

# Global Strength Evaluation of High-speed Catamaran by Sectional Load Calculation under Quartering Sea and Lattice Beam Modelling

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## Abstract

In the application of naval architecture and ocean engineering, various geometric configurations require calculating of stability and strength in still water due to safety. Traditionally calculation of sectional load by integrating along longitudinal direction; for transverse load calculation for catamarans this integral method will not be proper. In this study, the wetted surface of floating body is discretized into a number of triangular panels, and the hydrostatic pressures on all the triangles are accurately calculated by analytical methods. The wave induced displacements at fore/aft bodies and port/starboard sides are treated as virtual masses located at centers of buoyancy. The section load can then be calculated as the weight distribution is provided, that is, the load in four directions: shearing, compression, bending and torsion, can be used as a subsequent structural analysis or strength verification. The present method assesses the pitch-connecting moment of a catamaran under quartering sea condition, i.e. the torsion of the centerline longitudinal section, and compared with Rules. The simplification of the cross-deck structure of a catamaran represented by lattice beam structure is then derived and verified the deflection and stress distribution against full ship finite element model.

**Keyword:** Catamaran, transverse loads, pitch connecting moment, cross-deck strength.

## 1. INTRODUCTION

The two pillars of ship safety are stability and strength, and there are strict standards in the MARPOL and Class rules. The ship must meet the requirements under various loading conditions and damage conditions [1] to ensure that the hull does not overturn, and the target of the strength check is the allowable stress of the section, which is calculated by dividing the section load by the section modulus [2], as shown in Figure 1. In terms of longitudinal strength, the section modulus within 0.4 times the length of the midship consists of the hull longitudinal structural material, including: hull shell plating, side longitudinal, deck, inner bottom, longitudinal bulkhead, etc.; hence the section modulus is determined when the midship section is designed. The allowable stress is determined by the material and its safety factor, which is  $175 \text{ N/mm}^2$  for steel. Therefore, the only variable left to determine if the longitudinal strength of the hull is sufficient or not is the section load. The transverse bending moment and shear force are usually separated into still water bending moment/shear force, and the wave bending moment/shear force. The latter is determined by empirical or normative formula, and the former is directly calculated according to the shape and weight distribution of the hull.

Direct calculation of stability and strength that mentioned above is under the still water condition. To analyze the section load, the ship's external elongated shape can be used to divide the hull into multiple transverse sections, and calculate the still water characteristics of each two-dimensional section. Such "2.5-dimensional" calculations are reliable and have been widely adopted by using the trapezoidal rule or the "Simpson's rule" [4] to integrate will cause numerical errors, especially in the case where the section characteristics change drastically, such as the longitudinal section of the catamaran. Furthermore, the two-dimensional features are combined into three-dimensional features based on iso-section characteristics or linear changes. This study attempts to directly derive the analytical solution of still water performance in three-dimensional space and extend to wave condition. The pitch connecting moment is calculated as well as the structural response by utilizing either full finite element model or simplified lattice beam model.

## 2. NUMERICAL METHODS

### Sectional Load Calculation

Define the hull coordinate system: positive X for the stern to the bow, positive Y for the centerline to the port and positive Z for the baseline to the deck. The origin point of the coordinates is on the baseline of the after perpendicular. There are three inputs described in Figure 1. First, the hull surface is discrete as a triangular surface mesh, required to be a simple closed topology. Second, the section is defined as the transverse (Y-Z plane) or the longitudinal direction (X-Z plane), and the position of the neutral axis on each section is given. Third, the weight distribution includes mass, transverse/longitudinal spans, center of gravity position, center of gravity vertical height, etc. In order to achieve static balance, first calculate the total weight and center of gravity of a given weight, and balance with buoyancy and floating center. After completion, the static pressure distribution under the equilibrium posture is obtained; with the above weight distribution, the section load is obtained after the section cutting. The static buoyancy model, section definition, and weight distribution model are briefly described below.

Now consider a stable floating body in still water. According to the Archimedes' principle, the weight of the discharged water is buoyancy, and the volume center of the discharged water is the floating center. While the weight and the buoyancy have the same value, their direction is opposite. And they act on the same vertical line. At the same time, the horizontal plane intersects the closed floating body at the waterplane, and the method discretizes the floating body geometry into a triangular mesh, as shown in Fig. 2 (left). Therefore, the ways of the intersection between a triangle and the waterplane is as shown in Figure 2 (middle). The quadrilateral case in the two vertices submerged condition can be divided into two sub-triangles by connecting the diagonal vertices. Therefore, all submerged surface can be disassembled into triangles, and the hydrostatic pressure and force center of each triangle are calculated by equations (1), (2), and (3) [5]. Total buoyancy and buoyancy center can be obtained by summation the whole triangles' characteristics.

$$\vec{r}(u, v) = \vec{r}_0 + \vec{r}_{01}u + \vec{r}_{02}v \quad (1)$$

$$\vec{P}_j = \iint_A (\rho g r(u, v)_z) \vec{n}_j dA_j = \rho g r_{c_z} \vec{n}_j A_j \quad (2)$$

$$\vec{r}_f = \frac{1}{12r_{c_z}} (9r_{c_z}\vec{r}_c + r_{0_z}\vec{r}_0 + r_{1_z}\vec{r}_1 + r_{2_z}\vec{r}_2) \quad (3)$$

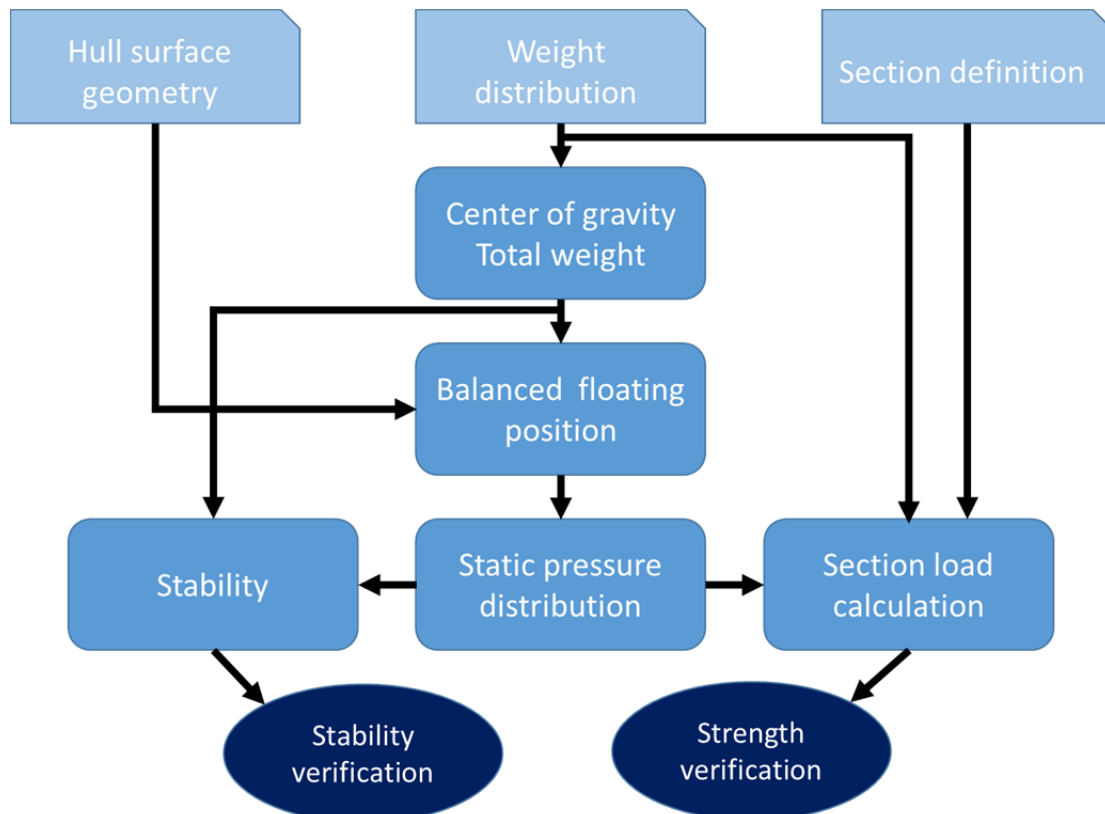
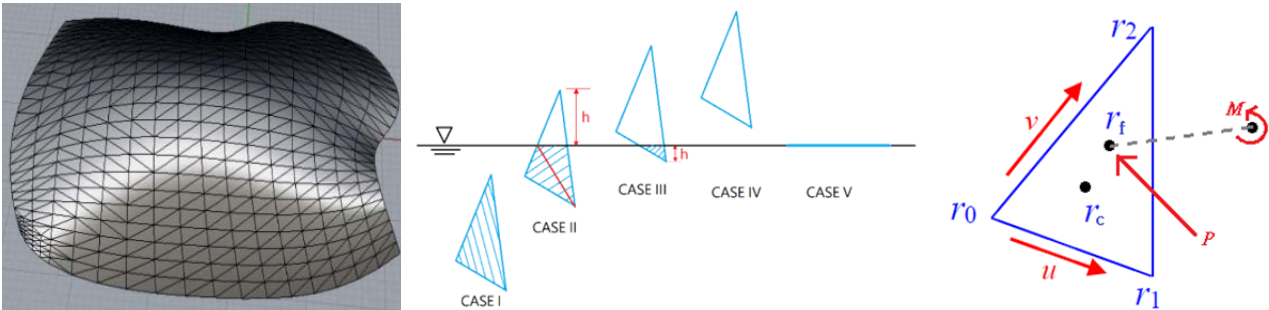


Fig. 1 Flow chart of still water characteristic calculation

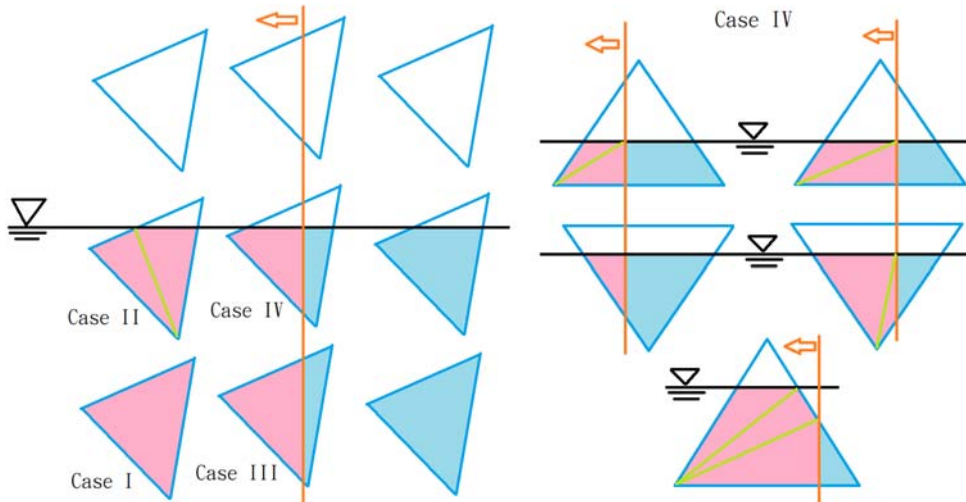
Now consider the triangular buoyancy acting on the load of a certain section, it is necessary to cut the waterplane and section of the triangle at the same time, as shown in Figure 3 (left). There are nine conditions, of which only the red area needs to be added to the target section, so there are only four conditions that need to be considered: completely submerged and completely in the same section, part of submerged and completely in the same section, completely submerged and part in the section, and part of submerged and part in the section. The second and third conditions are cutting the triangle once, and the method to calculate the hydrostatic pressure of the sub-triangles is described in the previous section. In the fourth situation, it is further divided into five double cuts. The pentagon is cut into three sub-triangles from the connection between the original triangle vertex submerged and the two intersections after two cuts, as shown in Figure 3(right). Therefore, all the surfaces that fall on the normal side of the section can be disassembled into triangles, and the hydrostatic pressure and force center of each triangle are calculated by equations (1), (2), and (3).

On the weight distribution side, since the ship structure usually follows the longitudinal and transverse structures, its weight distribution generally follows this architecture, as shown in Figure 4. The weight distribution model of the method is a rectangular surface weight, the two sides are aligned with the X and Y directions, and the center of gravity is  $Z_g$ . The center of gravity position  $X_g$  and  $Y_g$  are specified in the rectangle. If the gravity center is not in the rectangular center, that is, the uneven density, the partial weight and the center of gravity on the normal side are calculated by the proportional constant density distribution method.

The analysis of the ship structure is often limited to the two directions of the transverse section and the longitudinal section, as shown in Figure 4. The transverse section is the Y-Z section at different longitudinal positions, and the normal direction is toward +X. The longitudinal section is the X-Z section at different transverse positions, and the normal direction is toward +Y. Each section specifies a coordinate on its surface, which is the neutral axis, that is, the center of rotation under the hydrostatic pressure and weight. For the transverse section, the force direction ( $F_x, F_y, F_z$ ) represents the compressive force, the transverse shear force, and the vertical shear force. Moments ( $M_x, M_y, M_z$ ) represents the torsion, the vertical bending moment, and the transverse bending moment. For the longitudinal section, the force direction ( $F_x, F_y, F_z$ ) represents the rake force, the split force, and the vertical shear force, respectively. Moments ( $M_x, M_y, M_z$ ) represents the transverse bending moment, the pitch connecting moment, and longitudinal bending moment [6].



**Fig. 2** Surface discreteness(left) and the static pressure model(middle and right)



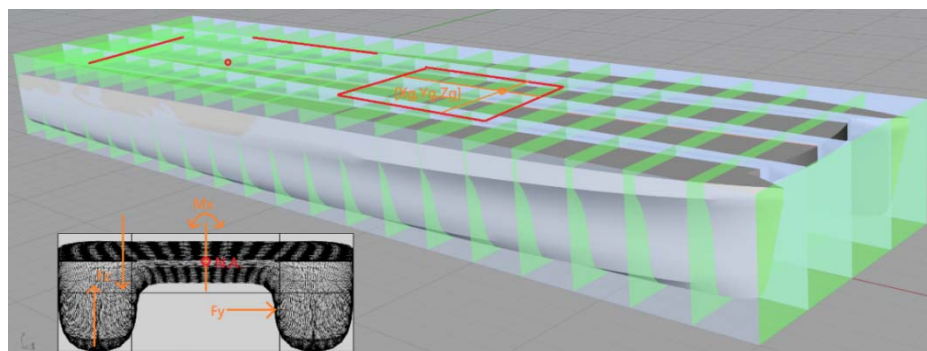
**Fig. 3** Triangle, waterplane, and section geometry relationship

## Structural Model of Catamaran

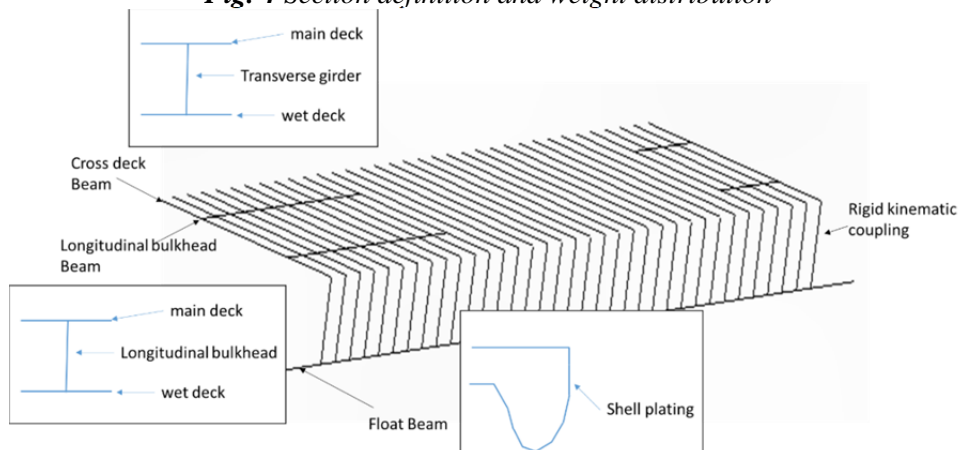
The principle dimensions and the number of meshes and nodes in the method mentioned above are shown in Table 1. The full Finite Element Method (FEM) model of this catamaran has 233428 nodes and 252612 elements as shown in Figure 7. Since the target is the strength at the connection of the float and the Cross-deck, the super structure has been removed under the conservative consideration. Since building a full model of a catamaran takes too long, it is necessary to construct a rapid and reliable method of simplifying the detailed FEM model. There are a lot of simplified methods to approach the structural response at the Cross-deck and float connection of the catamaran. In this study, an advanced method based on BV's rule is used[7]. Like other methods, the whole Cross-deck is divided into multiple transverse beam elements, and the float is simplified into a longitudinal beam. The section modulus of these beams are decided by the actual structural component. The section modulus of the Cross-deck beam is decided by the thickness of the upper deck, the wet deck, and the bulkhead, while the float beam is determined by the shell plate geometry and part of main deck from the basal theory of material mechanics. Additionally, the longitudinal bulkhead of the real ship is also modeled as an I-beam. As shown in Figure 5, the rigid element is used to connect the Cross-deck and the float beam. The constrains is set as follow: the port side is totally fixed, the longitudinal midship is pin supported, and the x-deflection and the z-rotation is fixed at the starboard side, as shown in the blue triangles in Figure 6. The red arrow in Figure 6 is the uniform loading condition, which transforms the moment into a series of positive Z-direction forces and negative Z-direction forces. The same pitch-connecting moment is loaded on the detailed model and the simplified model described above, and these two loading conditions are both using uniform distribution.

**Table 1.** Principle dimensions and geometry discreteness

Length of waterline, $L_{WL}$ (m)	39.5
Displacement, $\Delta$ (tonne)	169.57
Breadth, B(m)	10
Float width amidship, $B_W$ (m)	2.6
Depth, D(m)	3.4
Draught, d(m)	1.33
Block coefficient, $C_B$	0.56
Number of meshes	6986
Number of nodes	3495



**Fig. 4** Section definition and weight distribution

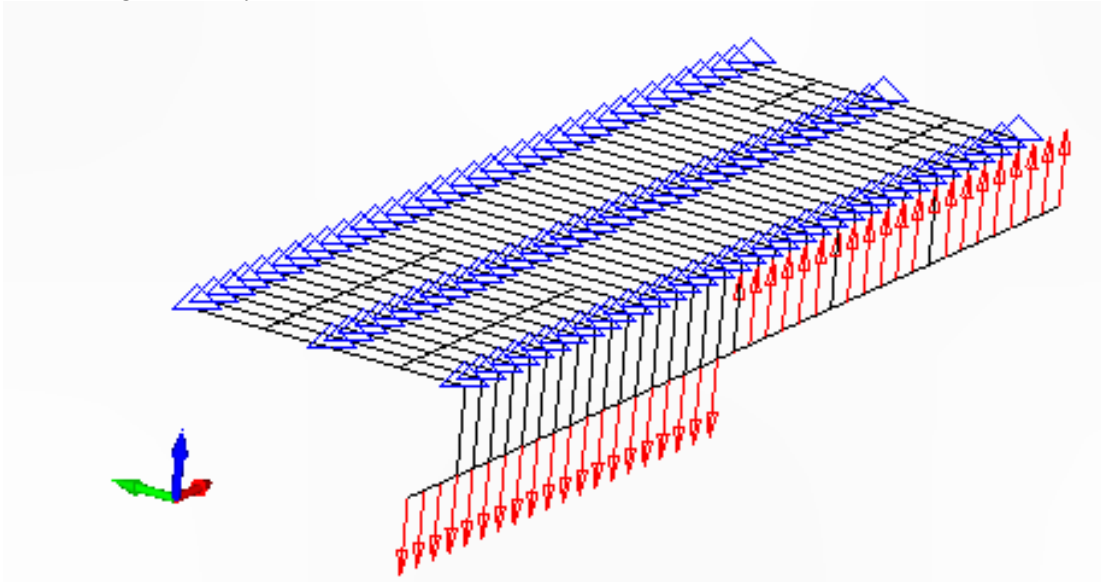


**Fig. 5** Simplified beam model of catamaran

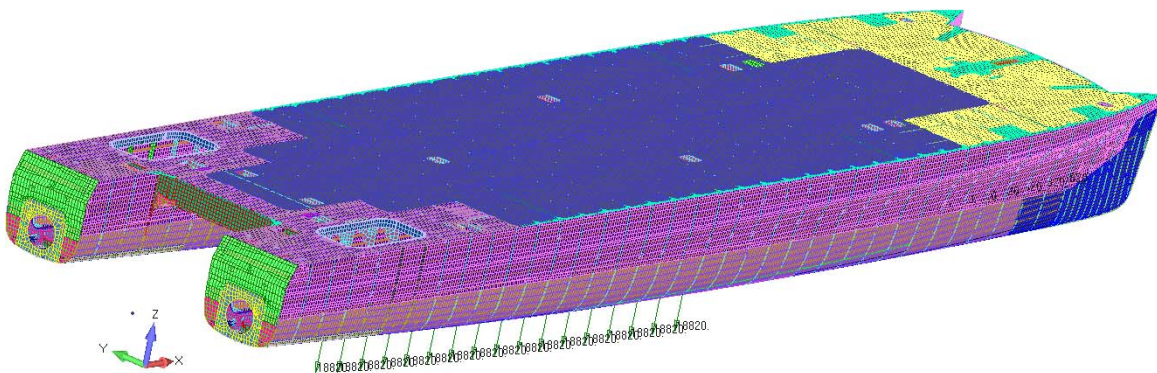
### 3. PITCH CONNECTING MOMENT IN WAVES

Following the method which is mentioned above, we calculate the pitch-connecting moment and the structural response of the catamaran as verification. First, use the shell plating geometry and the static wave which can cause the maximum pitch-connecting moment to obtain the sunk volume difference under the still water and the static and regular wave condition, as shown in Figure 8 and equations (4) and (5). Since the section load calculating program mentioned above can only input the weight distribution, the difference of the volume is converted into four mass blocks according to Archimedes' principle. These mass will be added at the forward-port, forward-starboard, after-port, and after-starboard side individually, then the pitch-connecting moment can be identified. If the sunk volume in still water is larger than in static regular wave at one of the sides, the positive mass will be added at that side and vice versa. By the rules[6], there is another way to obtain the pitch-connecting moment, as shown in equations (6) and (7). The pitch-connecting moments under different wave height obtained from two ways are compared with each other, as shown in Figure 9 (right).

Because of the dynamic pressure influence, there is an about 9% error between the CR rule and the calculation result. In order to fully understand the cause of the moment when the wave height is zero, the weight distribution is set to symmetry for the plane  $y=0$ . The four mass blocks at the four corners all share the same value. The forward-port and the after-starboard side are positive, while the after-port and the forward-starboard side are negative, as shown in Figure 10(left). In Figure 9(right), it is obviously that when the 0.75 tonnes mass block is added at the forward-port and the after-starboard side, and -0.75 tonnes mass block is added at the after-port and the forward-starboard side, the corresponding pitch-connecting moment is very close to the moment in Figure 9 when the wave height is zero. Thus, the method of loading uniformly at four corner on the FEM model is verified.



*Fig. 6 Constrains and loading condition of simplified model*



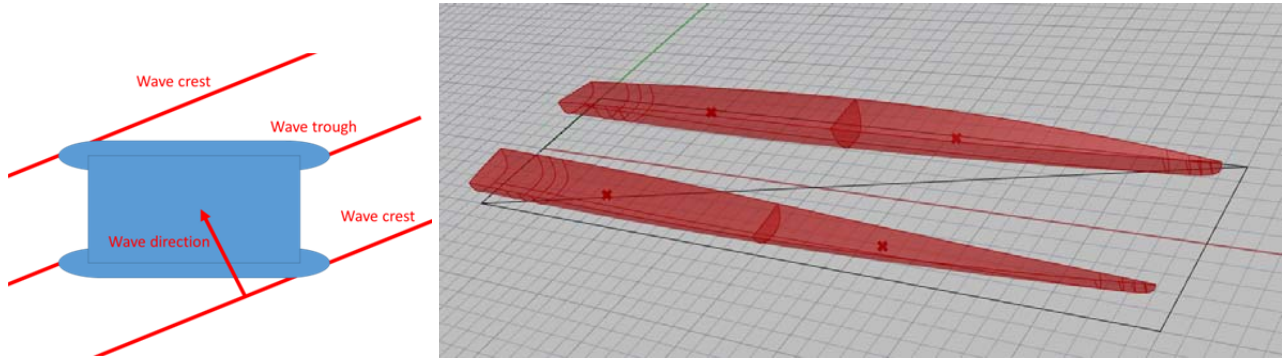
*Fig. 7 Detailed model of the catamaran*

$$\lambda = \frac{2bL}{\sqrt{L^2 + b^2}} \quad (4)$$

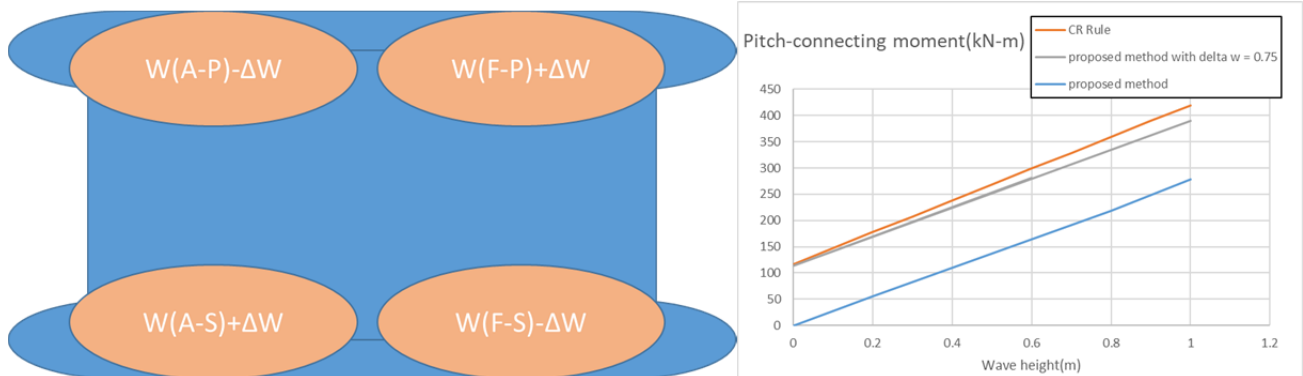
$$\theta = 90^\circ + \tan^{-1} \frac{b}{L} \quad (5)$$

$$a_{CG} = \frac{7.6\tau \times 10^{-6}}{dC_b} \left( 12H_1 + B_w \right) (50 - \beta_{CG}) \left( \frac{v}{\sqrt{L_w}} \right)^2 g \quad (6)$$

$$M_p = \frac{1}{8} \cdot \Delta \cdot L_{WL} \cdot a_{CG} \cdot g \quad (7)$$



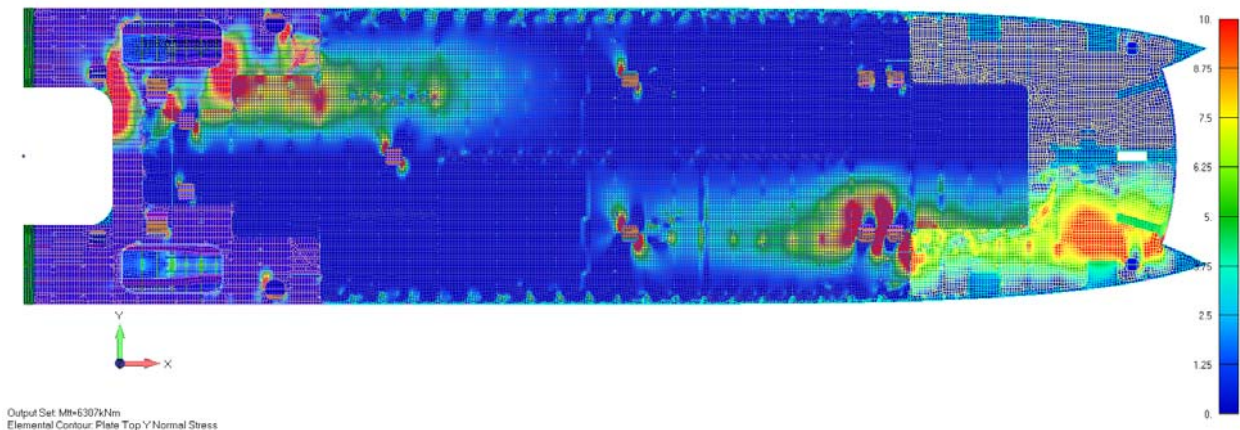
**Fig. 8** Regular static wave to cause maximum pitch-connecting moment



**Fig. 9** Model of adding four masses at four corners(left) and pitch-connecting moment against wave heights (right)

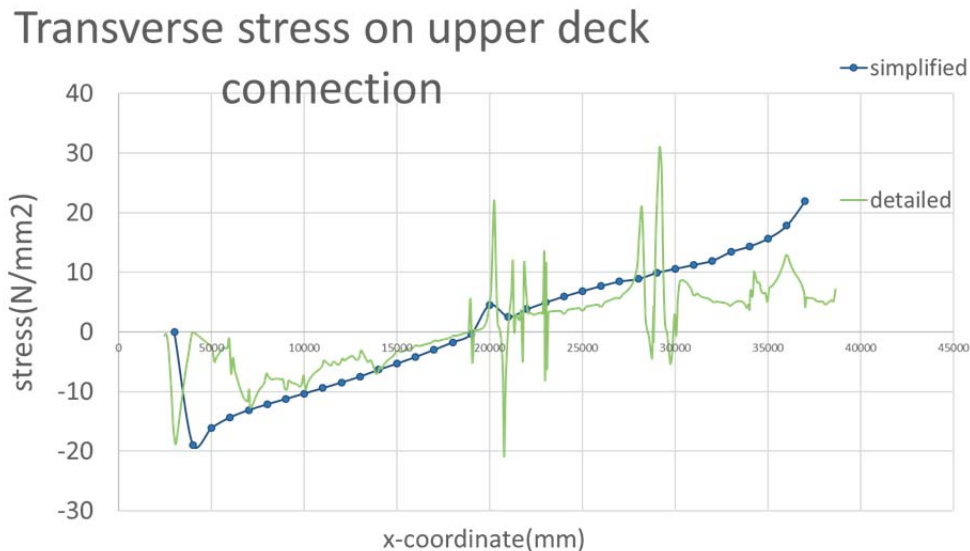
#### 4. RESULTS AND DISCUSSION

Based on the two structural models (full FEM and simplified lattice beam) and the previous calculated pitch connecting moment, uniformly applied on the models, the static and linear structural analyses were performed. This study focuses on the cross-deck structural response, so the transverse stress on the upper deck is shown in Figure 10. The global stress regions are at fore-starboard and aft-port corners, which is considered to be reasonable. However, it is obvious that the local stress distribution concentrated as the influence of local structure discontinuities, such as openings and frames. Compared to the stress longitudinal distribution of the simplified model in Figure 11, it is smooth with similar global tendency as the full model. The hatches on the cross-deck have stress concentration, which can not be resolved in the simplified model.

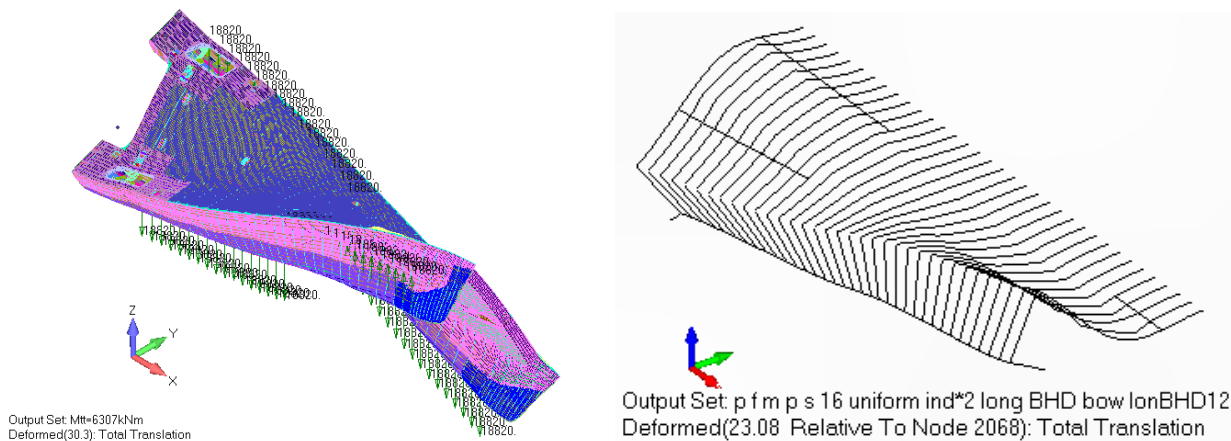


**Fig. 10** Top view of the FEM model with the contour of the transverse stress on the upper deck

Following the results of the stress, the deflection is then compared, as shown in Figure 12, and is expected little affected by the local structural discontinuities. The deflection of the two model at the connection of the float and the cross-deck have been compare with to verify the practicality of the simplified method, as shown in Figure 13. There is a small error between detailed model and the simplified model mentioned above in Figure 13. Therefore, the proposed simplified model can be validated for the global response, while the issue of local stress concentration needs to be treated by details models. Finding a valid way to compare the stress at the connection between two models is an important step in the future.

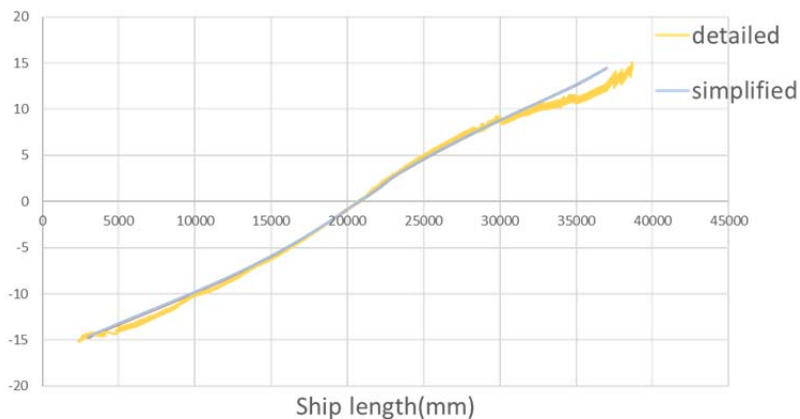


**Fig. 11** Transverse stress on the upper deck of full and simplified models



**Fig. 12** The total deformed view of the detailed model(left) and the simplified model(right)

### Connection z-deflection (mm)



**Fig. 13** Z-direction deflection at float and Cross-deck connection along the ship length

## 5. CONCLUSIONS

This paper proposes a new method to directly calculate the pitch-connecting moment of cross-deck of a catamaran. The wetted surface of floating body is discretized into triangular panels, and the hydrostatic pressures on the panels are calculated by analytical formulation. The wave induced displacements at fore/aft bodies and port/starboard sides are treated as virtual masses. The equivalent design wave for the pitch connecting moment was then defined as the oblique wave direction and this definition was also verified by comparing to Rule values. On the structural part, the cross-deck structure of a catamaran represented by lattice beam structure is built and verified the deflection and stress distribution against full ship finite element model. The global response at fore-starboard and aft-port corners shows good agreement for the two models, which concluded that the validity of the proposed simplified structural approach, while the local stress concentrations at deck openings need to be address separately.

## ACKNOWLEDGEMENTS

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## REFERENCES

- [1] “International Convention for the Prevention of Pollution from Ships(MARPOL)”, Consolidated Edition (2011).
- [2] “Rules for the Construction and Classification of Steel Ships”, *CR Classification Society* (2013).
- [3] Adrian Biran, Ruben Lopez Pulido, “Ship Hydrostatics and Stability”, 2nd Edition, Butterworth-Heinemann (2013).
- [4] Philip J. Davis, Werner Rheinbolt, Philip Rabinowitz, “Methods of Numerical Integration”, Academic Press (1984).
- [5] Jie Tong, Tsung-Yueh Lin, Min-Mei Shih, Jen-Shiang Kouh, “An alternative method for computing hydrostatic performances of a floating body with arbitrary geometrical configurations”, *Ocean Engineering*, Vol.160, 15 July 2018, pp.301-310.
- [6] “Rules for the Construction and Classification of High-speed Craft”, *CR Classification Society* (2008).
- [7] Bureau Veritas, Hull Structure and Arrangement for the Classification of Cargo Ships less than 65 m and Non Cargo Ships less than 90 m, NR600, (2014).