Design of multilayer Marine transportation tooling for large wind turbine blades

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Abstract. Aiming at the long-distance cross-sea transport of offshore wind turbines blades, and proposing a solution of multilayer marine transportation through the analysis of the characteristics and requirements of marine transport of blades. Designing a multilayer marine transportation tooling for the large wind power blade GW90 which is 90 meters long and weighs 32 tons. Designing the main structure to solve the problem of complicated and large load on blades, designing the connecting structure to solve the problem of stable connection between each multilayer tooling, designing the position structure to solve the problem of installation and positioning of blades and tooling, and using the finite element analysis method to verify the design. Finally, a multilayer offshore transportation tool with safe structure, clear function and feasible design is proposed, which provides new exploration and ideas for the efficient and safe transportation of offshore wind power blades.

1. Introduction
In today's world, wind energy is one of the most important renewable resources, which have been widely used and accounted for 16% of the world's renewable energy output. Compared with onshore wind power, offshore wind power has advantages such as more stable wind power, higher fan utilization rate and larger installed capacity of single machine. But offshore wind turbines are far from the coast with an average distance of 43.5 kilometers, large ships are required to carry them across the sea. At the same time, large wind power blades are long in length, heavy in weight and large in wind-borne area, so waves and ship movement have great influence on the stability of blade transport. Therefore, the efficient and safe offshore transport of large wind power blades has a very important impact on the construction and development of offshore wind power. This paper proposes a multilayer Marine transport scheme for large wind power blades based on the analysis of blade transport mode, and design a Marine tooling which take the GW90 blade as the object. Then, simulate and
verify the design by finite element analysis method. Finally, this paper provides a new way to explore and train of thought for the offshore transport of large wind turbine blades.

2. Analysis of blade transport mode
With the continuous development of wind power, the wind turbine is marching towards the direction of large scale and intelligence. As one of the most important power parts of wind turbines, blades are constantly lengthening and widening, which length is close to 100 meters. Moreover, the blades are made of composite materials and the manufacturing process is complicated. Therefore, the blades is very fragile and could not be assembled on the installation site, but can only be transported as a whole. Hence, the transportation of large blades has always been the focus and problem of the industry.

At present, the most common method of land transport is by truck. According to the characteristics of blade transport, the transport vehicle is specially modified to adapt to different length of blade and reduce the impact and pressure produced by the blade. In addition, for the rugged and complex road conditions of mountainous areas, adopt blade transport vehicle with rotary platform which hold the blades in the air. The blade transport vehicle with rotary platform is used to transport the ultra-long blade, and the hydraulic device is used to adjust the blade attitude to avoid obstacles and crosswise wind, thus effectively solving the difficult problem of wind power blade transport in mountainous areas. When the wind field is close to the railway, the railway transportation is not only less risky for long-distance transportation, but also can transport multiple sets of blades at one time, which greatly reduces the cost.

Compared with land transport, marin transport has certain particularity and complexity, mainly reflected in the following aspects: 1) The single transport capacity of ships is much larger than that of land vehicles and also not be conditioned to road restrictions. Multiple sets of wind turbines can be transported from mainland to wind farms at one time. 2) Offshore winds are much stronger than onshore winds, the blades will be affected by heavy wind and wave load during transportation. 3) The stability of ship transport is worse than that of land vehicles, the wind and wave load of ship will transmit a large impact to the blades. 4)The single layer transport mode which commonly used covers a large area and has low transport efficiency.

According to the characteristics of offshore wind turbine blade transport, multi-layer transport mode is proposed to improve the efficiency of blade transport. In spite of this, there are some problems with multilevel transportation: 1) The weight, wind, wave and impact acceleration load of multiple blades will stack with each other in multi-layer transportation, so the requirements for the strength and stiffness of the transport tooling are much greater than those for single-layer transport. 2) The multi-layer transport tooling needs a solid and reliable connection structure to combine multiple single-layer tooling together and ensure the overall stability of the tooling, and the connection structure is more vulnerable to damage than the main structure. 3) The end face diameter of large blades is more than 3 meters, and the blade length is more than 90 meters, it has higher requirements on the positioning accuracy, installation and disassembly convenience of the blade. According to the above problems and requirements, the design of multi-layer offshore transport tooling for large wind power blades is carried out to meet the requirements of multi-layer offshore transport of blades.

3. Analysis of marine transport conditions
In this paper, GW90 wind turbine blade is taken as the object for design, and blade parameters are shown in Table 1.

| Table 1 Blade Parameters |
|--------------------------|
| **Length** | **End face diameter** | **Weight** | **Barycenter position** | **Windward area** |
| 90m         | 3.7m                  | 32.038t    | 26.73m From the end face | 117.54m²        |
Coordinate system is shown in Fig. 1. Concretely speaking: 1) The center of blade end face is the origin of coordinates. 2) The direction of the blade’s root points to the tip is X+ direction. 3) The plumb direction is Z+ direction. 4) The right hand coordinate system determines the Y+ direction.

In the process of transportation, the load on the blade mainly includes: gravitational load of blade, wind and wave load, and acceleration load of ship. The above three loads are analyzed respectively.

3.1. Gravitational load of blade
The blade length is up to 90 meters and the total weight is 32.038 tons. The blade was divided into 450 differential regions with a length interval of 0.2 meters, and calculate the gravitational load distribution. According to the characteristics of blade structure, two-point support is adopted. The point 1 is located at the end face of the blade, that is, the blade root tooling, and the support point 2 is close to the blade tip, that is, the blade tip tooling, which apart 56 meters. Taking the blade end face as the fulcrum, the total moment of the blade is calculated.

\[
T = \sum_{i=1}^{450} G_i \times (0.2i - 0.1) = 8392.42 \text{ kNm}
\]

According to the moment equation, the concentrated forces of the two support points can be obtained as

\[
F_{z1} = 164.11 \text{ kN}
\]

\[
F_{z2} = 149.87 \text{ kN}
\]

3.2. Wind and wave load
Wind load is calculated according to GB5009-2012 Load Code for Building Structures.

\[
W_K = W_0 \beta_z \mu_z \mu_s
\]

Concretely speaking, \(W_0\) is fundamental wind pressure, and hurricane’s speed is 32.6 meters per second, so \(W_0 = 0.7 \text{kN/m}^2\). \(\beta_z\) is wind vibration coefficient and \(\beta_z = 1.0\). \(\mu_z\) is shape coefficient of wind load and \(\mu_z = 1.4\). \(\mu_s\) is height coefficient of wind load and \(\mu_s = 1.52\). Then the uniformly distributed wind load acting on the windward face of the blade is

\[
W_K = 1.5 \text{kN/m}^2
\]
The windward surface of the blade was divided into 450 differential regions with a length interval of 0.2 meters. The windward area, wind load and moment relative to the blade end face are calculated respectively. The windward area is

$$A_w = \sum_{i=1}^{450} A_i = 117.54 m^2$$

(6)

Total wind load of blade is

$$F_w = 176.31 kN$$

(7)

The total torque of the blade wind load relative to the end face is

$$T_w = 4807.75 kN\text{m}$$

(8)

According to the moment equation, concentrated force of supporting point 2, that is the blade tip tooling, is

$$F_{w2} = \frac{T_w}{56} = 85.85 kN$$

(9)

concentrated force of supporting point 1, that is the blade root tooling, is

$$F_{w1} = F_w - F_{w2} = 90.46 kN$$

(10)

In addition, for the part of the blade less than 2 meters, the splashing force of the waves also exists in the transportation process, the total force is 45kN acting on the root of the first blade.

3.3. Acceleration load of ship

According to the Safety Code for Cargo Stowing and Securing from THE International Maritime Organization (IMO), the blades are affected by the ship's acceleration during transport under hurricane: The forward direction of the ship is the maximum acceleration in the X direction of the blade is $a_x=3.8$ m/s$^2$. The lateral direction of the ship is the maximum acceleration in the Y direction of the blade is $a_y=7.4$ m/s$^2$. The vertical direction of the ship is the maximum acceleration in the Z direction of the blade is $a_z=9.2$ m/s$^2$.

The blade acceleration load is transferred to the blade root and tip tools, the concentrated force generated by acceleration is calculated by the moment equation respectively.

$$F_{ax1} = 121.74 kN$$

(11)

$$F_{ay1} = 123.92 kN$$

(12)

$$F_{ay2} = 113.16 kN$$

(13)

$$F_{az1} = 154.06 kN$$

(14)

$$F_{az2} = 140.69 kN$$

(15)

3.4. Total load

According to the above calculation results, the Marine loading parameters of the blades are shown in Table 2.

|                | X direction | Y direction | Z direction |
|----------------|-------------|-------------|-------------|
| Root Tooling(point 1) | 121.74kN    | 259.37kN    | 318.17kN    |
| Lip Tooling(point 2)    | 199.02kN    | 290.56kN    |             |
4. Marine transportation tooling design
According to the functional requirements and key problems to be solved for the multi-layer Marine transport tooling, and combined with the loading conditions of maritime transport. The main fixture structure, connection structure and installation positioning structure are designed and shown by fig. 2.

Fig. 2 Three layers of Marine transport tooling

4.1. Main structure design
During the multilayer marine transportion, the gravitational load, wind and wave load, acceleration load of the blades are superimposed on each other. There is a very high requirement for the strength and stiffness of the main structure, because it has tremendous concentration force, especially bottom layer tooling not only bear the enormous weight of multiple blades, but also bear the enormous torque generated by the upper blades.

Fig. 3 Root Tooling Main Structure

Root tooling main structure is shown by fig. 3. It is mainly divided into two parts: pedestal and pillar. The middle part of the pedestal is box-like structure which be welded by 12 steel plate according to the outer cut square twenty-four-quadrilateral of the blade end face circle, and welding cruciform stiffeners under the steel plate increases structural strength and stiffness. Both sides of the pedestal are reinforced pillar which be welded together with the middle part, and arrange 5 layers of stiffeners internally according to the force distribution of the tooling. In addition, there are also working platforms, storage boxes and other auxiliary facilities welded on the pedestal. There are two pillars with the same function and symmetrical structure, which docked on to the left and right hands. The pillars adopt the welded box structure, and has 7 layers of reinforcement plates arranged inside according to the force distribution. The top and bottom of the pillars are connecting structures, and the
top hook also satisfies the hoisting function. During the marine transportation, the pillars are connected with the pedestal of the upper and lower root toolings respectively, thus realize the multi-layer transportation function of tooling.

![Fig. 4 Tip tooling Main Structure](image)

Tip tooling Main Structure is shown by fig. 4. Tip tooling make a two-point support to the blade with the root tooling together and be made up of upper and lower frame. The tip tooling frame is mainly made of square pipe with layer welding, and connect each layer by angle parts. In addition, d-rings are welded to the frame for lifting and strapping.

4.2. Connection structure design

The fixture connection structure is one of the key factors to realize the multi-layer transport of blades. Compared to the welding type of the main structure, the connection structures are more vulnerable to damage caused by wind wave and acceleration load during transportation, and the installation of tooling in the open air should be as simple and convenient as possible. Hence, the design of connection structure not only ensure the fastness and stability of tooling connection, but also Consider the convenience and feasibility of tooling installation and disassembly.

![Fig. 5(a) Connection between pillar and same layer pedestal](image)

![Fig. 5(b) Connection between pillar and upper layer pedestal](image)

Connection between pillar and same layer pedestal is shown by fig. 5(a). The positioning between pillar and same layer pedestal is carried out through the rectangular slot, and connect with twelve M16 bolts on each side to make the pillar and pedestal a whole. Connection between pillar and upper layer
pedestal is shown by fig. 5(b). The positioning between pillar and same layer pedestal is carried out through the rectangular slot with slant, and connect with fixed pin and fixed plate to secure the pillar and pedestal.

4.3. Installation and positioning structure

The blade is subjected to large wind wave load and acceleration load during transport, therefore, the special positioning structure is designed to ensure the reliability and safety of blade transportation. The blades are connected to the root tooling by 5 positioning structures, each with an interval of about 45°, which is shown by fig. 3. Due to different installation positions, positioning structures are divided into two types: Location structure 1 is shown in fig.6(a), which installed in root pedestal on both sides to strengthen pillars. Location structure 2 is shown in fig.6(b), which installed in root pedestal central chamber structure.

![fig.6(a) Location structure 1](image)

![fig.6(b) Location structure 2](image)

The positioning structure is divided into two parts, one part is attached to the blade: Firstly, the positioning sleeve is arranged on the blade stud, and then the pressing plate and the sleeve are tightly combined and fixed by the nut, so that the blade is connected with the positioning structure as a whole. The other part is connected with the pedestal: Firstly, the positioning slot on the pressing plate is passed through the pedestal stud, and the pressing plate can slide along the orientation of the positioning slot to adapt to the vane deflection of ±0.5°, finally, the two are fixed by the nut.

5. Marine transport simulation

The multi-layer Marine transportation tooling is complicated, so the calculation could not be done by rigid body dynamics alone. Therefore, finite element method is used in this paper to simulate the tooling structure and verify the feasibility of the design.

5.1. Finite element model

Based on the three-dimensional model of the multi-layer offshore transport tooling, the finite element model is established according to the basic requirements of finite element modeling in combination with the operating conditions and structural characteristics of the tooling: 1) The overall size of the offshore transport tooling is nearly a hundred meters, and the distance between the blade root and tip tooling is 56 meters, which is not suitable for the overall modeling. Therefore, the modeling and analysis of the blade root and tip tooling are carried out respectively. 2) The tooling is mainly made of welded square pipe, and the overall size is large, so the finite element model is mainly constructed by
using the form of surface element. 3) On the premise of ensuring the accuracy of finite element calculation results, the bolts in the structure are simplified and the welding positions in the structure are treated with common joints. Finite element model is shown by fig.7.

![fig.7(a) Root tooling Finite element model](image1)

![fig.7(b) Tip tooling Finite element model](image2)

Marine transport tooling is mainly made of Q345 steel welded, therefore, the material parameters of the finite element model are set according to the material parameters of Q345, which is shown by table 3.

|            | elasticity modulus | Poisson ratio | density     | yield strength |
|------------|--------------------|---------------|-------------|---------------|
|            | 206GPa             | 0.3           | 7850kg/m²   | 345MPa        |

5.2. Boundary conditions

Marine loading parameters of blades is shown by table 2, the boundary conditions of blade root and tip tooling were set respectively.

Boundary conditions of root tooling: 1) The root tooling model is constrained on the underside to simulate the tooling is fixed on the ship deck. 2) The Y-direction load is applied to the tooling’s left position which contact with the blade of each layer to simulate wind and wave load, as well as, Y-direction Marine acceleration load. 3) The X-direction load is applied to the contact position between each layer of tooling and the positioning plate to simulate the acceleration load in the X direction of marine transportation, and the forward is X+ direction, and the backward is X- direction. 4) The Z-direction load is applied to the load at all positions where the tooling and the blade were in contact, simulating the gravity and Z-direction acceleration load. 5) The acceleration field of the tooling was applied to simulate the marine acceleration load and gravity of the tooling. 6) Add contact pairs between pillars and pedestals of each layers.

Boundary conditions of tip tooling: 1) The tip tooling model is constrained on the underside to simulate the tooling is fixed on the ship deck. 2) The Y load is applied to the lateral position of each layer to simulate the action of wind and waves in Y+ direction and Y- direction respectively. 3) The Z-
direction load is applied to the vertical position of support frame to simulates gravity and Z- direction marine acceleration loads. 4) The acceleration field of the tooling was applied to simulate the marine acceleration load and gravity of the tooling.

5.3. Analysis result
According to the above boundary conditions, the finite element calculation of blade root and tip tooling was carried out respectively. The analysis result of root tooling is shown by fig.8. The maximum stress is 280.53mpa, which locate at the interlayer junction, and less than the allowable stress of the material. The maximum displacement is 59.88mm, which locate at the top of the third layer of tooling.

![fig.8 Analysis result of root tooling](image)

The analysis result of tip tooling is shown by fig.9. The maximum stress is 353.053mpa, which locate at diagonal support frame welding position. There is the stress concentration caused by drastic change of shape, as the material Q345 used in the tooling is plastic material, it has no influence on the strength of structural parts under static load, generally, the corresponding processing technic is used to eliminate the influence of stress concentration. The maximum displacement is 12.62mm, which locate at the top of the third layer of tooling.
6. Conclusion

1) This paper analyzes the transport requirements and methods of large wind power blades, sorts out the particularity and complexity of offshore transport, proposes the transport mode of multi-layer blades, and analyzes the difficulties and problems that need to be solved in multi-layer transport.

2) Aiming at the problems and requirements of multilayer Marine transportation, design the transport tooling which taking GW90 wind turbine blades as the object. The design mainly includes the main structure for bearing the main load of the blade, the connection structure design for the stable connection between the multi-layer tooling, and the installation and positioning structure design for the blade installation and positioning.

3) According to the complicated working conditions in the multi-layer Marine transportation of blade, determining the boundary conditions of finite element analysis. Establishing the analysis model according to the basic requirements of finite element modeling and carrying out the structure simulation analysis of the tooling. The analysis results show that the offshore multi-layer transport tooling structure meets the strength requirements and the design is feasible.

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