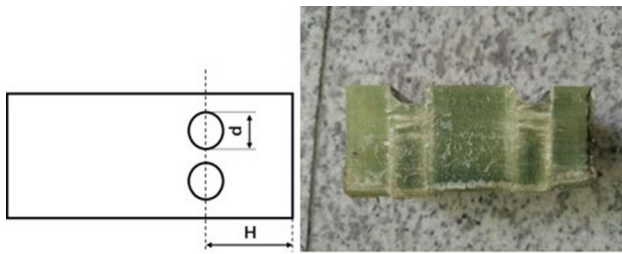J Fail. Anal. and Preven. (2020) 20:1437–1444

Fig. 16 Failure of the leaf spring bolt hole

greatest extent. At the same time, sufficient hole margins [12–14] shall be ensured in the design. If the ratio of the spring hole-end distance H to the hole diameter d is low, the leaf spring will suffer from shearing and a tension failure, as shown in Fig. 16.

Conclusion

Because of the damping characteristics of its structure, the dynamic stiffness of the composite leaf spring is lower than that of the benchmark steel leaf spring. In order to ensure that the offset frequency of the vehicle is consistent with the original one, it is recommended that the stiffness of the composite leaf spring be 10–20% higher than the target value.

Due to the influence of U-bolt clamping, central of the leaf spring, stress concentration will occur at the interface between the spring body and the metal plate. In actual situations, excessive stress concentration may cause damage to the spring body and the cover plate. It is suggested that a layer of soft materials be added between the cover plate and the spring body to scatter stress concentration so as to protect the spring body, the up plate and the down plate.

Sufficient hole margins shall be ensured in the design of the spring ends. If the ratio of the spring hole-end distance to the hole diameter is low, the spring will undergo shearing and a tension failure. In addition, the resin Tg point shall be considered during material selection. It is suggested that the Tg point should be higher than 80 °C.

Further studies need to be conducted on the large lateral displacement of the composite leaf spring.

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