Development of A High-Speed Aluminum Ferry with Floating Frames

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Abstract

This paper presents the results of a three-part investigation on the suitability of using hull panels with alternating fixed and floating frames for a 30-40 knot aluminum catamaran ferry. In Part I, prototype 4.6-m x1.8-m bottom hull panel with alternating frames is analyzed numerically and physically tested. The corresponding finite element analyses of the panel and test results are in good agreement. The results show that the floating frame hull panel design is a feasible structure for an aluminum catamaran. In Part II, the floating frame structure was then used for a 33-knot, 250-passenger aluminum catamaran ferry designed to meet the ABS High Speed Craft rules. A midship section of the catamaran hull was analyzed using the finite element method. The results show that the alternating floating frame structure is in compliance with the ABS rules stress allowables. In Part III the problem of stress concentration and fatigue is examined.

INTRODUCTION

One of the critical design elements in high-speed ferries is the use of lightweight, high-strength hull structure, typically constructed of aluminum (Lee, 1996), (Kennell, 1998). In a large number of high-speed aluminum crewboats, (Spencer, 1975), (Henrickson, 1982) the hull panels are stiffened with longitudinals and alternating fixed and floating frames (frames welded on top of longitudinals). In addition to weight savings, the shipyards also indicate a significant reduction in hull fabrication man-hours.

The introduction of high-speed craft rules open two questions:

1. Is the floating frame structure in compliance?
2. What is a suitable design?

In order to answer these questions, the authors completed a three-part study, summarized in Table 1.

Studies I – III were completed in the sequence summarized in Table 1. During Study I, the ABS High-Speed Craft rules were under development, so the panel used was designed to be in compliance with the DNV High-Speed Craft Rules (Anon., 1994). In Studies II and III, the structure was revised for compliance with the ABS Rules for High-Speed Craft.

STUDY I, PROTOTYPE PANEL TEST

Study I (Latorre, et. al., 1997) (Herrington and Latorre, 1998) focuses primarily on Questions 1 and 2, is the floating frame in compliance and what is a suitable design? The study focused on the development of a 4.6-m x 1.8-m (15-ft x 6-ft) aluminum bottom panel for a 40-kt, 160 – 200-ton aluminum catamaran (Table 2). The resulting test panel used a 0.794-cm Al 5086-H116 bottom plate with 4 – 7.62-cm Al 5086-

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H111 I-beam longitudinals and alternating 5-17.78-cm Al 5086-H111 transverse fixed and floating frame. Comparing the design with the DNV rules (Part 3, Chapter 3) the plating was found to be 27% thicker than the 0.62-cm required and have a 10.5% higher stiffener section modulus than required.

The prototype paned was instrumented (Figure 1) and tested in the University of New Orleans structural test system as shown in Figure 2 (Latorre, 1997). To understand the panel load-displacement behavior, two line loads were applied to a maximum of 26.7 kN (6000-lbs). Repeated tests showed a maximum panel deflection that is in good agreement with the finite element analysis (Herrington and Latorre, 1998). The agreement between tests and finite element results is shown in Figure 3. These results provided the positive answer that the panel with floating frames is in compliance with the classification rules.

OPTIMIZATION FOR MINIMUM WEIGHT DESIGN

In order to obtain a lighter weight design, a local optimization was performed for this bottom panel. Two optimization techniques were used to determine the minimum weight panel. The techniques used were the sup-problem approximation method, and the first order optimization method. Both techniques are incorporated within the ANSYS finite element software package.

To determine the sensitivity of the objective function to the design variables, the gradient of the objective function was calculated at the initial design point. Figure 4 shows the change in objective function versus a plus or minus 1% change in the design variables. In this figure, 'Thick' refers to the plating thickness, 'Iyyt' and 'Iyyl' refer to the moment of inertia in the transverse and longitudinal directions, respectively. As can be seen from the figure, the thickness design variable has the largest effect on the objective function.

The optimization procedure was performed and results were obtained using continuous design variables. However, due to the expense of using non-standard sizes for plating and stiffeners, the optimum sizes were increased to the nearest standard size. Results from the optimization analysis are given in Table 3. In this case, the optimized design varies from the original design in terms of plating thickness, longitudinal stiffener size and spacing, and transverse stiffener size. The final design features a rolled plating thickness of .635 cm, which is a standard size. This thinner plating required the use of an additional, yet slightly smaller, longitudinal stiffener. The longitudinal stiffener requirement may be met by the use of five extruded standard I-beams 7.62 cm (3" x 1.64 lb/ft), with a section modulus of 24.42 cm^3. Keeping a constant width required a longitudinal spacing of .254 m. In terms of the transverse stiffeners, the optimized plate retains the same number of fixed and floating frames, and retains the same stiffener size for the floating frames. However, the fixed transverse frame size may be reduced to a 12.7 cm (5" x 3.7 lb/ft) extruded aluminum standard I-beam. The weight of the optimized panel is 294 kg, resulting in a weight savings of approximately 15%.

Table 1. Project Tasks for Development of Catamaran Hull with Floating Frames

Study	Task	Description
I	I.1	Development of structural test frame – (6.1-m x 3.05-m x 3.05-m with six $1x10^4$ kN hydraulic actuators)
	I.2	Design and fabrication of a 4.6-m x 1.8-m aluminum hull panel for catamaran "A"
	I.3	Structural tests: strain gage and displacement measurements
	I.4	Finite element analysis of panel and comparison with test data
	I.5	Optimization of panel elements for minimum weight
II	II.1	Preliminary design of the 33-knot catamaran
	II.2	Development of hull with floating frame
	II.3	Check of scantling with ABS high speed rules
	II.4	Finite element analysis of hull structure with floating frames
III	III.1	Review of aluminum fatigue and fatigue of high-speed craft
	III.2	Hydrodynamic seakeeping analysis of catamaran hull structure
	III.3	Fatigue analysis algorithm
	III.4	Fatigue tests of welded aluminum T-stiffener
	III.5	Finite element analysis of welded aluminum T-stiffener
	III.6	Recommendations for fatigue damage control
	III.7	Post-weld fatigue improvement

Table 2. High-Speed Catamaran Designs

Catamaran	"A"	"B"
Length (m)	40	33
Beam (m)	11	10.84
Draft (m)	1	1.33
Displacement (metric tons)	160 – 200	115
Speed (m)	40 – 45	30
Material	Aluminum	Aluminum
Class	DNV	ABS
Design Pressure (kN/m^2)	138	
Study	I	II, III

Table 3. Optimized Hull Panel Geometry

Item Description	Item Value
Plating material	Aluminum 5086-H116
Stiffener material	Aluminum 5086-H111
Panel length	4.572 m (15 ft)
Panel width	1.829 m (6 ft)
Plate thickness	.635 cm (.25 in)
Longitudinal stiffeners	5 - 7.62 cm (3" x 1.64 lb/ft) Al I-beam
Span between longitudinal stiffeners	.254 m (10 in)
Span between transverse stiffeners	.762 m (30 in)
Transverse floating stiffeners	3 - 17.78 cm (7" x 5.8 lb/ft) Al I-beam
Transverse stiffeners	2 - 12.7 cm (5" x 3.7 lb/ft) Al I-beam

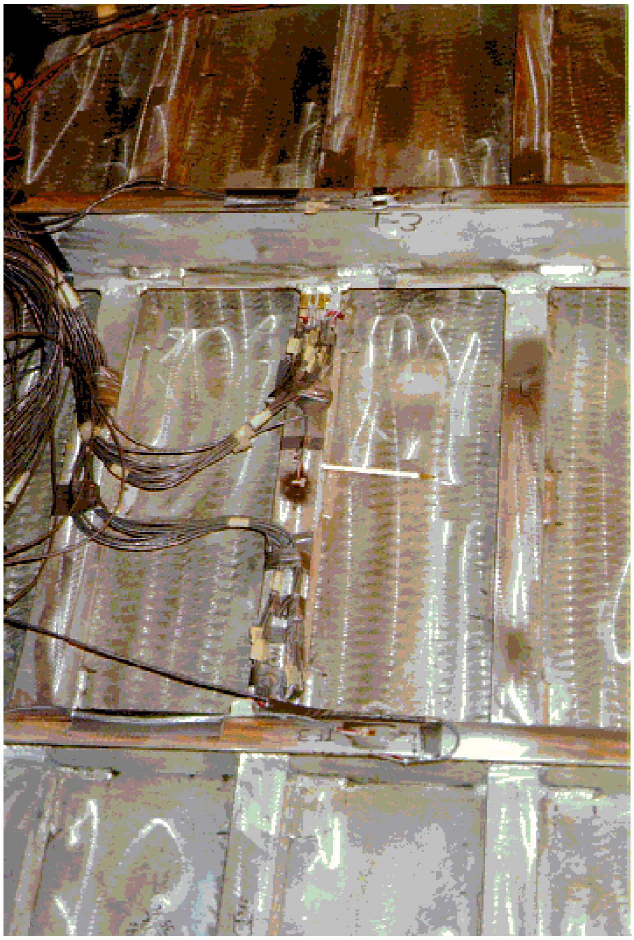

Figure 1. Prototype 4.6-m x 1.8-m Aluminum Hull Panel with Alternating Floating Frames.

Figure 2. Structural Test System.

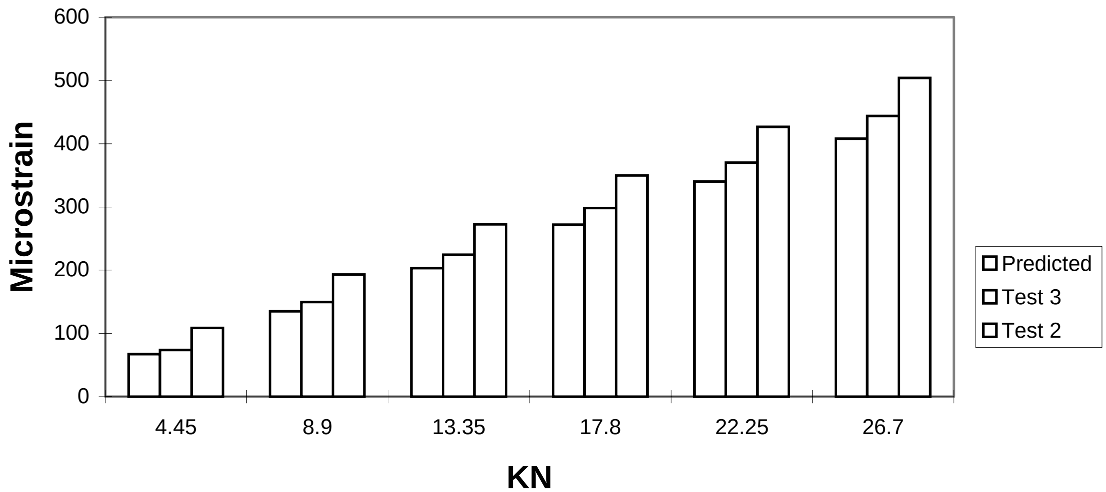

Figure 3. Comparison of Test Data and Finite Element Prediction.

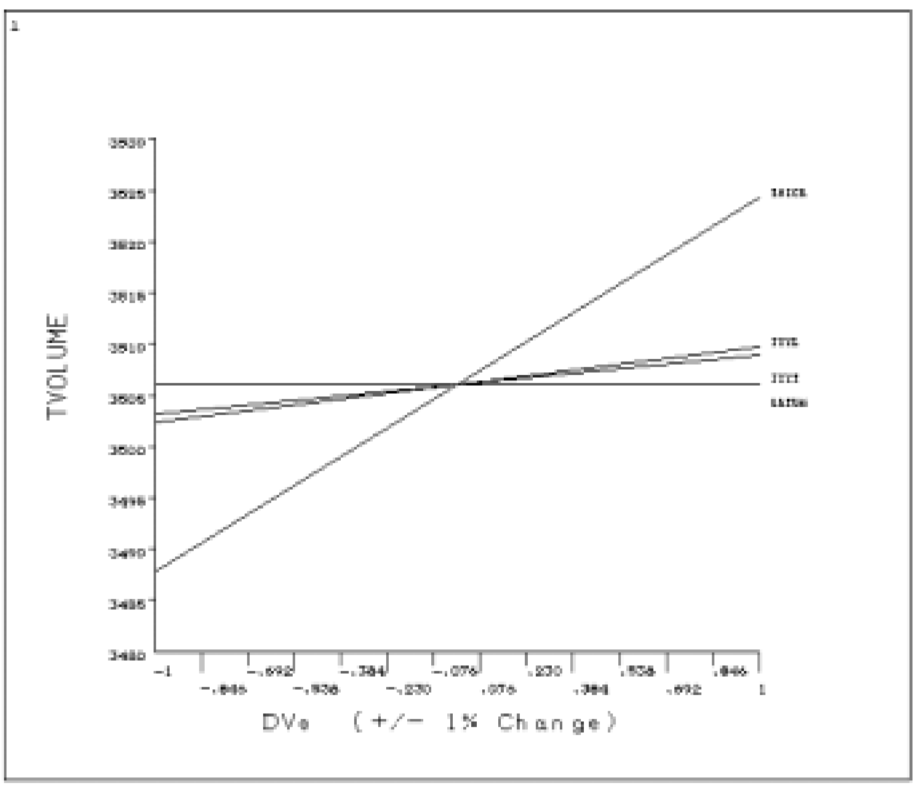

Figure 4. Gradient of Design Variables.

STUDY II – 33-KNOT CATAMARAN FERRY DESIGN WITH FLOATING FRAME HULL STRUCTURE

Following the good results obtained in Study I, the structural model was extended to a 33-knot aluminum catamaran ferry. In order to perform the structural analysis, the basic design of the ferry was completed. The particulars for the aluminum ferry are summarized in Table 2.

Catamaran General Arrangement

The midship section used for structural calculations is shown in Figure 5. The hull form, as shown in Figure 6, incorporates a surface piercing bow. The deck arrangement accommodates 250 passengers, 198 passengers on the main deck, and 62 on the second deck.

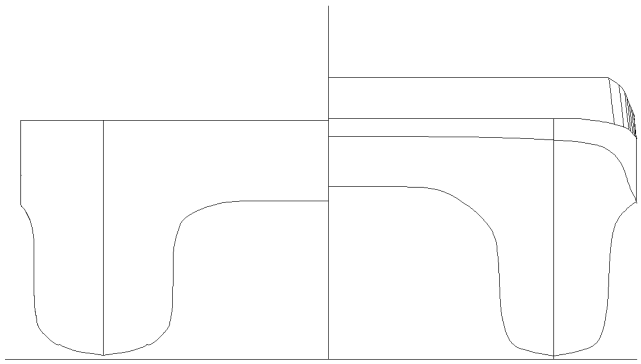

Figure 5. Hull Midship Contour Used in Structural Calculations

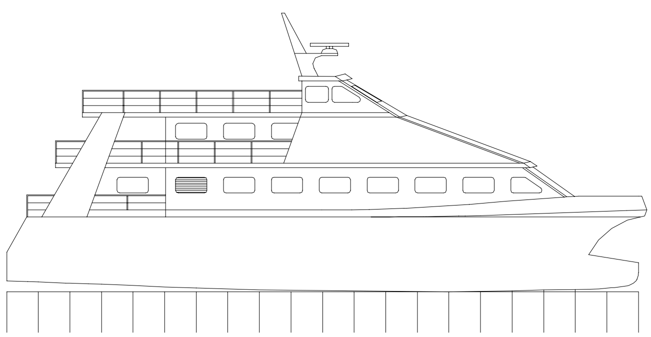

Figure 6. Outboard Profile

Impact of Hull Structure on Catamaran Weight

Table 4 summarizes the hull weight groups. The 145-ton full load represents 250 passengers with 4000 gallons of fuel aboard. This 43-ton payload represents 37.4% of the vessel weight. This structural weight is comparable to the 31.4-ton aluminum structure (27.3% of total). These values reinforce the observation of the need to develop strong lightweight hull structures for high-speed craft.

Table 4. Weight Summary of 33-knot Aluminum Catamaran Ferry

Group	Description	Weight LTSW	Percent of Total
1	Structure	31.4	27.3
2	Propulsion	23	20
3	Electrical	3.5	3
4	Electronics	0.7	0.6
5	Auxiliaries	2.4	2.1
6	Outfitting	11	9.6
7	Loads (including 250 passengers and fuel)	43	37.4
Total		115	100

FINITE ELEMENT ANALYSIS

A structural analysis of the mid-ship section of the catamaran was performed using a three-dimensional finite element model. The catamaran hull was constructed using an assembly of floating frame hull panels. The objective of the finite element analysis was to investigate the feasibility of using the floating frame structure. A number of finite element models and loading conditions were analyzed to investigate the structural response of the hull and to verify that the catamaran design met classification society rules.

Finite element analyses of the mid-ship catamaran cross section was performed using the ANSYS® finite element code (Anon., 1996). The program is a general-purpose analysis tool with a large library of element types, as well as extensive pre-processing and post-processing capabilities. The analysis followed the guidelines published by the Ship Structure Committee for effective use of the finite element method for typical ship structures (Basu, 1996).

The various models developed all contained elements that have six degrees of freedom (three translations and three rotations) at each node. The models were of a scale appropriate to investigate the intermediate and local response of the mid-ship section. Global hull response was not investigated since the ABS and DNV classification societies require a local strength analysis for vessels of the length being considered here (less than 50-m).

The objective of this analysis is to study the structural response of the mid-ship structure of a 34-m aluminum catamaran. For the final design, it is necessary to analyze the hull bottom and side floating and fixed frames as a complete system. Therefore, the extent of the finite element model is such that the hull structures between two watertight transverse bulkheads are considered. Outer shell plating, longitudinal girders and stiffeners, as well as fixed and floating transverse frames are modeled. Since the vessel is symmetrical along its longitudinal axis, only one-half of the cross section was modeled. Figures 7 through 10 show the finite element model of the structure.

In addition to the static sea pressure, three critical load cases need to be considered when performing a structural analysis of a catamaran cross section. The critical load cases are the transverse vertical bending moment, the torsional moment, and vertical shear force, as shown in Figure 11. The ABS rules for high-speed craft give guidelines for calculating the magnitudes of each load case (Anon., 1997). Once these magnitudes were calculated, an equivalent pressure was applied to the bottom hull of the model.

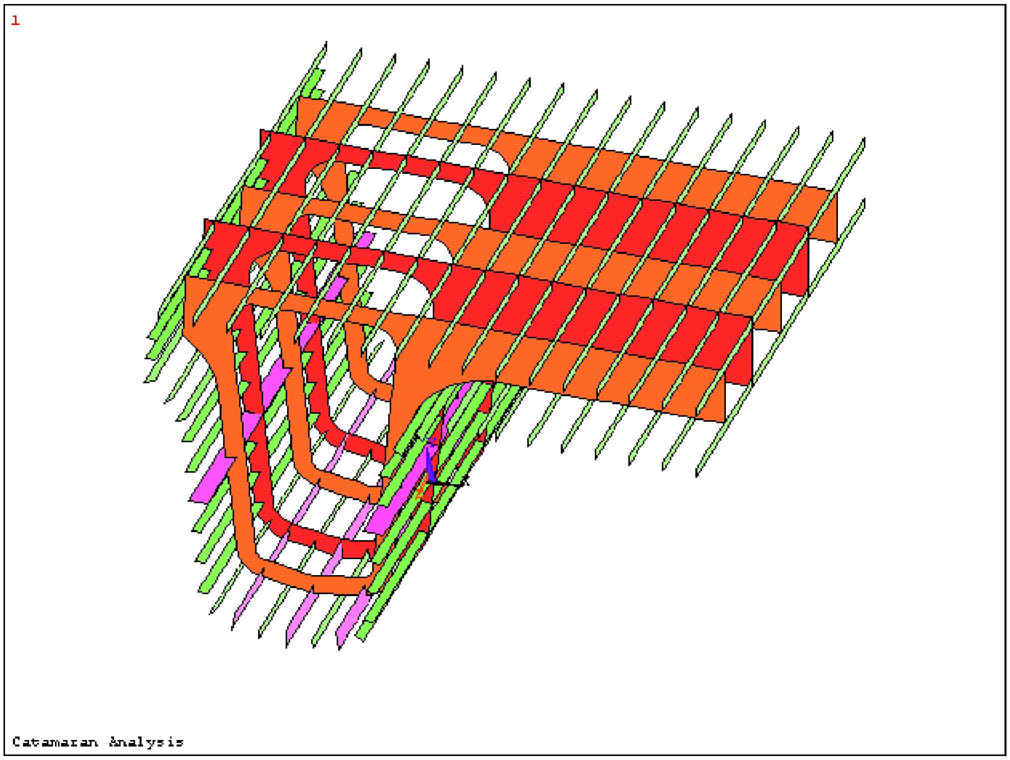

Figure 7. Finite Element Model of Mid-Ship Section

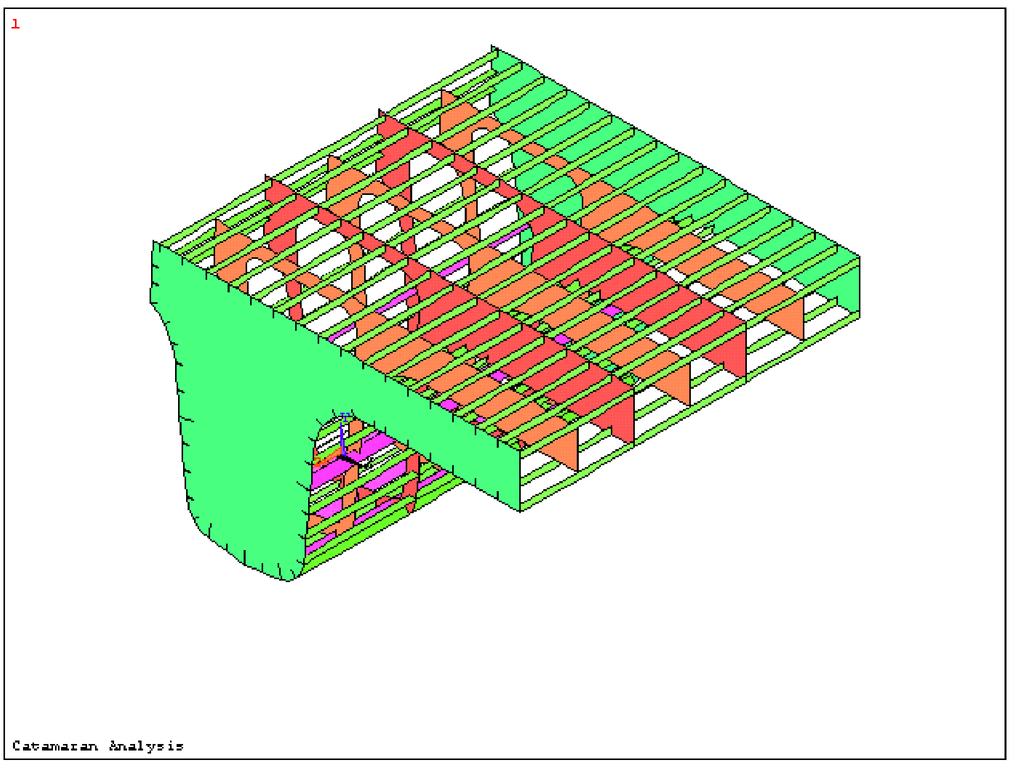

Figure 8. Finite Element Model of Mid-Ship Section

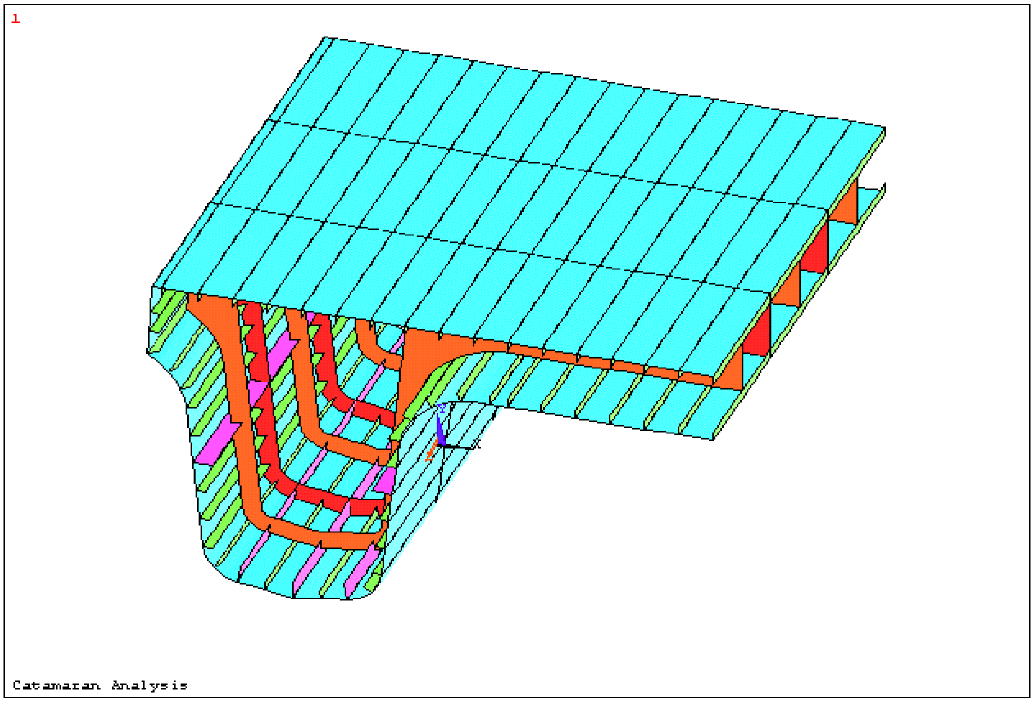

Figure 9. Finite Element Model of Mid-Ship Section

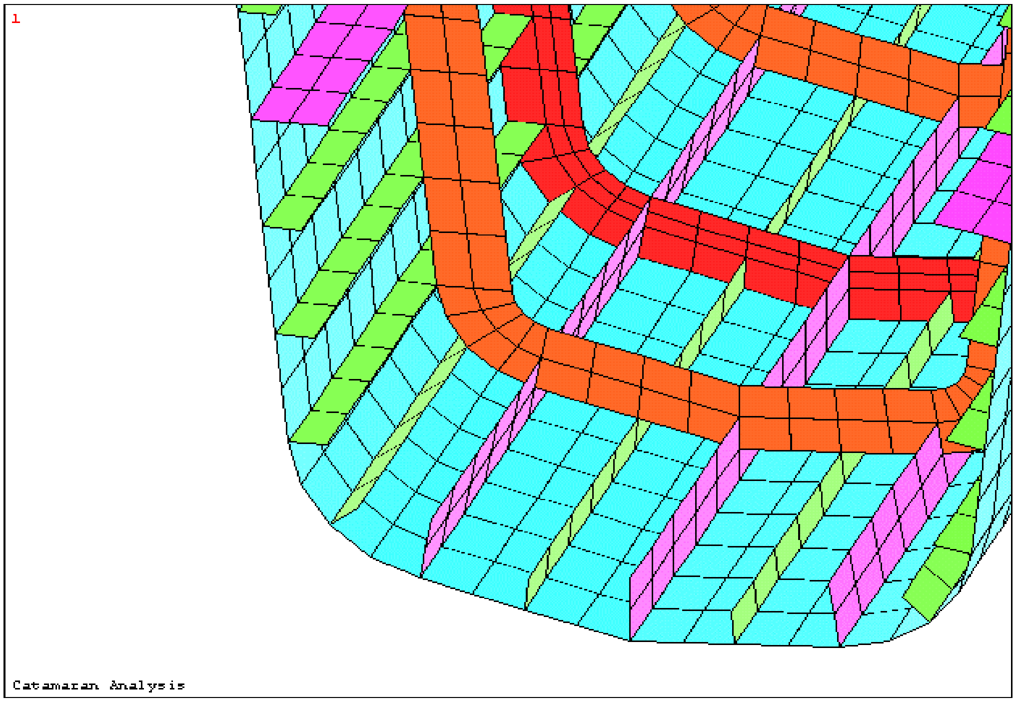

Figure 10. Detail View of Mid-Ship Section Model

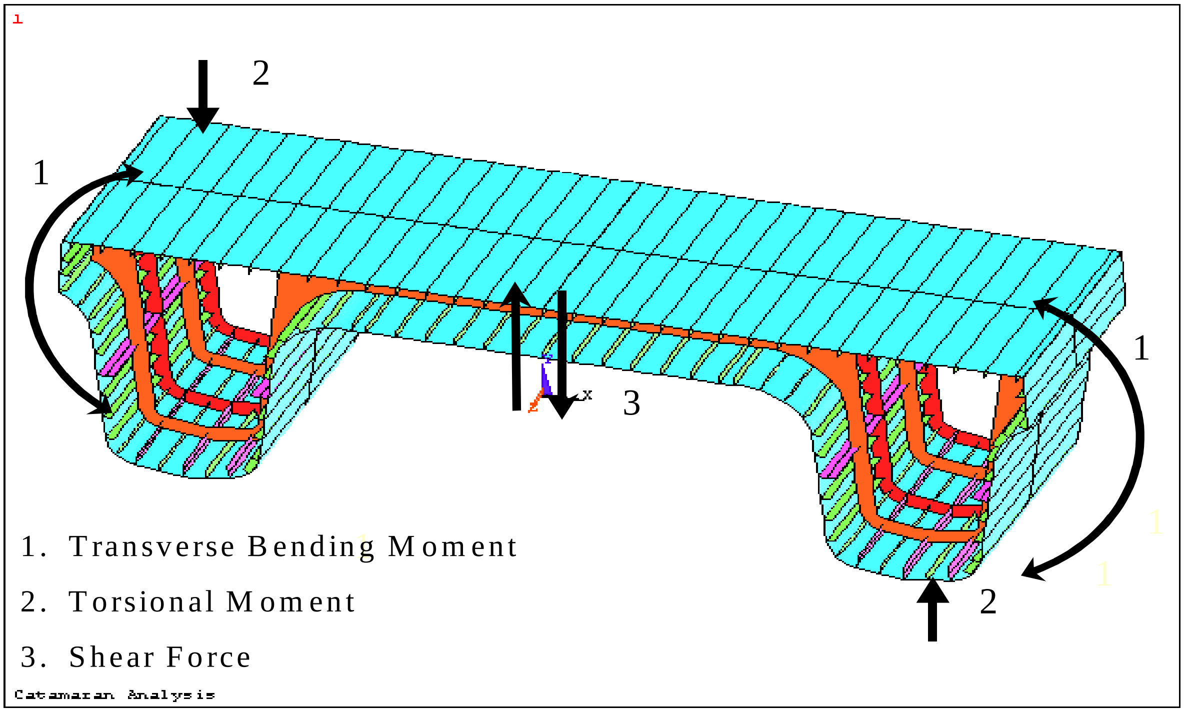

Figure 11. Catamaran Critical Load Cases

Uniform pressure loading was applied to determine the cross section structural response. Bottom pressure loading was used to simulate the result from a wave-induced transverse bending moment and vertical shear force. To simulate a wave-induced torsional moment, a positive pressure was applied at the fore end of the model and an equal magnitude, but negative pressure was applied at the aft end of the model. Figure 12 illustrates the applied loading required to model a torsional moment.

In addition to the three load cases considered above, three slamming cases were examined. The first case considered slamming pressure to be applied to the bottom, sides, and tunnel sections of the hull. The magnitude of the tapered pressure along the sides of the hull was calculated using the ABS rules for high-speed craft. Two other slamming cases were examined, one that assumed the pressure was applied from the hull center line to vessel centerline, and the other that assumed the pressure was applied from the hull center line to the outside edge of the vessel. From these two load cases, the effect of wave-induced transverse or side forces was investigated. In all loading cases, the pressure load was applied to the face of the shell elements representing the outer plating. The direction was normal to the shell face and was assigned a magnitude that corresponded to the various pressures as outlined by the ABS classification society. Table 5 lists the load cases considered.

Table 5. Load conditions.

Load case number	Loading condition
1	Transverse bending moment
2	Torsional moment
3	Vertical shear
4	Bottom slamming
5	Inboard slamming
6	Outboard slamming

To model the base plating, bulkheads, and framing webs, ANSYS Shell63 quadrilateral elements were used, having both bending and membrane capabilities along with six degrees of freedom at each of the four corner nodes, namely, Ux, Uy, Uz, θx, θy, and θz. The element is designed for linear analysis of flat or warped, thin shell structures. A linear displacement shape exists between nodes in both in-plane directions.

Several models created to simulate the catamaran cross structure varied mainly in their representation of the longitudinal and transverse frames and stiffeners. Initial models incorporated beam elements to represent the stiffeners. ANSYS Beam44 elements, a three-dimensional elastic beam element, were used to model the stiffeners. This element, like the shell elements used for the plating, also has three translational and three rotational degrees of freedom at each node, and has tension, compression, torsion, and bending capabilities. Progressively finer meshes were evaluated until the results converged to like solutions. A summary of results from all load cases is given in Table 6, where the maximum stress is the Von Mises equivalent stress. As seen from Table 6, the most critical load is the full slamming load case. While under the given load, the resulting stresses are acceptable. The locations of maximum stress are potential sites for crack initiation and propagation. Future studies involving the fatigue response of the floating frame structure are warranted.

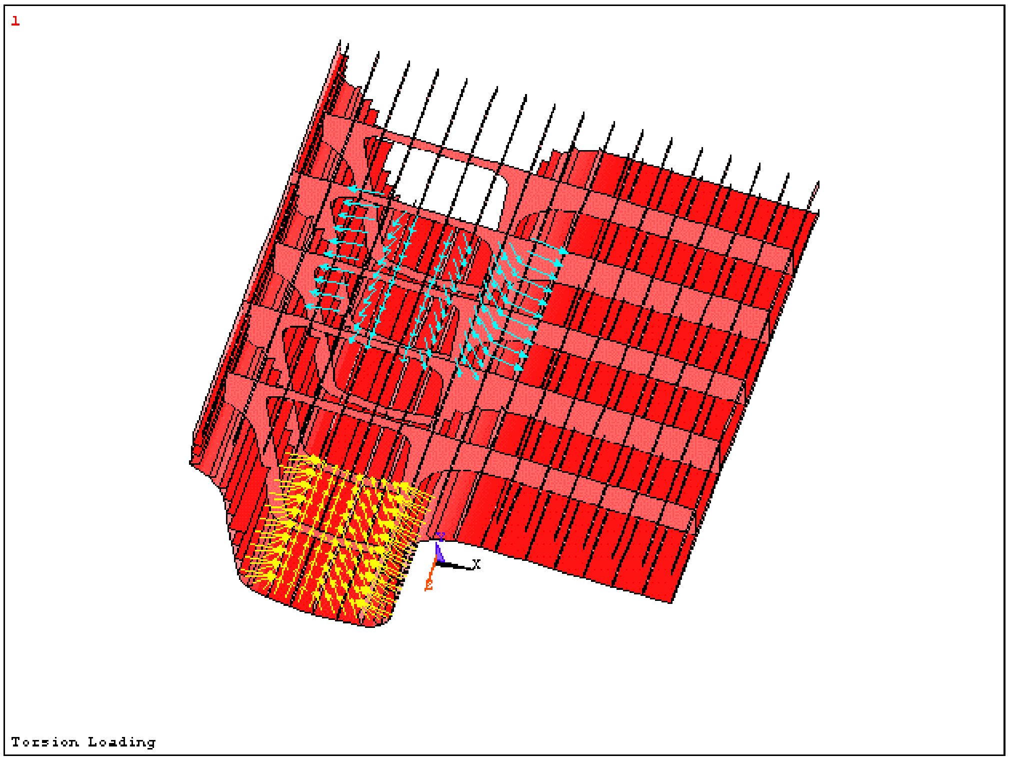

Figure 12. Torsional Loading Case

Table 6. Summary of Finite Element Results

Full Slamming Load	Maximum Stress Mpa (ksi)	Location of Maximum Stress
Shell Plating	52.5 (7.6)	Intersection with bulkhead and with floating frame members; bottom of hull
Longitudinal Girders and Stiffeners	80.7 (11.7)	Intersections with floating frame members
Floating Transverse Frames	84.5 (12.3)	Interior lower edge of frame
Fixed Transverse Frames	102.0 (14.8)	Interior lower edge of frame
Inboard Slamming Load		
Shell Plating	39.9 (5.8)	Intersection with bulkhead and with floating frame members; bottom of hull
Longitudinal Girders and Stiffeners	56.5 (8.2)	Intersections with floating frame members
Floating Transverse Frames	64.8 (9.4)	Upper interior edge, inside of hull centerline
Fixed Transverse Frames	74.4 (10.8)	Upper interior edge, inside of hull centerline
Outboard Slamming Load		
Shell Plating	65.5 (9.5)	Intersection with bulkhead and with floating frame members; bottom of hull
Longitudinal Girders and Stiffeners	100.7 (14.6)	Intersections with floating frame members
Floating Transverse Frames	104.8 (15.2)	Lower interior edge, outside of hull centerline
Fixed Transverse Frames	104.8 (15.2)	Lower interior edge, outside of hull centerline
Bottom Slamming Load		
Shell Plating	66.9 (9.7)	Intersection with bulkhead and with floating frame members
Longitudinal Girders and Stiffeners	102.7 (14.9)	Intersections with floating frame members
Floating Transverse Frames	69.6 (10.1)	Upper interior edge, near intersection with cross structure and hull
Fixed Transverse Frames	102.0 (14.8)	Upper interior edge, near intersection with cross structure and hull
Torsion Loading		
Shell Plating	37.2 (5.4)	Bottom of hull
Longitudinal Girders and Stiffeners	58.6 (8.5)	Intersections with floating frame members
Floating Transverse Frames	40.7 (5.9)	Lower interior edge of frame
Fixed Transverse Frames	37.2 (5.4)	Lower interior edge of frame

STUDY III – FATIGUE AND WELDED JOINTS

During the course of this research, the question of the fatigue life of the welded structure was raised. Unfortunately, the limited service data has limited the development of high-speed guidelines. In order to address this problem the authors completed Study III to develop guidelines.

As part of this study a finite element model of the welded aluminum joint shown in Figure 13 was developed (Latorre, et. al., 1999). This model is presently being refined to evaluate the results obtained when the aluminum test panel was subjected to a uniform load by creating an interior vacuum.

This represents a current ongoing R&D activity of this project.

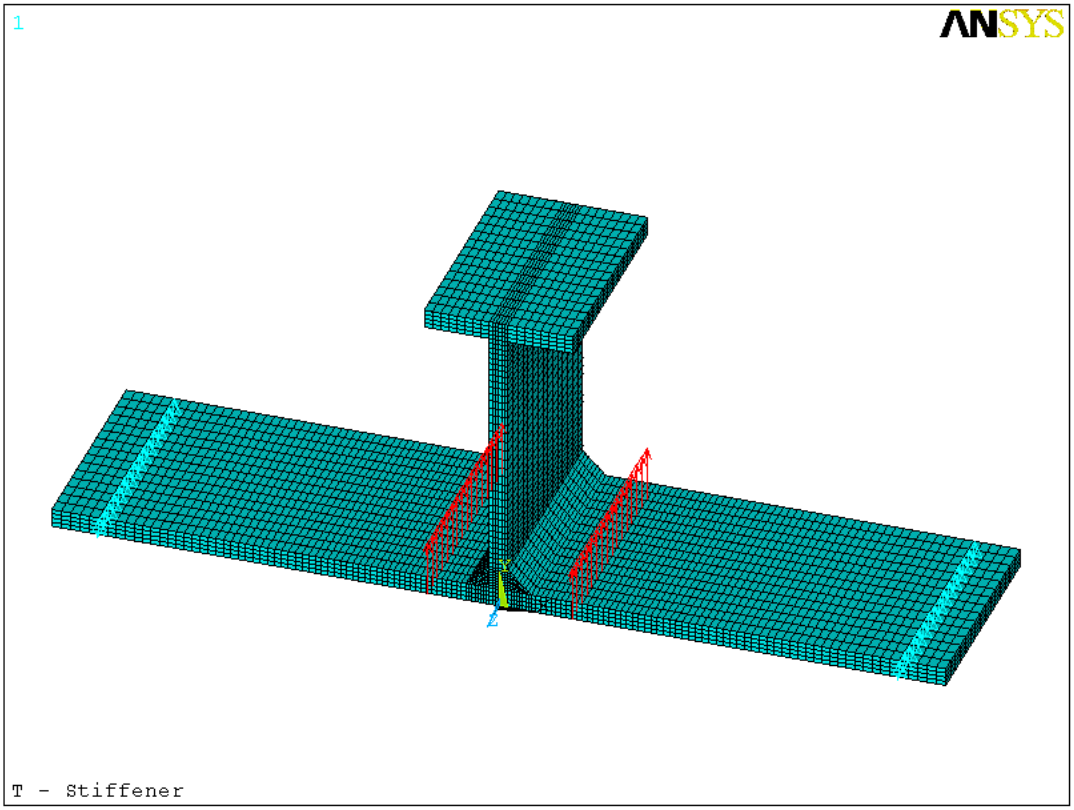

Figure 13. Finite Element Model of Welded T-Stiffener.

CONCLUDING REMARKS

This paper has presented an overview of a three-part study completed under the sponsorship of the Gulf Coast Maritime Research Center (GCRMTC) at the University of New Orleans. The results presented lead to the following conclusions:

1. It is possible to design a bottom panel for a high-speed craft using alternating fixed and floating frames.

2. The optimization of the panel indicated that by using a thinner plate and corresponding larger structural stiffening, a weight reduction of 15% could be achieved.

3. The finite element analysis of the catamaran hull with alternating fixed and floating frames showed high stresses in the hull-cross structure connections.

As a result of Studies I and II, the authors began Study III concerning the fatigue behavior of welded structural connections. This ongoing work is helping to clarify the stress concentration in the welded structure.

It is expected the implementation of these results will enable naval architects to design the lightweight, high strength structures needed for the next generation of high speed craft.

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