Impact Damage Analysis of Fiber Reinforced Plastic Structure with Rib

Xiong Linghua,1,2 Ming Zhimao,2 Zhao Kelun,2 and Wang Fan1

1MOE Key Lab of Disaster Forecast and Control in Engineering, Jinan University, Guangzhou 510632, China
2Guangzhou GRG Metrology & Test Co. Ltd., Guangzhou 511458, China

Correspondence should be addressed to Xiong Linghua; xiong_linghua@126.com

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1. Introduction

FRP is a composite material with excellent performance. It has the characteristics of high specific strength, small molding shrinkage, good dimensional stability, good chemical resistance, and electrical insulation performance [1]. At present, some traditional metal structural parts have been replaced by FRP, such as automobile oil sump. FRP structure is usually made into corrugated shape or using ribs to improve its rigidity and impact resistance [2]. Especially, for some sealed shell containers, the surface ribs can absorb the destruction energy during accidental impact and protect the shell body. Ribs on the shell body are often injection molded together with the body. Too large or too small stiffness of ribs are not conducive to energy absorption and shell body protection [3]. When the stiffness is too large, more strain energy is transferred to the shell body and causes body failure. However, if the stiffness is too small, the impactor can easily penetrate the ribs and hit the shell body. In addition, the energy absorption effect of the ribs is also related to the mass, size, impact angle, and velocity of the impactor, so the design of the FRP structure should fully consider the application scene.

This study takes the glass fiber reinforced plastic (GFRP) automobile oil sump as the object. This kind of oil sump is installed under the chassis of the car, and it is often hit by the flying stones rolled up by the tires. In order to prevent the shell body from being damaged, the outer layer of the oil sump structure is designed with multiple rows of ribs. A large number of failure events show that the design of external ribs will directly affect the life of oil sump. The width, thickness, and spacing of ribs have an important influence on the impact resistance of the shell body. When the vehicle is driving on different roads, the geometric size of flying stones, the throwing speed, the impact point, and the incidence angle are different. How to design the geometry and...
arrangement of the reinforcing ribs of oil sump is the key to improve the impact resistance and service life of oil sump. In order to solve the problems of oil sump design and optimization, through test and simulation, the impact failure mode of the GFRP shell body structure with ribs is analyzed and how to design ribs on the shell body is discussed.

1.1. Impact Performance Test. The weight of GFRP automobile oil sump is about 1/5 of the steel sump of the same size (Figure 1). Because of the lightweight trend of cars, oil sump made by GFRP gradually replaces metal oil sump in new models. Impact damage is a common form of damage to oil sump [4, 5]. The main cause of impact is flying stones which are rolled up by wheels. Such irregularly flying stones sometimes hit chassis suspension or other parts such as the sump, causing damage to structural surfaces or internal cracks. The ribs on GFRP oil sump can effectively improve the rigidity of the shell body and also prevent the shell body from being seriously damaged by accidental flying stone impact [6].
Research shows that the speed of flying stone is related to the driving speed of the car. The incidence angle range of the flying stones is fixed because the flight trajectory is basically on the line between the bottom of the front wheel and the incidence site [7]. Under the framework of Chinese road traffic law, the geometry size and quality of flying stones are statistically related to road grade [8]. At present, the energy range of medium- and low-speed flying stone test for passenger car parts is roughly in the range of 10 to 40 joules. According to relevant Chinese standards, the maximum amount of flying stones on a grade 3 highway shall not exceed 60 g, and the maximum amount on a grade 1 highway shall not exceed 20 g. After being rolled up, the speed of flying stone is variable relative to the ground, but China’s highway has the maximum speed limit of 120 km/h, and the speed of flying stone relative to the body is generally around 120 km/h. Based on the information above, the range of the impact intensity can be basically determined, as shown in Table 1. In the test, spherical metal balls will be used instead of irregularly shaped flying stones.

The impact test is performed based on an acceleration device (Figure 2). The launcher uses elastic potential energy to accelerate the flying stone, similar to a crossbow. During the test, the strain of the shell body is monitored, and the
impact site is captured by a high-speed camera at the moment of impact. Structural damage and cracks are observed after the test.

In order to monitor the response of the oil sump body during impact, strain gauges were attached to the back of the shell. Figure 2(d) is a view showing the attachment position of the back strain gauges. Considering the symmetry, the position of the strain gauges is centered on the position, where the ball flight trajectory passing through the shell body, and is evenly arranged in the horizontal and vertical directions.

1.2. Impact Test Analysis. Generally, flying stone coming from the front to the rear of the vehicle is more common. The position indicated by the arrow in Figure 3 is frequently

Figure 6: Strain changed at the back of the oil sump body under the impact of a 131 g ball.
subjected to flying stone impact. In the test, the flying ball is used to simulate flying stone by the acceleration device [9]. The ball hits the oil sump at a certain initial speed and rebounds. Figure 4 shows a form of aiming point positive impact on the ribs, namely, the flight trajectory line, the projectile ball center, and the end of the rib on the same straight line.

Figure 5 is photographs of the impact site after test. It can be clearly seen that the damage and failure volume (which has been clearly separated from the original structure) of the ribs was greater after the 45° impact. When the impact capacity reached the maximum 90 J, no obvious cracks were found in the oil sump body after the 45° impact, but the oil sump body cracked after the 90° impact.

Figure 6 is schematic diagrams of the strain measurement sites on the back of impact site. The strain level with an incident angle of 90° was higher than 45°. After impact, each measuring site had residual strain [10]. When the energy reached 90 J, the maximum strain of the two measuring sites numbered “1” and “5” closest to the impact center exceeded the instrument range instantly. After the test, the residual deformation was relatively large, and the cracks had been observed by naked eyes. With the incident angle of 45° and the energy of 30 J or 60 J, the ball continued to touch the adjacent ribs after reflection, so two pulses could be seen from the strain diagrams.

At the same energy, small mass balls with smaller contact area at hit have greater velocity than large mass ones, and the damage effect is theoretically different from large mass ones [11]. Figure 7 is photos of the impact site of a 19 g ball after the impact test. It can be clearly distinguished that the failure volume at the same energy is larger than that of a 67 g ball, as shown in Figure 8.

However, when the mass of the ball increased to 67 g, the failure volume at the same energy did not further expand. As shown in Figure 8, the energy impact of 90 J did not cause the body to crack.

Tables 2 and 3 show the damage and failure conditions under various masses and energies. Due to the dispersion of test objects and equipment, only a qualitative description of the damage is given. It can be seen from the results in Table 2 that, under several test conditions, the shell was not damaged by the flying stone with small incident angle. When the incident angle was 90°, the shell was damaged more easily by the flying stone with medium mass than that with large mass. In addition, the shell would be damaged only when the energy exceeded 60 joules.
Table 2: Test results I.

| Angle | Mass (g) | Energy (J) | The body is cracked after 10 times test | Angle | Mass (g) | Energy (J) | The body is cracked | Strain pulse peak |
|-------|----------|------------|----------------------------------------|-------|----------|------------|--------------------|-----------------|
| 90°   | 131      | 2/10       |                                        | 90°   | 0/10     | 0.017      |                    |
| 90°   | 67       | 0/10       |                                        | 67    | 0/10     | 0.011      |                    |
| 90°   | 19       | 0/10       |                                        | 24    | 0/10     | 0.017      |                    |

Note: the strain range of the measuring instrument is $-0.035$ to $0.035$. It can be seen from the results in Table 3 that, under several test conditions, the shell was not damaged by the flying stone with a small incident angle. When the incident angle was $90°$, the shell was more likely to be damaged by the flying stone with medium and large mass. The large mass flying stone has a larger size and can contact at least two ribs at the moment of impact, so the impact energy is more dispersed. Even if the energy is larger, the shell cannot be completely damaged.

Table 3: Test results II.

| Angle | Mass (g) | Velocity (km/h) | The body is cracked | Angle | Mass (g) | Velocity (km/h) | The body is cracked |
|-------|----------|-----------------|--------------------|-------|----------|-----------------|--------------------|
| 90°   | 131      | 2/10            |                     | 90°   | 0/10     | 0.017            |                    |
| 90°   | 67       | 0/10            |                     | 67    | 0/10     | 0.011            |                    |
| 90°   | 19       | 0/10            |                     | 19    | 0/10     | 0.017            |                    |

Table 4: Test results III.

| Angle | Velocity (km/h) | Mass (g) | Radius (mm) | Interval size between two ribs (mm) | Cracked after 10 times test |
|-------|-----------------|----------|-------------|-------------------------------------|-----------------------------|
| 90°   | 120             | 44.1     | 15.0        |                                     | 3/10                        |
|       |                 | 47.1     | 15.5        |                                     | 3/10                        |
|       |                 | 50.2     | 16.0        |                                     | 7/10                        |
|       |                 | 53.3     | 16.5        |                                     | 8/10                        |
|       |                 | 56.6     | 17.0        |                                     | 9/10                        |
|       |                 | 60.0     | 17.5        |                                     | 8/10                        |
|       |                 | 63.5     | 18.0        |                                     | 8/10                        |
|       |                 | 67.1     | 18.5        |                                     | 9/10                        |
|       |                 | 70.7     | 19.0        |                                     | 7/10                        |
|       |                 | 74.5     | 19.5        |                                     | 3/10                        |
|       |                 | 78.4     | 20.0        |                                     | 2/10                        |
|       |                 | 82.4     | 20.5        |                                     | 2/10                        |

Table 5 shows the impact test results of flying stones with the same mass and velocity, but different incident angles. When the incident angle exceeded $75°$, the shell failure began. The larger the angle was, the more the failure samples were.

2. Simulation Analysis

Generally, FRP is regarded as anisotropic material [12]. However, the oil sump is injection molded with short glass
Table 5: Test results IV.

| Mass (g) | Velocity (km/h) | Angle | The body is cracked |
|----------|-----------------|-------|--------------------|
| 67       | 120             | 45°   | 0/10               |
|          |                 | 50°   | 0/10               |
|          |                 | 55°   | 0/10               |
|          |                 | 60°   | 0/10               |
|          |                 | 65°   | 0/10               |
|          |                 | 70°   | 1/10               |
|          |                 | 75°   | 3/10               |
|          |                 | 80°   | 7/10               |
|          |                 | 85°   | 7/10               |
|          |                 | 90°   | 9/10               |

Figure 9: Scanning electron microscope image of oil sump material sampling (1 mm × 1 mm).

Figure 10: The engineering stress-strain curve of oil sump material (left: stretch curve; right: stretch-release-stretch curve and strain rate).

Figure 11: Simplified finite element model and mesh of oil sump.
fibers whose length is less than 0.05 mm (the thickness of the oil sump shell is about 3 mm) and a thermoplastic resin called polyhexamethylene adipamide [13, 14]. From the scanning electron microscope image of the material slice (Figure 9), it can be seen that the fiber distribution is uniform and the fiber orientation is random after the material formed. At the same time, the tensile test of the shell material slice also shows that the tensile curves in different directions are not significantly different. Therefore, the material can be regarded as an isotropic homogeneous material.

Slicing and tensile tests are performed on the flat smooth shell material without ribs with the strain rate of the same magnitude as that measured in the flying stone impact test (test 102 s\(^{-1}\)). The tensile curve of the material obtained is shown in Figure 10. There is no obvious difference in the engineering strain-stress curves of different tensile directions, and the slight difference in elongation at break may be related to the processing factors of the specimen. The elongation at break of the 3.55 mm thick specimen is about 5%, and ultimate strength is 139 MPa.

Considering the amount of calculation, the overall finite element model of the oil sump has not been established completely [15]. Figure 11 is the finite element simulation model and mesh. The mesh is refined at and near the collision site to ensure that there are at least 2 elements in the thickness direction of ribs [16]. The total mesh number is 40136, and the mesh type is hexahedral solid unit. Bilinear and isotropic material is selected for the constitutive material [17]. The yield strength is 70 MPa, the yield strain is 1%, the ultimate strength is 139 MPa, and Poisson’s ratio is 0.41. Figure 12 is the finite element simulation results, showing the stress distribution of the ribs after the ball impact.

It can be seen from Table 6 that, by adjusting the spacing of ribs, the shell will be damaged when the mass range of flying stone is 54 g–72 g or more than 106 g under high-speed condition. The impact energy of the flying stone with the mass range of 10 g–53 g is too small, while that of the flying stone with the mass range of 73 g–105 g is too large. It can contact multiple ribs during the impact, so the impact energy is more dispersed, and there is no damage to the shell.

3. Conclusion

Test results show that medium mass balls (between 53 g and 70 g) are more likely to cause shell damage at the incident angle of 90° and the same impact energy, while large mass balls cannot cause shell damage unless the impact energy is large enough. Both simulation results and high-speed images showed that large mass balls have larger contact area with ribs. Because at the moment of impact, large mass balls will

| Velocity (km/h) | Mass (g) | Angle | Failure position when the rib spacing is 11 mm | Failure position after adjusting the rib spacing to 9 mm |
|----------------|----------|-------|-----------------------------------------------|-----------------------------------------------------|
| 120            | 10–53    | 90°   | On rib                                        | On rib                                              |
|                | 54–72    | 90°   | On rib and shell body                         | On rib                                              |
|                | 73–105   | 90°   | On rib                                        | On rib                                              |
|                | 106–150  | 90°   | On rib and shell body                         | On rib and shell body                                |
|                | 60°      |       | On rib                                        | On rib                                              |
|                | 62°      |       | On rib                                        | On rib                                              |
|                | 64°      |       | On rib                                        | On rib                                              |
|                | 66°      |       | On rib                                        | On rib                                              |
|                | 68°      |       | On rib and shell body                         | On rib and shell body                                |
|                | 70°      |       | On rib and shell body                         | On rib and shell body                                |
| 120            | 63       | 60°   | On rib                                        | On rib                                              |
|                |          | 62°   | On rib                                        | On rib                                              |
|                |          | 64°   | On rib                                        | On rib                                              |
|                |          | 66°   | On rib                                        | On rib                                              |
|                |          | 68°   | On rib and shell body                         | On rib                                              |
|                |          | 70°   | On rib and shell body                         | On rib                                              |

Figure 12: Finite element simulation results.
contact with more than one rib and the energy of impact is
more dispersed, less density energy is transferred to the shell
and the shell is more safe. It is found that medium or small
mass balls are more likely to cause shell damage, while large
mass balls are less likely to cause shell damage unless they are
very fast.

Test results show that the larger the incidence angle is,
the more the shell damage is likely to occur. Testing with
medium mass ball at maximum velocity, we found that the
failure can only be caused by the incident angle more than
80°. It indicates that only when the incident angle is very
close to 90°, the impact energy will be fully transferred to the
shell structure and cause the damage.

According to the national standards of China road
traffic, large mass flying stones are allowed to appear on low-
grade roads where the speed limit is very low (≤ 60 km/h), so
the impact energy of flying stones cannot reach enough to
damage the shell. Therefore, the flying stones of high speed
and small and medium size on high-grade roads should be
considered in the oil sump design.

It can be found that the arrangement of the ribs should
be more closely to avoid the damage of medium mass and
size flying stones, but the rib overassembly arrangement will
increase the manufacturing cost. According to the result in
Table 4, the resistance to the impact of 50 g to 70 g flying
stone is more necessary. Therefore, according to the density
of common stones, spacing between ribs in the range of
23.8 mm–28.2 mm is appropriate.

Data Availability

The basic test data used to support the findings of this study
are restricted by the author in order to protect privacy.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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