Innovative Design of Climbing Assistance System for Tower Cranes Based on Ergonomics

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ABSTRACT
Tower cranes are the most commonly used large-scale mechanical equipment in high-rise construction, playing a very important role in high-altitude material handling, on-site material handling and distribution, and other functions. Its unique structure and unmatched height by other machinery enable tower cranes to efficiently carry out high-altitude material handling work. As a result, drivers and maintenance personnel of tower cranes face many safety issues while climbing. Based on safety considerations for the majority of tower crane operators, this study aims to design an intelligent climbing assistance system specifically designed for tower cranes, so as to reduce the safety issues that workers may face to a certain extent. The implementation of this system will help improve work efficiency, protect the safety of staff, and improve their work experience.

Keywords: *Tower crane, Driver, Efficiency.*

1. INTRODUCTION: RESEARCH PURPOSE AND SIGNIFICANCE

Due to the rapid development of the market economy, in order to overcome the rapid increase in demand for large-scale construction caused by China's rapid urbanization process, more construction machinery and personnel are needed. Tower cranes ("Figure 1"), as necessary construction facilities, play an indispensable role.

Figure 1 Tower crane.

a Image source: https://cn.bing.com/images/search

Tower cranes, as the main large-scale construction machinery, have important functions in urban construction, such as high-altitude material handling, on-site material handling and distribution, construction site safety, and multi-working radius coverage. Tower cranes, with their unique structure and unparalleled heights beyond the reach of other equipment, can effectively carry out high-altitude material handling work. It is precisely because of its special structure and height that the drivers and maintenance personnel of tower cranes face many safety issues during work.

At present, both tower crane operators and maintenance workers rely on their physical abilities to climb tower cranes that are tens or even hundreds of meters tall. The manual climbing operation method ("Figure 2") not only requires high physical fitness for personnel, but also faces significant safety hazards. At the same time, there have been incidents in China where tower crane personnel fell during the climbing process due to physical and psychological reasons.

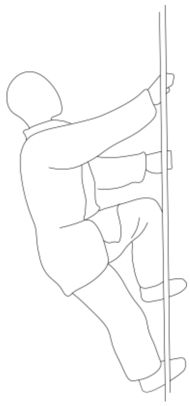


Figure 2 Climbing method of tower crane.

a Image source: Self-drawn.

While tower cranes create high performance and convenience, frequent safety accidents during driving also plague every driver. The data shows that among the 162 tower crane accidents in China, the main cause of the accidents was collapse, accounting for 66.5%, followed by tower arm fracture, lifting fall, and component detachment, accounting for 9.88%, 6.17%, 6.56%, and 4.94%, respectively. These data all reflect the problems of tower cranes, which are very difficult to conduct safety inspections on the entire tower crane. At the same time, operators do not have corresponding safety protection when climbing tower cranes. These problems put every tower crane driver and inspector in danger.

This study aims to design an intelligent climbing assistance system for tower cranes based on ergonomics, to some extent, to solve the safety issues faced by tower crane operators and maintenance personnel in their work, and improve work efficiency, optimize safety, and enhance the work experience of staff. This study will add additional automatic equipment to the internal foundation of tower cranes to assist workers in quickly and safely reaching the top. This article will mainly focus on designing the mechanical structure and appearance of climbing equipment, while also designing the intelligent system of the equipment to make it more user-friendly, and fully considering the issue of human-machine integration in the operation of mechanical equipment. This article conducts an in-depth analysis of the human force exerted on the equipment during operation to address comfort and safety issues, providing strong support for the theoretical design and research and development of the equipment.

2. RESEARCH AND ANALYSIS

2.1 Human Machine Analysis of Tower Crane Climbing Methods

As shown in "Figure 3" and "Figure 4", the tower cranes require the drivers to climb barehanded during the climbing process. The diameter of the climbing ladder is relatively small, and the contact area with the hands and feet of the climber is small. Therefore, the reaction force experienced by the climber during the climbing process is significant, especially for climbers with a larger weight base. In addition, the vertical climbing ladder structure also brings greater challenges to the climber. The prolonged climbing process, the pain in hands and feet caused by the huge reaction force, and the extraordinary height of the tower crane make climbing the tower crane increasingly difficult and dangerous.

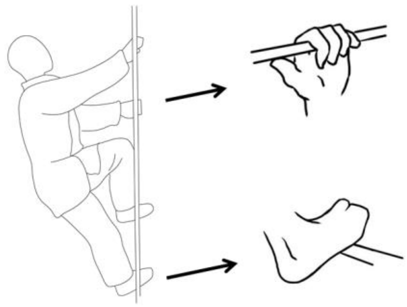


Figure 3 Detailed diagram of the climbing process.

a Image source: Self drawn.

Figure 4 Climbing ladders and drivers.

a Image source: https://cn.bing.com/images/search

2.2 Analysis of Related Products

Through preliminary research and comparison of similar products in the market, this article analyzes the advantages and disadvantages of devices that can be used for tower cranes, and provides reference and suggestions for the design of product design and functionality in the later stage.

This product ("Figure 5") can be installed with specialized installation tools on building windows, balconies, or flat roofs. It can also be installed on elevated fire trucks to rescue victims in high-rise building fires. Its advantages lie in its relatively simple and lightweight structure, while its disadvantages are also obvious. Based on the height of the tower crane, its safety is not high, and the risk factor is too high when encountering adverse weather conditions such as strong winds.

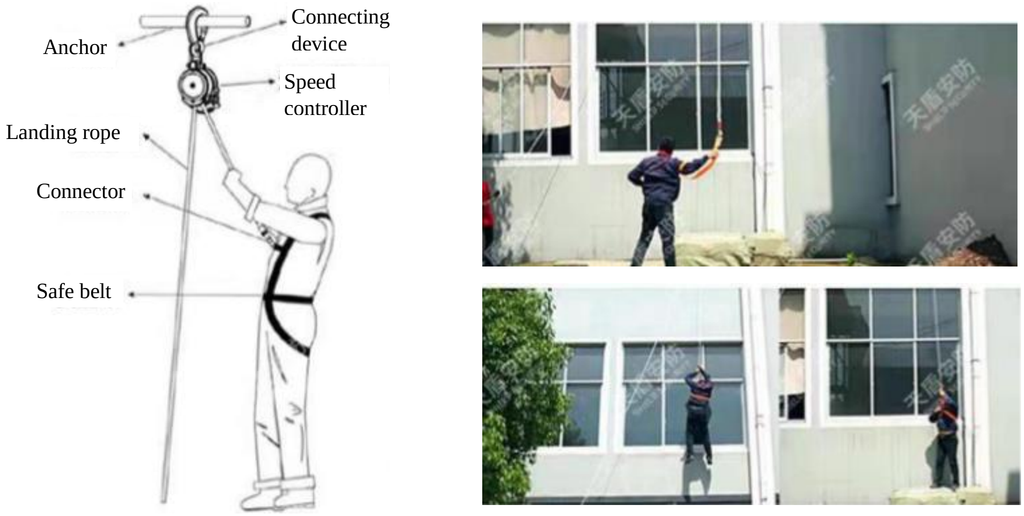


Figure 5 Slow descent device.

a Image source: https://cn.bing.com/images/search

Figure 6 High altitude escape and rescue device.

a Image source: https://cn.bing.com/images/search

The second version of the climber ("Figure 6") is more concise compared to the previous one, and has some improvements. It has a fixed device to ensure that workers do not experience too severe shaking when descending. However, his shortcomings are still consistent with the former, requiring a second person to climb to the top of the tower for operation. If the height is too high, it is necessary to climb to the top first before operation, which cannot be used at any time and is inconvenient to use.

Figure 7 Train rescue.

a Image source: https://cn.bing.com/images/search

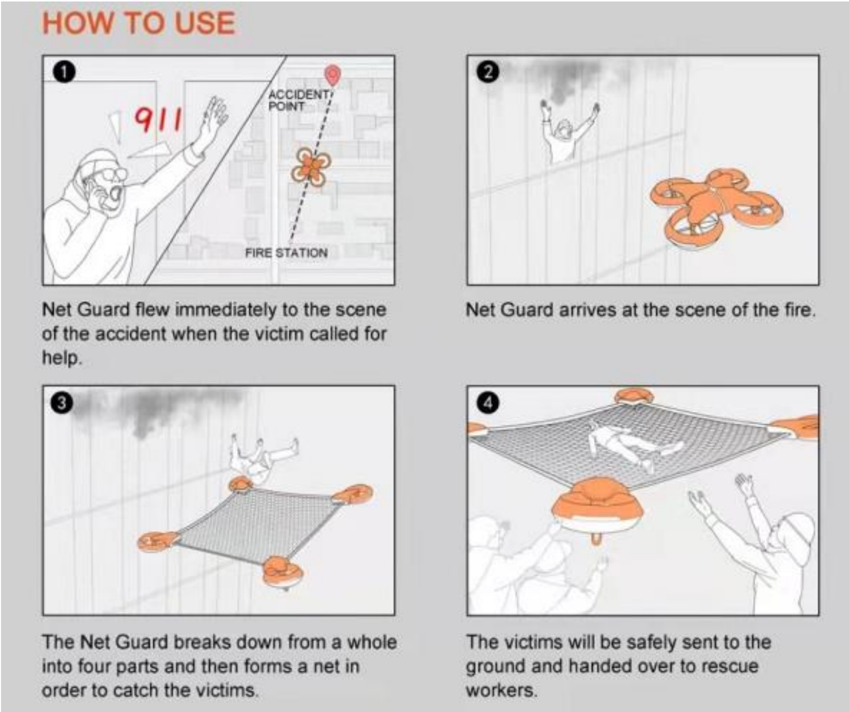


Figure 8 Rescue drone.

a Image source: https://cn.bing.com/images/search

The remaining similar products ("Figure 7", "Figure 8") are applied to train rescue and high-altitude rescue for fires, respectively. The former's reference form is not suitable for the limited space of the environment where tower cranes are located, nor is it stable like elevated tracks. The latter's application form is completely independent of tower cranes and is a new type of unmanned aerial vehicle design unrelated to tower cranes. However, these open ideas provide a design basis for the later design and research of tower crane climbing devices.

3. DESIGN PRACTICE

3.1 Sketching Deduction

Based on previous research on similar products, an initial design sketch was made ("Figure 9", "Figure 10"). Overall, the former is similar, but lacks strong protection. The researchers sketch and deduce the process of climbing onto the top of the tower crane ("Figure 11", "Figure 12"), and select the optimal solution.

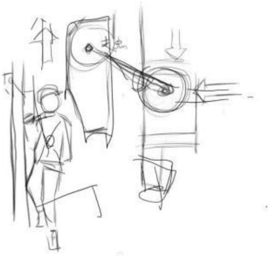


Figure 9 Sketch.

a Source: self-made.

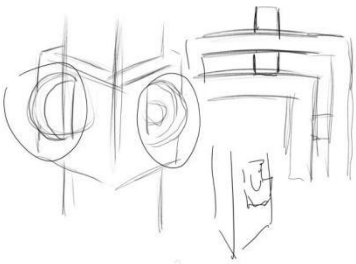


Figure 10 Sketch.

a Source: self-made.

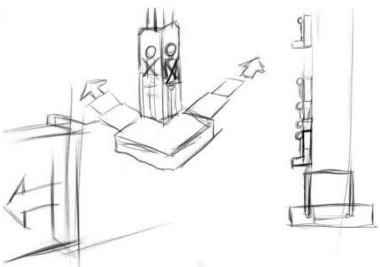


Figure 11 Sketch.

a Source: self-made.

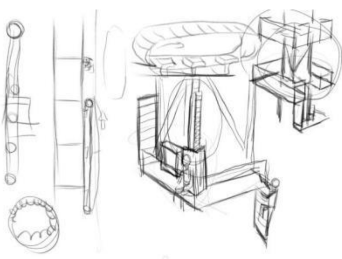


Figure 12 Sketch.

a Source: self-made.

Researchers ultimately make the final design decision on the shape of the tower crane climbing device, divide the flexible part from the seat according to modularization and create two device parts for separate design. ("Figure 13", "Figure 14")

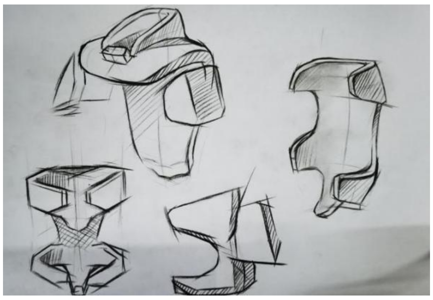


Figure 13 Sketch.

a Source: self-made.

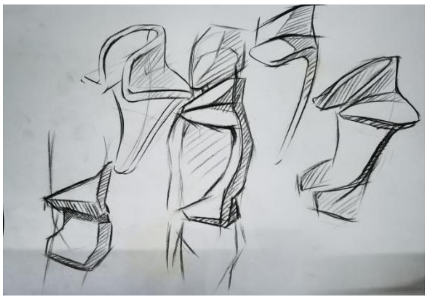


Figure 14 Sketch.

a Source: self-made.

3.2 Presentation of Renderings and Exploded Views

The lifting device is mainly composed of two main parts: wearable equipment and seat equipment, as well as tracks. The rendered images in "Figure 15" and "Figure 16" show the wearable part of the product. The rendering images in "Figure 19" and "Figure 20" show the human-machine display of the wearable part. The rendering image in "Figure 21" shows the appearance of the seat section. The rendering images in "Figure 17" and "Figure 18" show the overall body style.

Figure 15 Wearing case display.

a Source: self-made.

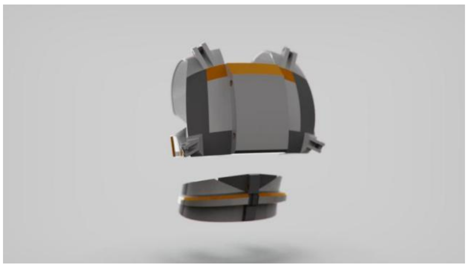


Figure 16 Wearing case display.

a Source: self-made.

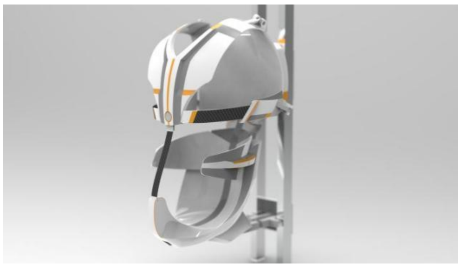


Figure 17 Overall display.

a Source: self-made.

Figure 18 Overall display.

a Source: self-made.

Figure 19 Wearable part human-machine display.

a Source: self-made.

Figure 20 Wearable part human-machine display.

a Source: self-made.

Figure 21 Seat display.

a Source: self-made.

As shown in the explosion diagram ("Figure 22"), the entire device is divided into two parts, namely the wearable device and the seat device. The wearable device is further divided into two small units: upper body armor and waist armor. Soft materials are embedded in the wearing part to make wearing more comfortable.

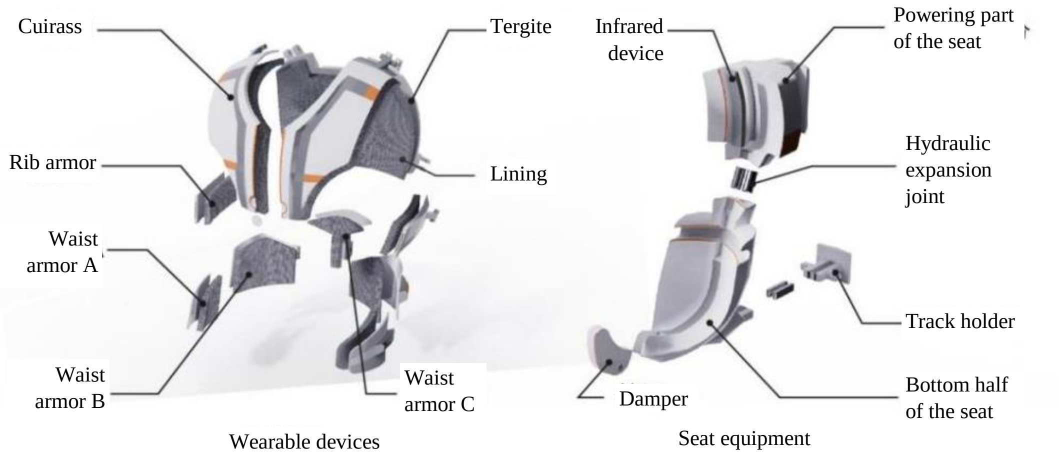


Figure 22 Explosion diagram display.

a Source: self-made.

3.3 Research on the Human-Machine Usage Process of Fixed Devices

As shown in "Figure 23", it is estimated that the contact area between the human buttocks and the seat is approximately $0.09m^2$, and the estimated mass of an adult is 70 kilograms. According to the pressure formula:

F=G=mg=70kg×10 N/kg=700N

According to the gravity calculation formula, the gravity of the human body is about 700N (N/Newton).

During the movement of the lifting equipment up and down, the force it receives will also be accelerated by gravity. Due to the limitations of current research status, it is not necessary to calculate it too finely, so a score of approximately $10m/s^2$ can be taken.

$P=F/S=G/s=mg/s=(70kg\times10N/kg)/0.09m^2=700 N/0.09m^2=7777.777$

It approximately equals to 7777pa, and the pressure exerted by the human body on the seat is approximately 7777pa (Pascal). This pressure value is actually very small and relatively comfortable for users to use.

At present, only rough calculations have been made to roughly determine the feasibility of the device. More detailed calculations require testing after the successful production of the device to obtain more accurate data. The current conclusion is for reference only.

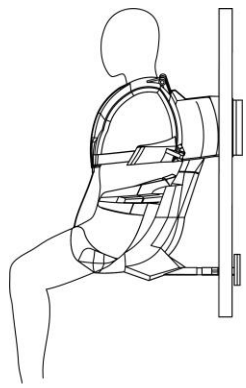


Figure 23 Human-machine display.

a Source: self-made.

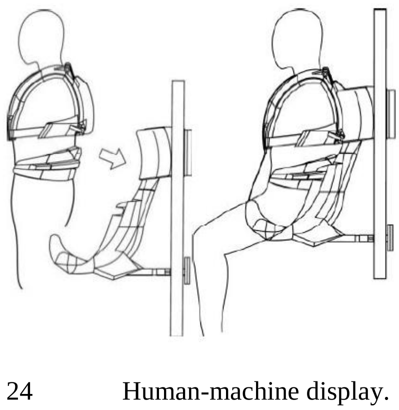


Figure 24 Human-machine display.

a Source: self-made.

Therefore, as shown in "Figure 25", there are expansion joints distributed in the middle and rear of the seat to ensure a better fit for people of different heights.

The upper part of the seat is equipped with an infrared device that automatically aligns with its back, providing a faster and more accurate connection.

After putting on some armor, the driver only needs to sit directly near the seat, but there are also problems. During use, due to the differences in height and weight of each person, there may inevitably be differences when sitting, so the machine needs to further synchronize with the human body while sitting to allow people to sit more quickly and conveniently.

Simply put, the wearable part separates from the seat and can be connected to form a complete body as shown in "Figure 24", performing mechanical movements up and down on two tracks ("Figure 26", "Figure 27").

After seating, the user can control the climbing device to move up and down through Bluetooth on their mobile phone.

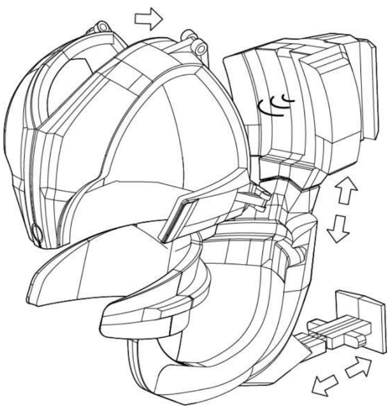
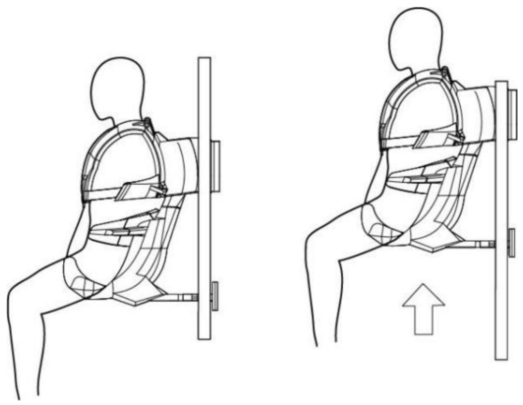


Figure 25 Equipment operation interpretation diagram.

a Source: self-made.



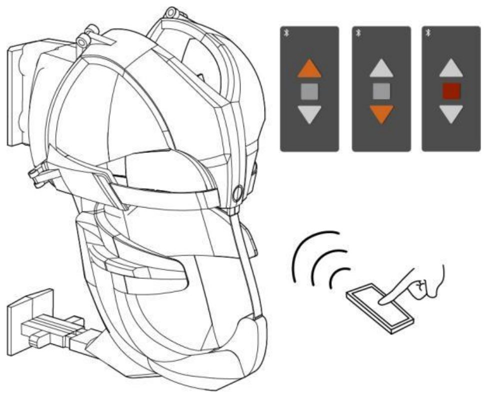


Figure 26 Display of device operation.

a Source: self-made.

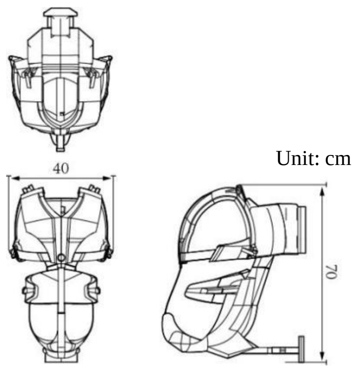


Figure 27 Three views.

a Source: self-made.

4. POWER ENERGY SELECTION

4.1 Application Prospects of Lithium Batteries

Lithium batteries have high energy density, which means they can store more electricity in a relatively small volume and weight. This makes lithium batteries an ideal choice for portable electronic devices, electric vehicles, and other fields, providing longer usage time and higher performance. Moreover, the self discharge rate of lithium batteries is relatively low, allowing them to maintain charge even when not in use for a long time. This makes lithium batteries perform well in situations that require long-term storage or periodic use, which caters well to the working environment of climbing systems. In addition, lithium batteries have almost no memory effect, which means they can maintain good performance without completely discharging or charging. Users can charge or partially discharge the battery at any time without worrying about affecting its lifespan or performance.

And it has a high charging and discharging rate, which can complete charging or release electricity in a short time. This is very important for applications that require frequent charging or require a large amount of energy output in a short period of time. Compared with ordinary batteries, lithium batteries have a relatively longer lifespan and can withstand multiple charging and discharging cycles while maintaining good performance. In addition, they usually have high safety and stability, and are less prone to safety issues such as overheating and explosions. Compared to traditional nickel cadmium batteries, lithium batteries do not contain harmful substances such as heavy metals, so their impact on the environment is relatively small. With the increasing emphasis on environmental protection and sustainable development, lithium batteries have obvious advantages in replacing traditional batteries.

Overall, lithium batteries have many advantages such as high energy density, low self discharge rate, no memory effect, fast charging and discharging ability, long lifespan and stability, and environmental protection, making them the preferred battery type in various application fields. Therefore, replacing ordinary batteries with lithium-ion de-intercalation power batteries will become the most important and inevitable development trend, and this lightweight, convenient, safe, and inexpensive new energy will also be favored by more people. Choosing lithium batteries as the main energy source is also a trend in modern development.

5. MATERIAL SELECTION

5.1 Materials for Wearing Parts

Due to the special usage environment of the device, the wearing part should be made of wear-resistant, breathable, and quick drying materials. Therefore, the materials for the wearing part will be selected based on the mountaineering backpack, which is generally divided into polyester, nylon, and Cordura materials.

- Polyester: Wear resistant, durable, and elastic. Mountaineering bags mainly use 600D or 1000D polyester.
- Nylon: Lightweight and quick drying, the mountaineering bag mainly uses 420D Oxford nylon or 1000D nylon.
- Cordura: Lightweight, quick drying, wear-resistant, and elastic, making it the most ideal material for hiking bags, but with high cost, it is often used in branded hiking bags.

Considering cost and practicality, nylon material has a relatively high cost performance ratio.

5.2 Materials for Shell

In terms of mechanical casing materials, it is hoped to find materials that are lightweight but have high strength, because these materials can better enhance product performance advantages and make our products more suitable for application. Coincidentally, composite materials seem to be able to meet the demand. At present, many composite materials in the market have gradually banned metal materials. [1]

After investigation, it was found that carbon brazing composite materials ("Figure 28") have a wide range of applications, such as automotive carbon fiber products, ball clubs, bicycle accessories, and so on. It has advantages such as good toughness and light weight. Since the emergence of carbon fiber composite materials in the 1960s, it has been found that they have very high mechanical properties and are very lightweight. In actual research and development, it will be found that it also has advantages in high temperature resistance, corrosion resistance, friction resistance, conductivity, electromagnetic shielding, and other series. The products produced through carbon fiber composite materials have high designability, high structural stability, and creep resistance, making carbon fiber composite materials one of the best lightweight, high-strength materials, and have high advantages compared to titanium alloys. Applying carbon fiber composite materials to the wearable parts of products will significantly improve their performance.

After a series of studies, people's understanding of materials and the use of energy has become more thorough, clarifying the general ideas for material

1. Baidu - Application of Carbon Brazing Composite Materials

and energy selection in the subsequent device design.

Figure 28 Carbon brazing composite materials.

a Image source: https://tse1-mm.cn.bing.net/th/

6. CONCLUSION

There is very important practical significance to overcome the various difficulties and dangers that tower cranes encounter during use, facilitate staff climbing, reduce work difficulty, ensure personal safety of workers, improve work efficiency, and install climbing equipment in tower cranes to help staff climb tower cranes.

Through innovative ideas and designs on the machine structure and appearance of the climbing device, the external design of the device has been roughly completed, and the operation and usage process of the device have been clarified. Although there are still many issues with the details and feasibility of the device, such as the lack of a clear and detailed mechanical structure, and the lack of corresponding experiments on whether the device can operate normally in various complex construction environments, the entire product is still in the simple model stage. It is believed that these issues will be addressed in subsequent design research, and in the near future, this product will provide important guarantees for the safety of tower crane construction.

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