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Finite Element Modelling of Catamaran Structural Behaviour under Hogging and Sagging Conditions

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ABSTRACT

This study presents the structural behaviour of catamaran hulls under hogging and sagging conditions. A comprehensive nonlinear finite element analysis is carried out using ABAQUS software to simulate the structural behaviour of the hull across various configurations. The investigation evaluates the influence of span-to-length (S/L) ratios, frame spacing, and hull lengths on bending moment and tensile strength characteristics. The results reveal that increasing frame spacing reduces the catamaran's structural rigidity, while higher S-to-L ratios or extended lengths significantly enhance ultimate tensile strength and bending moment due to the larger bridge area and increased structural spacing. These findings highlight essential design trade-offs, providing valuable insights for optimising catamaran hull performance in terms of safety, structural integrity, and operational efficiency. This work contributes to advancing the design and analysis of high-performance catamarans, ensuring reliability under various structural conditions.

1. Introduction

In recent decades, the demand for high-speed multihull vessels, particularly catamarans, has significantly increased due to their growing use in both commercial and military sectors. Structural design for these vessels prioritises cost-effectiveness, safety, and weight reduction to ensure efficient operation. To address the inherent uncertainties in such designs, experts recommend the use of structural reliability analysis, which ensures both safety and economic viability, particularly for high-speed catamarans used as car and passenger ferries. This method offers a more comprehensive solution compared to deterministic approaches, effectively balancing operational efficiency with rigorous safety standards, and contributing to the long-term sustainability and success of these vessels [1].

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Expanding on the need for enhanced structural analysis, Fonseca *et al.,* investigated the influence of ship length on vertical bending moments induced by abnormal waves. They analysed containerships with varying Froude numbers and utilised a time-domain seakeeping simulation to solve the nonlinear equations governing the ship's response [2]. Xu *et al.*, performed both experimental and numerical analyses to assess the ultimate strength of inland catamarans subjected to vertical bending moments. Their study utilised a large-scale specimen and finite element analysis to compare experimental results with numerical simulations [3].

Similarly, Liu and Soares [4] proposed that the ultimate strength of ship hull structures subjected to cyclic bending moments may be lower compared to those exposed to monotonically increasing bending moments. This is due to the hull girder experiencing alternating bending moments in both hogging and sagging conditions, which can result in a weakened structural response under cyclic loading. This finding highlights the importance of considering dynamic loading conditions, such as alternating bending moments, when assessing the structural integrity and ultimate strength of ship hulls. Salazar-Domínguez *et al.,* [5] conducted a study analysing a barge midship section using finite element method (FEM) models, taking into account calm water and wave loads. Their results demonstrated that the calculated stress values did not exceed the material's yield strength, ensuring the structural safety of the barge under various conditions. Vu Van Tuyen [6] highlighted that the structural integrity of ship hulls, particularly those with extended service lives, residual stresses, and exposure to critical conditions, is significantly influenced by these factors. The study stresses the importance of understanding the residual strength capacity of the hull girder to ensure the safety of vessels, particularly under severe loading conditions [7,8]. Therefore, further studies are essential to deepen the understanding of the structural behaviours of catamaran hulls, particularly in relation to extreme loading conditions and the complex interactions of dynamic forces.

This paper presents the ultimate strength of catamaran hulls under hogging and sagging conditions using a finite element (FE) analysis approach. Here, the ABAQUS software is employed to achieve its objectives, enabling a detailed analysis of the structural behaviour of catamaran hulls under various loading conditions. In detail, this research investigates the effects of frame spacing, span-to-length (S/L) ratios, and ship lengths on the ultimate limit state. It emphasizes the amidships vertical bending moment caused by wave effects and focuses on evaluating the catamaran's ultimate tensile strength and bending moment. The model employed S4R shell elements with general surface contact and geometry definition and meshing were performed using ABAQUS/CAE. The Simpson's rule, with five integration points through the thickness, was applied for thickness integration, ensuring the development of a reliable finite element model that accurately predicts the catamaran's ultimate strength.

2. Methodology

2.1 Bending Moment Analysis

In ship design, analysing hogging and sagging is an important stage for evaluating hull bending behavior and ultimate strength. Hogging causes upward bending at midship, while sagging results in downward bending, both influenced by loading conditions and wave effects [9,10]. Hogging increases the bending moment at midship, inducing tensile stresses on the upper hull, whereas sagging leads to compressive stresses on the lower hull. Understanding these behaviors is essential for ensuring the ship's structural integrity and safety [11].

To model hogging and sagging conditions, bending moment equations are used to calculate the moment at any section of the hull, as shown in Eq. (1). Nonlinear finite element analysis in Abaqus helps assess the hull's strength and stress distribution under these conditions, providing insights to ensure vessel safety and optimal performance.

$$M = F \cdot d \quad (1)$$

where M is the bending moment at the section, F is the applied force at the section, and d is the distance from the section to the neutral axis.

Additionally, the bending moment in a beam under uniform loading can be determined by the equation:

$$M = \frac{w \cdot L^2}{8} \quad (2)$$

where w is the uniform load applied to the beam, and L is the span length of the beam.

The bending moment (M) can be related to the bending curvature (κ) and the material's Young's modulus (E) through the equation:

$$M = E \cdot I \cdot \kappa \quad (3)$$

Meanwhile, the bending curvature (κ) can be expressed:

$$\kappa = \frac{\varepsilon}{r} \quad (4)$$

where ε is the strain, and r is the distance from the neutral axis of the beam to the point of interest.

To analyze the bending moment involving strain and stress in a beam element use the equation below:

$$M = \int A \cdot \sigma_{\chi\chi} \cdot y \cdot dA \quad (5)$$

where M is the bending moment, $\sigma_{\chi\chi}$ is the normal stress in the x-direction, y is the distance from the neutral axis of the beam to the section being analyzed, and dA is the infinitesimal area element.

Furthermore, to analyse the bending moment in a structure typically employs the strain-displacement and stress-strain relations. The bending moment (M) can be related to the second derivative of the transverse displacement (w) with respect to the coordinate (x) through the equation:

$$M = -D\frac{d^2w}{dx^2}$$

where M is the bending moment, D is the bending stiffness of the section, and $\frac{d^2w}{dx^2}$ represents the second derivative of the transverse displacement.

The above equations are essential for analysing ship structures' bending behavior, assessing their response, and ensuring safety under different loading conditions using the finite element method.

3. Modelling of Finite Element Analysis on 3D Catamaran

3.1 Ship Data

The ultimate strength analysis was conducted based on approved analysis margins from ship classification rules of the American Bureau of Shipping (ABS) and DNV. The study analysed three catamarans with different lengths (25m, 45m, and 65m) and various S/L ratios to investigate the effects of hogging and sagging under different hull separations. The detailed ship data is completely summarised in Table 1.

3.2 Set-up Modelling

In the finite element analysis, 3D shells and beam elements with six degrees of freedom were utilized. Shell elements represented plate and frame components, accounting for in-plane, normal loads, and bending. Beam elements modelled longitudinal stiffeners, providing information on the neutral axis, second moment of area, and cross-sectional area. Various models were created based on the respective ship's particulars.

Table 1
Detailed of catamaran by different length

Parameter	Length waterline (m)		
	25	45	65
Draught (m)	1.421	1.137	1.706
Wetted surface area (m^2)	9.329	7.464	11.195
Volume (m^3)	0.2624	0.2095	0.3152
Displacement (kg)	263.192	210.550	315.835

In this study, the catamaran structure is reinforced with longitudinal stiffeners placed between frames, spaced approximately 0.4 m apart. These stiffeners are of two types: Type 1 (I-bar, 100 × 5 mm) and Type 2 (T-section, 100 × 100 × 5 mm), as illustrated in Figure 1. The finite element simulation examines the ultimate strength of the structure, considering three hull separation ratios (0.2, 0.25, and 0.3), along with variations in frame spacing and length. High Tensile Steel of grade S235Jr is selected as the material for the analysis, with its properties detailed in Table 2.

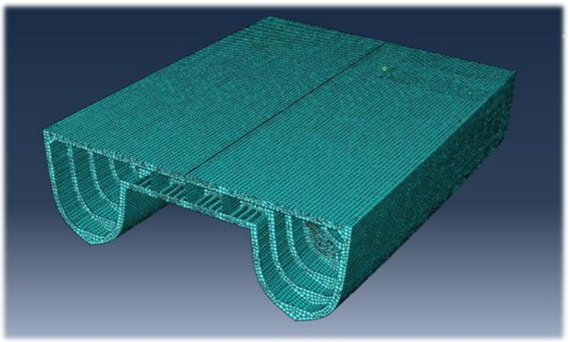


Fig. 1. 3D model of the transverse frames

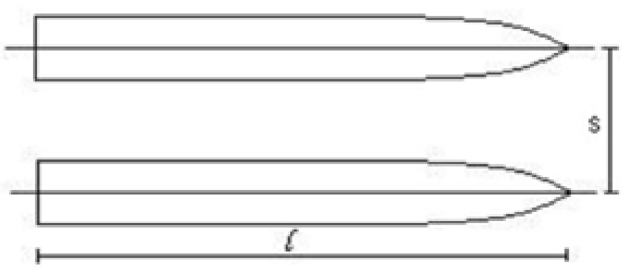


Fig. 2. S/L ratio of catamaran

Table 2
Material Properties of model

Properties	Value
Density	7850 kg/cm^3
Modulus of elasticity	210 GPa
Poisson's ratio	0.3
Yield strength	285 MPa
Density	7850 kg/cm^3

The study examines variations in the catamaran hulls' ultimate strength using the proposed S/L ratio, representing the distance between the two hulls (Figure 2). Table 3 shows the distances in meters from different catamaran lengths.

3.3 Loads and Boundary Conditions

The investigation employs the multi-point constraint method to model boundary conditions, ensuring dependent nodes align with the master node's displacement, positioned at the centroid and moved toward the aft frame. By incrementally controlling dependent nodes based on the master node, the ultimate strength bending moment of the catamaran is calculated (Figure 3). The master node at the structure's end is constrained rotationally along the Y-axis, with a reference angle applied to induce vertical bending and failure.

Table 3
Distance between the two hulls according to length and S/L ratio

Length waterline (m)	S/L ratio	Breadth (m)
25	0.20	5.00
	0.25	6.25
	0.30	7.50
45	0.20	9.00
	0.25	11.25
	0.30	13.50
65	0.20	13.00
	0.25	16.25
	0.30	19.50

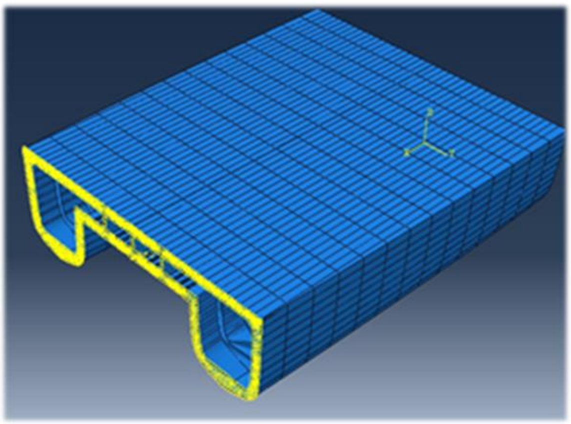


Fig. 3. Boundary condition of model

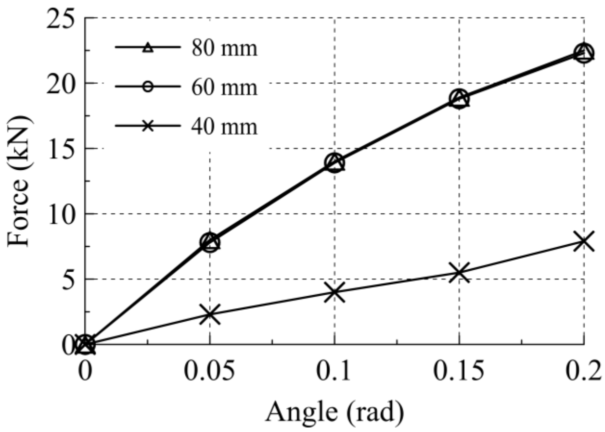


Fig. 4. The different of force between the different types of element sizes

3.4 *Mesh Convergence Study*

A mesh convergence study is performed to determine the optimal mesh for hogging and sagging analysis of the structures (see Table 4 and Table 5). The chosen mesh balances accuracy, computational resources, and reasonable computation time [12,13].

Table 4
Different mesh element size

Length (m)	Mesh element size (mm)		
25	40	60	80

Table 5
Total elements for each size of mesh

Mesh sizes (mm)	Total element
80	108844
60	100160
40	248287

The selected mesh element size for the project is 80 mm. Although mesh sizes between 40 mm and 80 mm reach convergence, the 80 mm size provides more accurate results. Figure 4 shows that the force value for 80 mm is higher than 40 mm, with fewer elements, reducing computational time.

4. Simulation Results

4.1 Bending Moment of Different Frame Spacing

The frame spacing significantly affects a ship's structural strength. The analysis considers three scenarios: minimum, calculated, and maximum frame spacing. Results indicate that maximum frame spacing leads to the highest strain values due to increased free area and fewer support members, resulting in a less stiff structure. Conversely, minimum spacing enhances strength by reducing the moment required to turn the structure, making it stiffer [14]. Table 6 summarises the varying maximum stress and strain values in the elastic region before reaching the plastic region, where material failure occurs. These findings provide valuable insights for optimising ship design and ensuring structural integrity.

Table 6
Values of different frame spacing

Frame spacing (m)	Bending moment (MN.m)	Angle	Stress (Mpa)	Strain	Deflection (m)
0.46	27.6	17.07	278	0.00154	0.114
0.61	27.3	15.87	282	0.00158	0.118
1.00	26.6	14.68	283	0.00138	0.123

The analysis demonstrates that maximum frame spacing leads to the highest bending moment and force on the structure as shown in Figure 5. This is due to reduced support members and increased free area between frames, resulting in higher bending moments and stresses on the hull. Conversely, decreased frame spacing results in a stiffer structure with reduced bending moments. These findings help understand critical loading conditions and offer valuable insights for optimising the ship's design to ensure structural integrity and safety. The results provide essential data for optimising the hull's design and ensuring structural integrity.

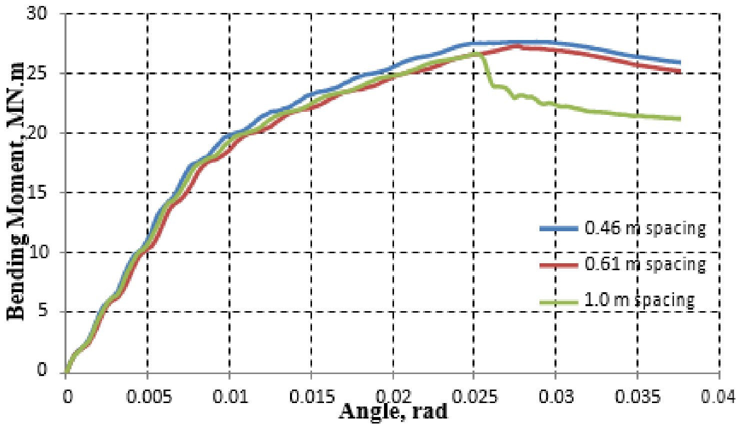
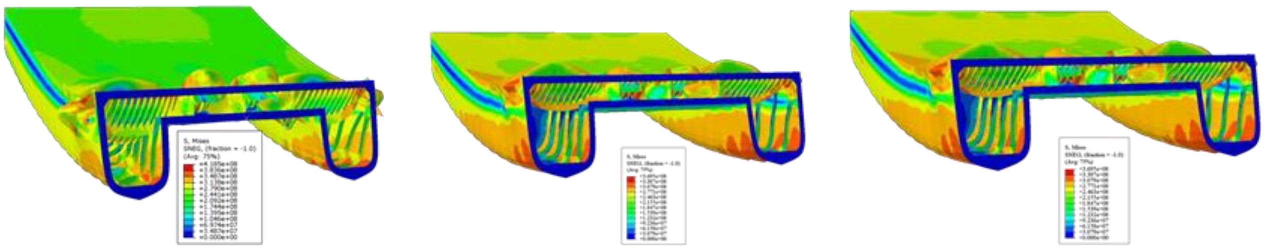


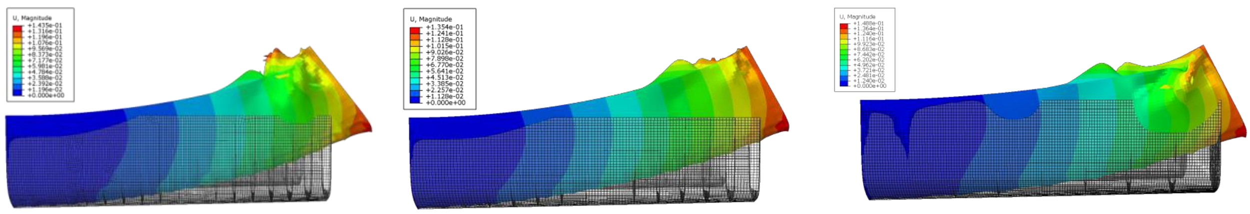
Fig. 5. Bending moment vs angle

The bending moment analysis for three different frame spacings (0.46 m, 0.61 m, and 1.0 m) reveals maximum bending moments at different structure deflections. At frame spacing of 0.46 m, the maximum bending moment occurs at 17° of structure deflection, while for 0.61 m spacing, it occurs at 15°, and at 1.0 m spacing, it occurs at 14.68°. The visualisation results in Figure 6 show similar fracture locations, but the stress values differ for each condition. The structure's deflection is illustrated in Figure 7, providing valuable insights into the hull's behaviour under various frame spacing conditions. The varying frame spacing conditions result in different stress distributions and bending moments along the hull structure. Increased frame spacing leads to higher bending moments and stresses due to fewer support members and larger free areas, as shown in Figure 7(c). Conversely, decreased spacing creates a stiffer structure with reduced bending moments, as closely spaced frames offer increased support [15]. This analysis addresses critical loading scenarios, refining ship design to enhance structural integrity and safety during operations.



(a) (b) (c)

Fig. 6. Visualisation in frame spacing (a) 0.46 m (b) 0.61 m (c) 1.0 m



(a) (b) (c)

Fig. 7. Deflection in different frame spacing (a) 0.46 m (b) 0.61 m (c) 1.0 m

4.2 Ultimate Tensile Strength at Various S/L Ratios

The analysis extends to include various hull separation ratios, also known as S/L ratios, in the calculation of frame spacing. Three S/L ratios (0.20, 0.25, and 0.30) are used to predict the ultimate tensile strength and bending moment under hogging and sagging conditions. Figure 8-11 presents the bending moment and ultimate strength of the high-speed catamaran for different S/L ratios during these conditions. This comprehensive study allows for a better understanding of the hull's behaviour under varying S/L ratios and critical loading scenarios, contributing to the optimisation of the catamaran's design for structural integrity and safety.

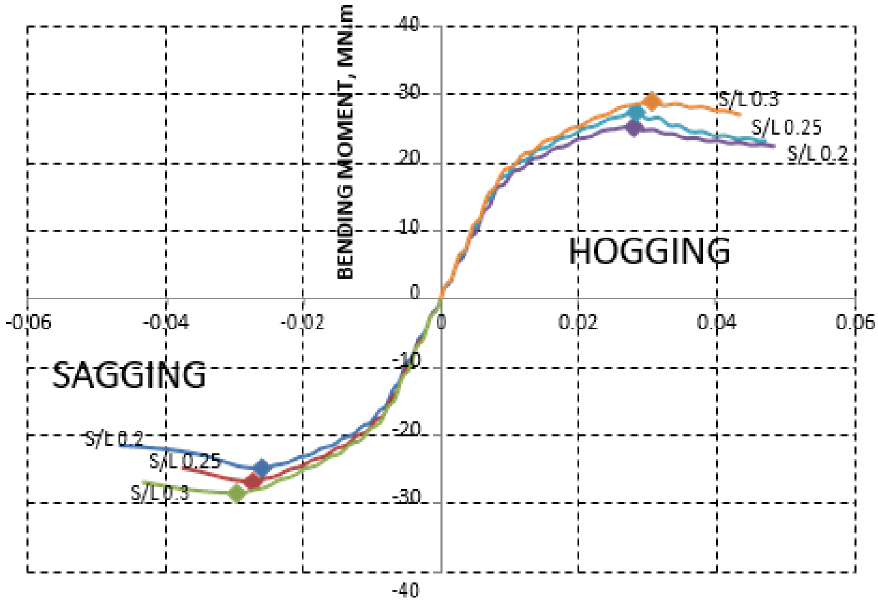


Fig. 8. Bending moment of S/L ratio in sagging and hogging condition

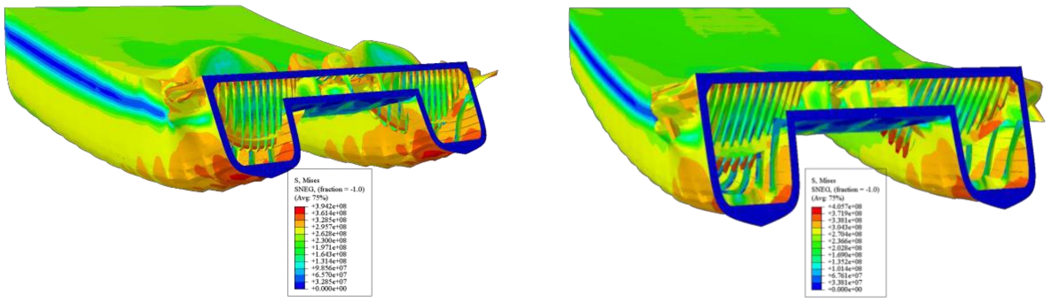
When the S/L ratio increases in the catamaran structure, the bending moment values also increase under both sagging and hogging conditions. These values are presented in Table 7 for both conditions.

Table 7
Bending moment of S/L ratios in sagging and hogging condition

Description	Sagging			Hogging		
S/L ratio	0.20	0.25	0.30	0.20	0.25	0.30
Maximum bending moment (MN.m)	25.2	27.3	28.9	25.3	27.5	29.1
Force (kN)	22.48	26.04	27.50	31.28	28.90	30.55
Deflection (m)	0.109	0.112	0.126	0.257	0.252	0.242
Ultimate tensile strength (MPa)	305	324	330	345	341	329

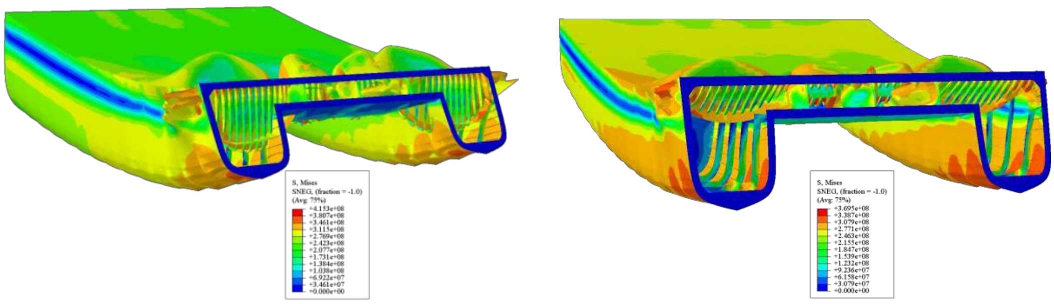
Figures 9 and 11 show the ultimate strength under hogging and sagging conditions. In sagging, the highest S/L ratio exhibits superior ultimate tensile strength at 330 MPa, while in hogging, the S/L ratio of 0.20 shows the highest tensile strength at 345 MPa. The force at the midship region exceeds that at the aft section. As the force increases, the bending moment rises, as seen in Table 7, due to insufficient support in the aft and forward sections, leading to higher gravitational forces at these points.

The variation in the graph plotted for both conditions is similar, where the S/L ratio of 0.30 records the highest force during both sagging and hogging conditions. When the structure fails in either condition, there is a drop in force, and the bending moment reaches its final value.



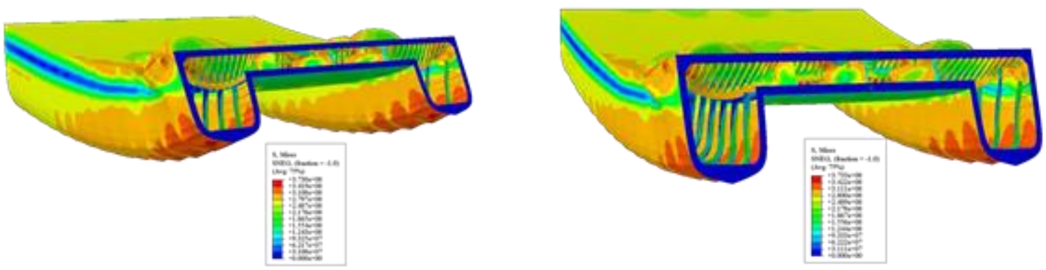
(a) (b)

Fig. 9. Visualisation in S/L 0.20 (a) Hogging and (b) Sagging



(a) (b)

Fig. 10. Visualisation in S/L 0.25 (a) Hogging and (b) Sagging



(a) (b)

Fig. 11. Visualisation in S/L 0.30 (a) Hogging and (b) Sagging

4.3 Bending Moment in Different Length of High-Speed Catamaran

From the simulation, three different catamaran lengths were analysed to study the ultimate tensile strength and bending moment of the structure under a fixed ratio condition. The frame spacing was kept constant at 0.61 m for all structures. Figure 12 illustrates the bending moment results for the different lengths. As shown in Table 8, the structure with a length of 65 meters experienced the highest bending moment, measuring 151 MN·m, along with an ultimate tensile strength of 401 MPa. Additionally, the bending moment increased significantly with each computational time step.

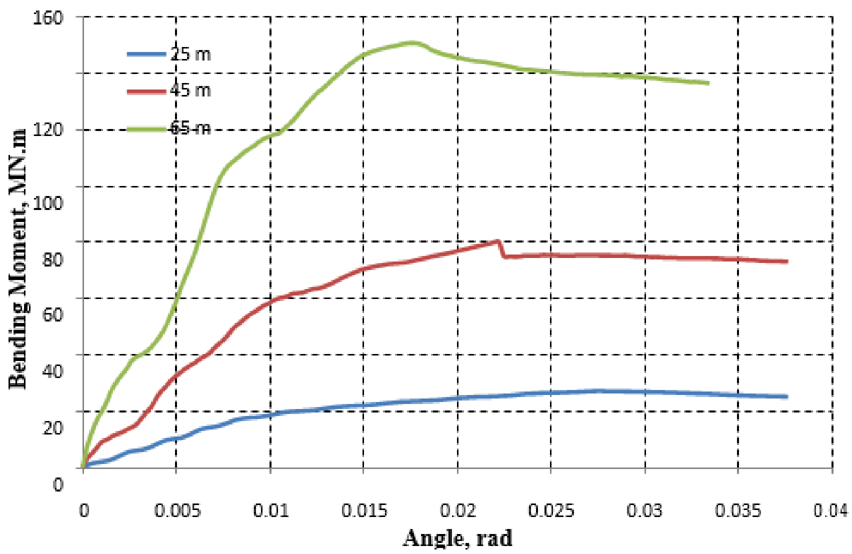


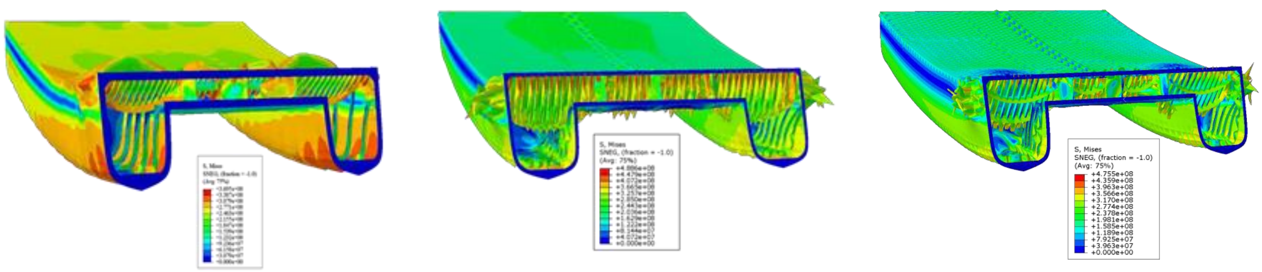
Fig. 12. Bending moment vs displacement angle

Table 8
Bending moment in different length

Description	Sagging			Hogging		
Length (m)	25	45	65	25	45	65
Maximum bending moment (MN.m)	27.5	83.4	154.4	27.3	80.2	151
Force (kN)	22.48	30.48	19.21	26.04	30.29	19.01
Deflection (m)	0.280	0.586	0.682	0.112	0.177	0.217
Ultimate tensile strength (MPa)	341	367	451	321	348	401

The maximum bending moment for a 25 m structure occurs at a deflection angle of 15.87°, with a value of 27.3 MN·m. When the length increases to 45 m, the maximum bending moment occurs at a deflection angle of 12.72°, with a value of 80.2 MN·m. The highest bending moment is observed at a length of 65 m, where the value reaches 151 MN·m at a deflection angle of 10.31°. From these values, it can be concluded that as the length increases, the failure occurs at lower deflection angles, and the bending moment increases, provided the frame spacing of the structure remains constant.

In a high-speed catamaran with a length of 25 m, a force of 26.04 kN is required to reach the maximum bending moment. When the length increases to 45 m while maintaining the same frame spacing, the force increases by nearly 80% to 30.29 kN. However, when the length increases to 65 m, the force decreases to 19.05 kN, despite producing a significantly higher bending moment. Figure 13 shows the visualisation result of stress in different lengths.



(a) (b) (c)

Fig. 13. Visualisation result of stress in different length

5. Conclusions

This study aims to analyse the bending moment and ultimate strength of a catamaran subjected to hogging and sagging conditions. The investigation is conducted through successful simulations performed using ABAQUS. A global finite element (FE) model is developed to evaluate the effects of varying frame spacings, different span-to-length (S/L) ratios, and various catamaran lengths. The findings are summarized as follows:

- The analysis reveals that increasing frame spacing reduces the catamaran's structural rigidity, resulting in lower ultimate tensile strength and bending moment capacity.
- Increasing the S/L ratio, while maintaining constant frame spacing, raises both bending moment and ultimate tensile strength due to the larger catamaran bridge area.
- Extending a high-speed catamaran's length increases bending moment and tensile strength due to the larger area and greater spacing between structural members.

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