Measurement and Analysis of Structural Stress Changes of River-Sea Direct Ships on Specific Routes During Navigation

Jiang Lei1a*, Yongbo Ji1b, Jianyong Xu2c

1China Waterborne Transport Research Institute Beijing, China
2Wuhan Rules & Research Institute of China Classification Society Wuhan, China

a* Corresponding author: jianglei@wti.ac.cn, 
bjyb@wti.ac.cn

Abstract—In order to study the dynamic response and motion response characteristics of the river-sea direct ship’s structure under different conditions and waves during the navigation of the river section and the sea section, a container ship on the route from Wuhan to Yangshan was tested by using dynamic strain gauge, motion sensor and wave height gauge. The test points are arranged in the front and rear end walls of the cargo tank area, the middle section of the ship, the corner of the hatch, the intersection of the longitudinal bulkhead and the inner bottom plate and other areas that may produce high stress. The test results show that the wave environment conditions of the route area of the Yangtze River estuary are more complex, and the response components of the ship structure are more variable, which is quite different from the response of the structure in the Yangtze River Estuary; the predicted value of wave load is similar to the measured value, and the predicted bending moment is slightly larger than the measured bending moment.

1. INTRODUCTION

By implementing "point-to-point" direct transportation, river-ocean direct transportation can effectively improve the transportation efficiency and reduce logistics costs and cargo damage. The construction specifications of ships designed for direct river-ocean route are slightly less demanding than those of similar ocean vessels. The construction cost can be reduced by about 20%, thus having economic advantages [1]. In 2017, the Ministry of Transport issued a series of policies and measures on advancing the development of specific river-to-sea vessels on specific routes, promoting the development of specific river-to-sea vessels from Yangtze River to Shanghai Yangshan Port Area [2]. However, due to lack of operation and test data, some shipowners remain dubious, slowing the process of popularization and application of specific river-to-sea ships. In order to build up experience summarization and scientific demonstration, optimize and improve ship structural performance, discuss the mechanism of structural stress changes during the course of direct sea-going ships on specific routes, provide reference for the design of similar vessel types and the formulation of related targets, it is necessary to carry out actual vessel testing analysis.

2. VESSEL PARAMETERS

The ship type is a container ship. Its length is 117.2m; the beam is 22m; the depth is 9.2m; the draft is 4.5m, and the designed container capacity is 636TEU and 8642 deadweight tons.
3. Test

3.1. Test System
Test instruments include EX1629 dynamic strain gauge (48 channels), bridge box (24 channels), multi-degree-of-freedom motion sensor (Dynacube), strain gauges (unidirectional sheet, bidirectional sheet, tridirectional sheet), three-core coaxial shielded cable, Wave height instrument (PY-IIG), special laptop for data collection, etc.

3.2. Test Principle
Structural dynamic response test principle: the resistance strain gauge is fixed on the measured component. When the component is deformed, the strain gauge will also deform so that its resistance value changes, causing the voltage in its loop to change. Through the dynamic strain gauge, the strain on the structure can be obtained by measuring and recording the corresponding voltage changes [3]. The movement of the hull is measured by a multi-degree-of-freedom motion sensor, thus the movement is directly collected and recorded by the computer. Wave environment test principle: put wave height meter into the wave, send the test signal through GPS, use computer to record and analyze to get real-time wave environment.

3.3. Layout of measuring points
The stress measurement points are mainly distributed in the front and rear walls of the hull cargo area, the mid-section of the ship, the hatch corners, the intersection of the longitudinal bulkhead, the inner bottom plate, and other areas where high stress may occur [4], a total of 28 measurement points. The motion sensor is set up at the center of the hatch on the starboard shelter.

| Table 1 Structural Stress Measuring Points |
|-------------------------------------------|
| **Area of the Measure Point** | **No. of measure point** | **Specific Location** | **Notes** |
| Hatch Corner Area | S1 | Midpoint of the arc of the starboard rear corner, 10mm from the arc edge | Vertical |
| | S2 | Midpoint of the arc of the starboard rear corner, 10mm from the arc edge | Horizontal |
| | S3 | Midpoint of the arc of the starboard rear corner, 10mm from the arc edge | 45° direction |
| | S4 | Rounded end of starboard rear corner, upper deck surface | Vertical |
| | S5 | Rounded end of starboard rear corner, upper deck surface | Horizontal |
| | S6 | Midpoint of the arc of the port front corner, 10mm from the edge | Vertical |
| | S7 | Midpoint of the arc of the port front corner, 10mm from the edge | Horizontal |
| | S8 | Midpoint of the arc of the port front corner, 10mm from the edge | 45° Direction |
| | S9 | Rounded end of port front corner, upper deck surface | Vertical |
| | S10 | Rounded end of port front corner, upper deck surface | Horizontal |
| **Rear Cargo Compartment Front Wall** | S11 | Port side hatch coaming side transverse deck strip center deck upper surface | Vertical |
| S12 | Port side hatch coaming side transverse deck strip center deck upper surface | Horizontal |
| S13 | Port side hatch coaming side transverse deck strip center deck upper surface | Vertical |
| S14 | Port side hatch coaming side transverse deck strip center deck upper surface | Horizontal |
| S15 | Upper surface of the deck in the middle longitudinal section of the center of the transverse deck strip of the hatch coaming | Horizontal |
| **Boathouse Area** | S16 | Side panel of the port side main deck is 10mm away from the side | Vertical |
| S17 | Side panel of the port side main deck is 10mm away from the side | Horizontal |
| S18 | Side panel of the port side main deck is 10mm away from the side | Vertical |
| S19 | Side panel of the port side main deck is 10mm away from the side | Horizontal |
| S20 | Port side hatch coaming side transverse deck strip center, upper deck surface | Vertical |
| S21 | Port side hatch coaming side transverse deck strip center, upper deck surface | Horizontal |
| **Front Cargo Compartment Rear Wall** | S22 | Middle longitudinal section of the center of the transverse deck strip of the hatch coaming, upper deck surface | Horizontal |
| S23 | Port side hatch coaming side transverse deck strip center, upper deck surface | Vertical |
| S24 | Port side hatch coaming side transverse deck strip center, upper deck surface | Horizontal |
| **Insole Area** | S25 | Upper surface of inner bottom plate in No. 2 cargo compartment, 100mm away from the starboard longitudinal bulkhead | Vertical |
| S26 | Upper surface of inner bottom plate in No. 2 cargo compartment, 100mm away from the starboard longitudinal bulkhead | Horizontal |
| S27 | Middle longitudinal section in cargo compartment 2, upper surface of inner floor | Vertical |
| S28 | Middle longitudinal section in cargo compartment 2, upper surface of inner floor | Horizontal |
3.4. Test conditions
This test combined with the testing vessel’s operating route to carry out the test of five working conditions, and collected and recorded its structural stress and vessel’s movement status. The weather was overcast and the ship was fully loaded. The specific working conditions are as follows.

| Case Number | Testing Time | Speed (kn) | Course | Wave Direction | Measurement Duration |
|-------------|--------------|------------|--------|----------------|----------------------|
| Case 1      | 17.29.16     | 7.8        | 195°   | Along the waves | Around 20 Minutes    |
| Case 2      | 18.21.51     | 9.2        | 175°   | Stern wave 20°  | Around 20 Minutes    |
| Case 3      | 19.24.09     | 7.6        | 209°   | Stern wave 14°  | Around 20 Minutes    |
| Case 4      | 19.48.31     | 10         | 150°   | Stern wave 45°  | Around 20 Minutes    |
| Case 5      | 22.02.46     | 8.2        | 302°   | First Oblique Wave 73° | Around 20 Minutes    |

| Testing Time | Significant Wave Height | Maximum Wave Height | Average Period | Measurement Duration |
|--------------|--------------------------|---------------------|----------------|----------------------|
| 20.34.04     | 0.71 m                   | 1.32 m              | 2.92 s         | Around 20 Minutes    |

4. TEST RESULTS AND ANALYSIS
4.1. Yangluo Port in the city of Wuhan to Waigao Bridge in the city Shanghai (River Section)
The statistical analysis results of the average value and maximum value of the mid-arch, sagging and full amplitude of the strain at each measuring point during the navigation of the river section are shown in Figure 1 below. The strain values of each measuring point are very small, and the maximum strain value of the full amplitude appears at the measuring point of S16, which is 7.344με; the strain values of the longitudinal measuring points of each deck near the intermediate cargo hold are relatively close.

![Figure 1. statistical results of average and maximum structural strain in river section](image)
4.2. Yangtze Estuary to Qushan (sea section)

The statistical analysis results of the average and maximum strain at each test point under the five test conditions in the course of navigation in the sea section are shown in Figure 2 below. It can be observed comparatively from the figures that the hull structure strain is larger under the working conditions, and the maximum strain measurement point appears at the port S20 measurement point, and the maximum value of the strain is 97.243με. The strain values at the corresponding measurement points S11 and S13, S12 and S14, S16 and S18, S17 and S19 at the left and right sides are relatively close. The strain values at the measuring points at the front corner is higher than that at the rear corner. Compared with the longitudinal strain value at the fore, the strain level at the corner is lower.

![Figure 2](image1.png)

4.3. Motion measurement and analysis

While measuring the structural strain response, the motion response of the hull (rolling, pitching and acceleration in x, y, and z directions) was measured. Following is the comparison of the results of the measured rolling values under various operating conditions: the maximum roll angle appears at working condition five, but the average rolling angle of working condition one is the largest, which is consistent with the maximum structural strain level of working condition one.

![Figure 3](image2.png)
4.4. Verification of Wave Loads

When the actual ship is sailing on a specific route, the measured additional bending moment value of the wave:

4.4.1. Measured Bending Moment

Based on the structural drawings of the ship’s aft section, the structural characteristics of the aft section were calculated. The section modulus at the hatch coaming and the strength deck were 2.901 and 3.598, respectively, and the steel elastic modulus was 206 GPa.

Through this test, the maximum dynamic stress of the deck appears at the S20 measuring point under working condition 1. The maximum strain of the center arch is 56.455 με; the maximum strain of the sag is 44.907 με; and the maximum strain of the full amplitude is 97.243 με. That is, the maximum dynamic stress of the deck is 56.455×0.206 MPa = 11.63 MPa.

It can be obtained by conversion that the maximum wave additional bending moment value that the real ship is subjected to is:

\[ M = W \times \sigma = 2.902 \times 11.63 \times 10^6 N \cdot m = 33750.3 KN \cdot m \]

4.4.2. Wave Load Forecast

According to the numerical prediction calculation, the design wave load of the midship arch of the test ship is 35320 KN\( \cdot \)m.

4.4.3. Comparison of Wave Loads

The comparison between the predicted wave bending moment of the ship and the measured wave bending moment is shown in the table below. According to the result comparison, the predicted value of the wave load is equivalent to the measured value, and the predicted bending moment is slightly larger than the measured bending moment.

| Wave Bending Moment                      | Value     |
|------------------------------------------|-----------|
| Actual Bending Moment (kN\( \cdot \)m)   | 33750.3   |
| Predicted Bending Moment (kN\( \cdot \)m) | 35320     |
| Predicted Bending Moment/Measured Bending Moment | 1.047 |

5. Conclusion

In this direct river-to-ocean vessel test, a single voyage test was completed, which was conducted in the river section and the sea section, and the maximum stress amplitude was calculated based on the maximum strain value of the test amplitude. See Figure 4 for details.

Through the analysis of test data, the following conclusions can be obtained:

Figure 4. Full amplitude of maximum stress
1) From the full amplitude of the maximum stress of the ship in all working conditions, it can be seen that the structural stress response and motion response of the first working condition are larger than those of other working conditions. The maximum full amplitude stress value is 20.032MPa (S20 measure point). That is to say, when the container ship is in a smooth wave, the surface stress on the side of the hatch coaming area of the ship's hull area is the largest, which is particularly worthy of the local structural strengthening.

2) The wave environment conditions in the sea area of the Yangtze River estuary are more complicated, and the hull structure should have more response components. Therefore, the strengthening of the hull structure should consider the wave environment and wave load in the sea.

3) By comparing with the wave load forecast results, it can be known that the wave load forecast value of the direct shipping container ship on a specific route from river to the ocean is equivalent to the actual measured value result, which further confirms the reliability of the forecast value.

ACKNOWLEDGMENT
The authors gratefully acknowledge China Classification Society for its contribution and support in testing scheme, equipment and data testing

REFERENCES
[1] J. Luo Xiaofeng. New trend of research and development and specifications of vessels for specific river to sea route. China Ship Inspection, 2018.09: 82-85.
[2] S. Ministry of Transport. Opinions on Advancing the Development of Direct Shipping on Specific Routes Between River and the Ocean. 2017.4.11.
[3] J. Ma Jian, Qian Shaoming, Hu Xiaxia. Test and analysis of the changes of structural stress during the launch of ship airbag. Ship Engineering, 2008.03:16-18.
[4] D. Zhang Wenting. Large-scale container ship structural strength analysis and node optimization research. Harbin: Harbin Engineering University, 2017.