Structural aspects of a new high speed pentamaran design
(Aspectos estructurales del nuevo diseño de pentamarán de alta velocidad) (*)

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Resumen del Contenido

El transporte marino a alta velocidad de pasajeros y vehículos no está teniendo la amplia aceptación y el prometedor desarrollo previsto hace una década. El número de barcos que entran en servicio esta decreciendo desde 1996. Hay muchas razones detrás de este hecho pero dos de ellas se reconocen en todos los foros como los factores clave para esta desaceleración: una falta de aceptable fiabilidad y unos costes de explotación altos.

IZAR trabaja junto con Nigel Gee Associates Ltd. para introducir un nuevo concepto: el pentamarán. La idea consiste básicamente en un monocasco muy fino con dos pares de patines laterales poco sumergidos para dar estabilidad.

Uno de los aspectos más críticos del concepto del pentamarán es el diseño estructural. El modo en que las cargas se introducen en el casco y la manera en que estas cargas se reparten y se expanden a través de la estructura del barco en términos de flujo de esfuerzos no es obvio y debe tratarse con cuidado.

En este artículo se tratan algunos de los retos básicos del diseño estructural y presenta las soluciones propuestas para la estructura del pentamarán.

Ventajas generales inherentes al concepto *pentamarán* son:

- Se minimiza la resistencia al avance y, consecuentemente, la curva potencia – velocidad.
- El concepto tiene un puntal inherente, lo que posibilita el uso de motores diesel de velocidad media, que queman fuel pesado en vez de fuel marino. Esto provee al operador lo que realmente está esperando: una factura baja del fuel de operación y un salto diferencial en fiabilidad del barco.

Después de un acercamiento inicial a diversos aspectos estructurales, basados en el flujo de tensiones desde el fondo y en la eficiencia de las cubiertas superiores, se adoptaron dos importantes decisiones para el análisis de la estructura del pentamarán:

- Concepto estructural tipo monocasco adaptado a las formas del casco del pentamarán.
- Solución híbrida, mamparo más pilares, para la transición entre garaje y cubierta de pasajeros.

Cualquier diseño innovador debe ser totalmente comprobado mediante cálculos directos en tres dimensiones, no sólo para el análisis estructural, también para el comportamiento hidrodinámico. Para un exhaustivo estudio, se ha desarrollado un modelo de elementos finitos global de la estructura mediante el programa MAESTRO. Los resultados muestran cómo las típicas consideraciones de los monocascos no son aplicables en diseños multicasco y específicamente en pentamaranes. Los niveles máximos de esfuerzos se localizan en distintas posiciones debido a la interacción, estructural e hidrodinámica, entre los patines y el casco central. La continuidad estructural entre el casco central y la estructura interna es crítica para asegurar un comportamiento eficiente y homogéneo de la estructura. El conocimiento de las cargas hidrodinámicas, mediante simulaciones numéricas y ensayos de comportamiento en la mar, que sufre este tipo de diseño tan innovador es esencial para una fiabilidad máxima de la solución adoptada.

Abstract

High-speed transportation of passengers and vehicles is not having the broad acceptance and promising development envisaged one decade ago. Number of ships entering in service is decreasing since 1996. There are several reasons behind this fact but two of them are recognised in

all the forums as the leading factors for this deceleration: lack of an acceptable reliability and high exploitation costs.

IZAR is working together with Nigel Gee Associates Ltd. in order to introduce a new concept: the pentamaran. The idea basically consists in a very-slender monohull with two pairs of slightly submerged lateral sponsons to provide stability.

One of the most critical aspects of a pentamaran concept is the structural design. The way in which loads are introduced in the ship hull and the way in which these loads are sheared and spread into the ship structure in terms of stress flow is not obvious and should be treated with care.

The paper discusses some of the basic challenges of the structural design and presents the solutions proposed for the pentamaran structure.

1.- Introduction to the Pentamaran Concept

Different ship concepts have tried to provide a sensible answer to reliability aspects and exploitation costs with moderate success. Catamarans are efficient but not too comfortable for specific routes; monohulls have a better sea-worthiness but speed can sometimes be costly; SES are efficient but expensive and provide a limited operability; wave-pierces, swath's, trimarans and, semi-swath's are concepts struggling to balance the equation speed-reliability-fuel bill-comfort in order to optimise results and provide an attractive product to the confused ship operators.

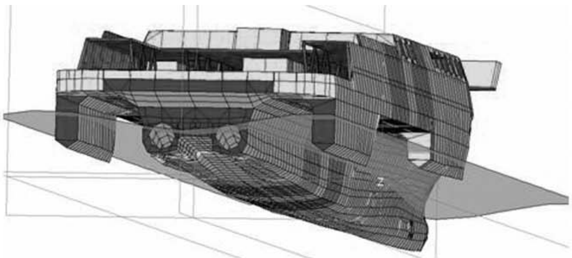


Figure 1 - Beam Sea. Aft view

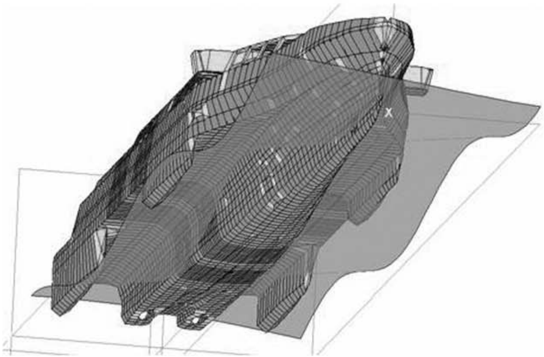


Figure 2 - Bow Sea. Bottom view

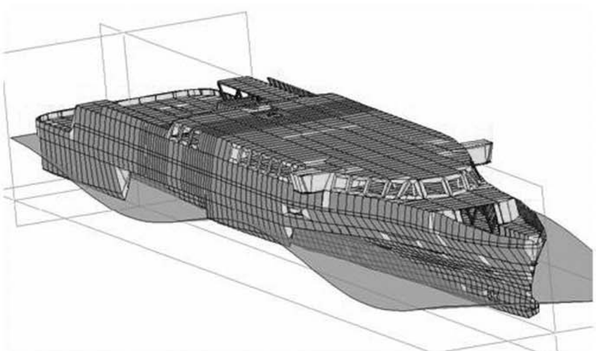


Figure 3 - Bow Sea. Upper view

General advantages inherent to the pentamaran concept are:

- Drag is minimised and so it is speed-power curve. Speed may be achieved at a relatively low cost and comfort is assured since it behaves like a very slender monohull. Equating this advantage in different terms, steel may again be on the picture for a still attractive speed, increasing the overall reliability of the platform.

- The concept has an inherent depth. The vehicle deck is naturally placed high enough as to permit the use of medium speed diesels, without interrupting the vehicle traffic. And these diesel engines, burning HFO instead of MDO, provide what operators are really expecting: a low operating fuel bill and a differential jump on ship reliability.

Structurally speaking, a pentamaran is also an innovative concept. On one side and, as any other member of the high-speed craft family, the need of low structural weight is governing over production costs: the structure has to be optimised with respect to weight. But on the other side, there is always an inherent risk in any innovative structure, specially considering that, in this case, not only a new structure has to be faced but also new loads will be on the picture.

A pentamaran structure shares some of the difficulties of other multihull structures: significant torsional behaviour in oblique seas, transverse overall loads (Fig. 1), potential slamming on a wet-deck, or racking effects on a wide vehicle deck.

On top of this, a pentamaran generates its buoyancy and accelerations due to global sea loads over a narrow central hull while its inertial global loads are mostly produced in a cross deck three times wider. The global loads are sheared up through unconventional paths, leading to a low efficient strength deck and a heavily loaded bottom, if proper care is not taken in the early structural layout.

When in oblique waves (Fig. 2 and 3), atypical transverse accelerations have been registered, again due to the fact of a non-continuous submersion of the sponsons. The interaction between the hull forms and the primary structure arrangement is essential to achieve efficiency, avoid buckling-prone load transfer and assure the fatigue life.

Another effect associated to the non-standard hull configuration has been detected. While the forebody is nearly a monohull, the aft body is more like a trimaran. This means that, during a complete hogging-sagging cycle, the loads are flowing in the structure in a quite different manner, depending on the number of sponsons submerged at each time step, leading to peculiar shear lag effects.

2.- Description of the Izar new high speed ferry pentamaran design

The basic design of the IZAR pentamaran family is propelled by four waterjets, each one operated by a medium-speed engine burning heavy fuel oil. The whole structure is constructed in High Tensile Steel HTS-36 and HTS-42.

Dimensions and general arrangement are showed in the next table and Figure 4. Hull lines have been optimised, reaching a length / beam ratio close to 15 which provides a much smaller hydrodynamic drag when comparing with an equivalent monohull. Vehicles are arranged in one single garage and shipped by aft and fore ramp doors. First and tourist class passengers are accommodated in the upper deck.

The great flexibility of the pentamaran concept allows for different designs with length up to 250 m and deadweight up to 7000 t. Naval applications are also envisaged.

Main Particulars of the Basic Pentamaran Design

Length Overall	175.7 m
Length Between Perpendiculars	160.0 m
Max. Beam	31.1 m
Max. Central Hull Beam	11.6 m
Design Draught	5.0 m
Design Speed	38 kn
Installed Power (kW)	4 x 12000
Full Load Deadweight	900 t
Passengers	1200
Only-Cars Garage config.	400
Only-Trucks Garage config.	34

3.- Initial approach to structural aspects of a pentamaran hull

Prior to develop an exhaustive analysis of the pentamaran structure, some conceptual aspects have been studied in order to establish initial decisions in the design. Most important of these aspects consists in the way that buoyancy loads raise from the bottom of a narrow central hull to a quite wider upper deck. The efficiency presented by this upper deck depends on the structural solution implemented between upper and garage decks.

For this analysis a simple finite element model has been made by extruding the main section geometry along a length of 75 m, which would represents aproximately the central cylindrical body of the pentamaran design.

An important point in this stress flow analysis consist in the proper simulation of the loading of the model, that is, buoyancy loads are introduced on the wet hull/sponson, while inertial loads act over all elements in the structure. MAESTRO FEM software has been used to perform all structural analysis, since it provides appropriated tools to simulate this loading scheme. Weight acts as a force on every element, and buoyancy forces are introduced as pressure in wet elements, once the wave is defined and the model is balanced to achieve the static equilibrium.

The model consists in three modules. The central 30 meter long module includes the sponson in order to analyse the structural interaction with the rest of the structure. A complete view of the model is shown in Figure 5. The midship section for longitudinal extrusion is depicted in Figure 6.

Different solutions have been tried to connect garage and upper decks. The model has been loaded with hogging and sagging waves. Initial results show that upper deck presents an efficiency near 90 % when longitudinal bulkheads are implemented between decks, while in a vertical pillars configuration, the efficiency decreases down to 60 %. An intermediate result is obtained when implementing vertical and diagonal pillars (close to 75 %).

This discrepancy in upper deck efficiency is explained by the shear stress flow presented with these different connecting options. Figures 7a, 8a and 9a show how shear stress flows from the bottom to the upper deck (transversal structure has been hidden in these pictures for viewing purposes). The effect of the shear 'delay' in longitudinal stresses in upper deck is shown in Figures 7b, 8b and 9b.

As shown in Figure 7a, **vertical pillars** do not permit a continuous transmission of shear stresses, so these stresses take a *winding* way through the vehicle deck to the hull side and up to the upper deck.

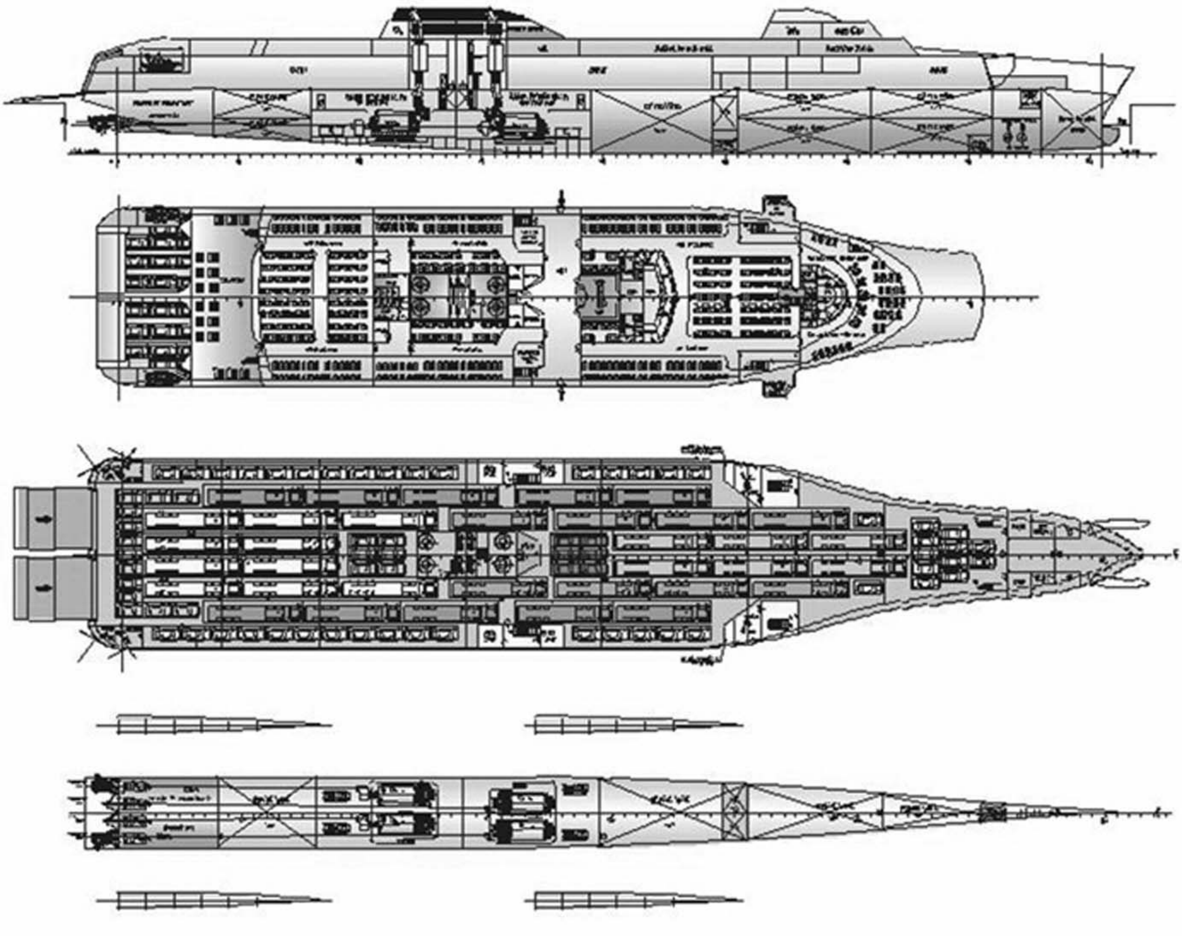


Figure 4: General Arrangement of the Basic Pentamaran

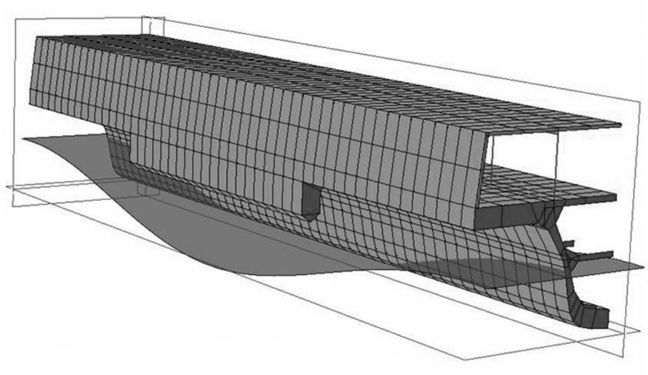


Figure 5.- Midship Section Extruded Model

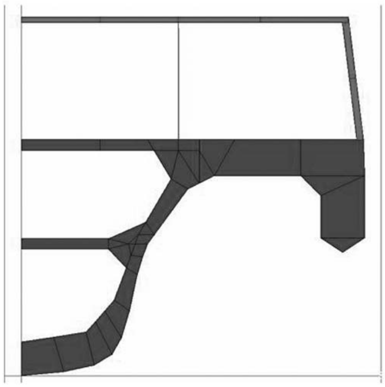
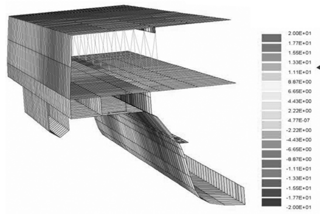


Figure 6.- Midship Section Initial Design

Figure 7.- Configuration with Vertical Pillars between deck



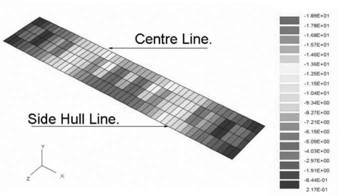


Figure 7A.-
Shear Stress flow (MPa)

Figure 7B.-
Longitudinal Stresses (MPa)

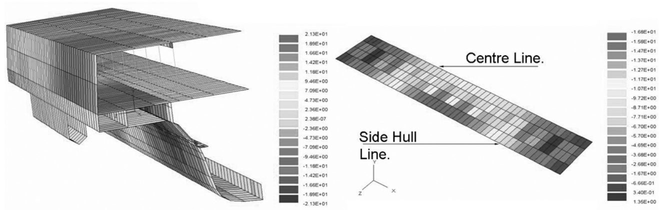


Figure 8.- Configuration with Vertical and Diagonal Pillars

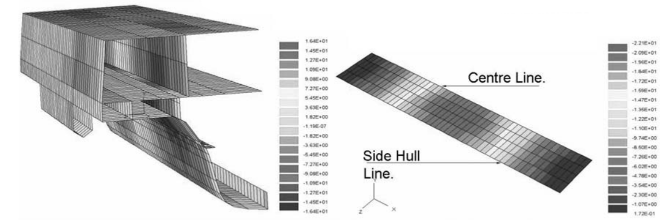


Figure 9.- Configuration with Longitudinal Bulkheads

This generates a strong "shear lag" effect in upper deck longitudinal stresses, which can be appreciated in Figure 7b. Combination of a *vertical and diagonal pillars* configuration produces a similar effect, but in a lower extent, as shown in Figures 8a and 8b. Stresses take a quite different pattern when **longitudinal bulkhead** configuration is introduced in the model. Shear flow raises from the vehicle deck directly to the upper deck trough the bulkhead, then the shear lag effect from the hull side is minimised (see Figures 9a and 9b).

4.- Structural Iteration

Two important decisions were adopted as a result to this first approach to the pentamaran structure analysis.

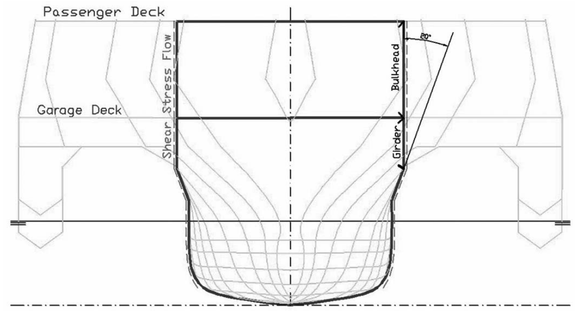


Figure 10.- Pentamaran hull forms adapted to create an "Internal Monohull"

4.1. Monohull structural concept adapted to pentamaran hull forms

Shear stress flow has been proved to be a decisive parameter to design an homogeneously efficiency structure for the pentamaran. If strength decks are not collaborating in a high degree, the low part of the hull side and the bottom will be overloaded. That means an inherent weight increment when scantling the structure as well as an unbalanced way of counteracting the wave bending moment.

A monohull structure allows a smooth transition of shear stress along the hull side plating that contributes to the longitudinal loading of decks. This concept has been implemented in the pentamaran structure by creating an "internal monohull", highlighted in blue colour in Figure 10. Thus, the narrow central hull is connected with the garage and passenger decks by means of bottom girders aligned with longitudinal bulkheads.

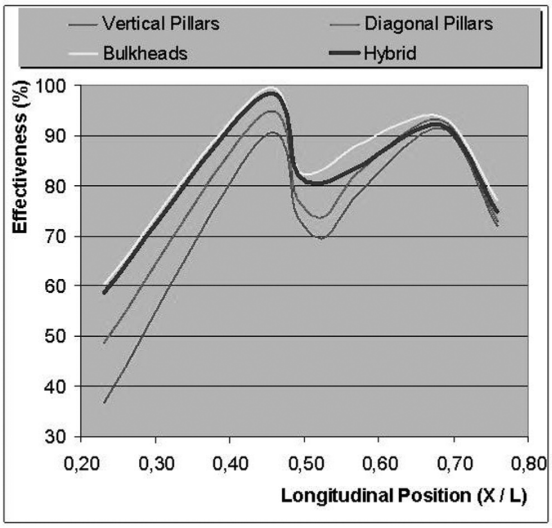
Hull forms have been optimised to obtain the lowest angle possible between the upper part of the central hull and the girder (~ 20 º), without penalising the drag resistance. This connection of the girder and both plates of the hull with different slope, has carefully been designed bearing in mind:

- Minimum angles necessary for welding requirements and
- Fatigue damage due to stresses concentration in the joint, since it is expected to appear cyclical transversal loads coupled with longitudinal "hogging-sagging" deformations of the ship.

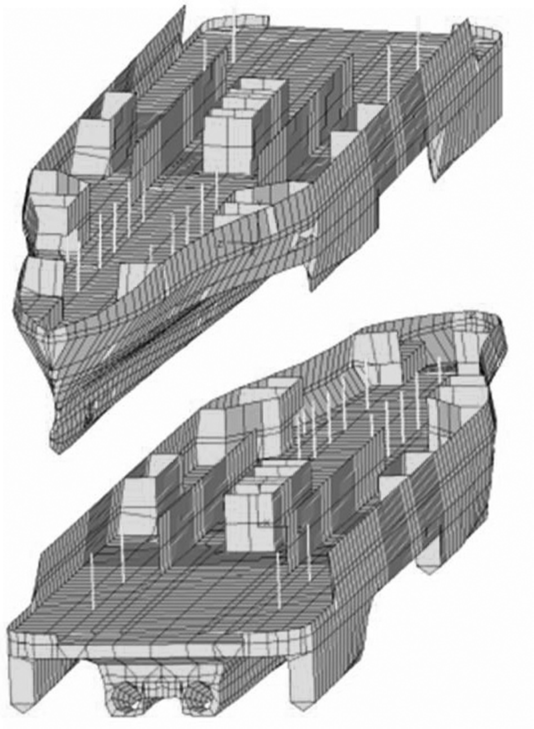
4.2. Hybrid solution (bulkhead + vertical pillars) for the transition between garage and passenger decks

Girder connecting the hull side with the lower deck must be arranged along the whole length. However, longitudinal bulkhead in the garage connecting the two decks can only be arranged along a limited length. As a general requirement for the design, the garage has to be as diaphanous as feasible in order to allow a fluid traffic of vehicles and avoid dark areas, not only for light but also for water, smoke and noise.

Thus, to select this certain length for the longitudinal bulkhead, the initial analysis presented in paragraph 3 has been repeated once the global FE model of the pentamaran was concluded. The same three solutions, along the whole garage, for the connection of the two decks



Graphic 1 - Upper Deck "Effectiveness Vurves"



Figures 11 - Garage Hybrid Arrangement

have been tested, and effectiveness of the upper deck has been calculated for several sections.

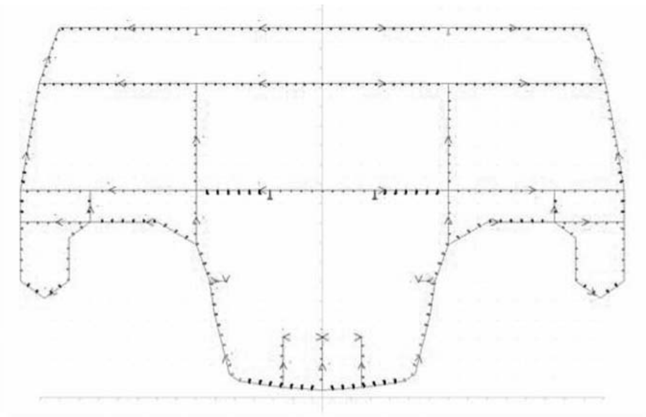
Results, summarised in Graphic 1, present quite different effectiveness values for each section of the passenger deck. Bulkhead solution provides highest values up to 0.7·L, and become to be equal to solution with pillars (vertical or diagonal) at the fore end of this upper deck (0.7<x/L<0.8).

This behaviour can be explained by the effect of the slender fore hull forms and the existence of other longitudinal bulkheads for exhaust casing and access trunks. Same reasons also explain the difference with theoretical values obtained with the extruded model in the previous analysis.

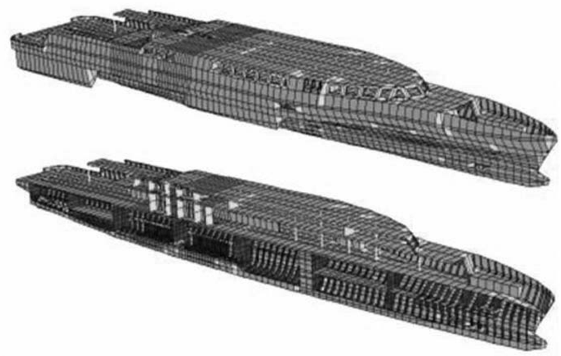
In the light of these results, an hybrid solution has been chosen for the structural arrangement of the garage. As shown in Figures 11, longitudinal bulkheads (50 m long) have been arranged between 0.25·L to 0.55·L, while the rest of the supporting structure consists of vertical pillars since this solution provides, for this length, the same effectiveness with a smaller weight. The *effectiveness* curve for this hybrid solution is also displayed in Graphic 1.

5.- Structural FEM analysis of the pentamaran ferry new design

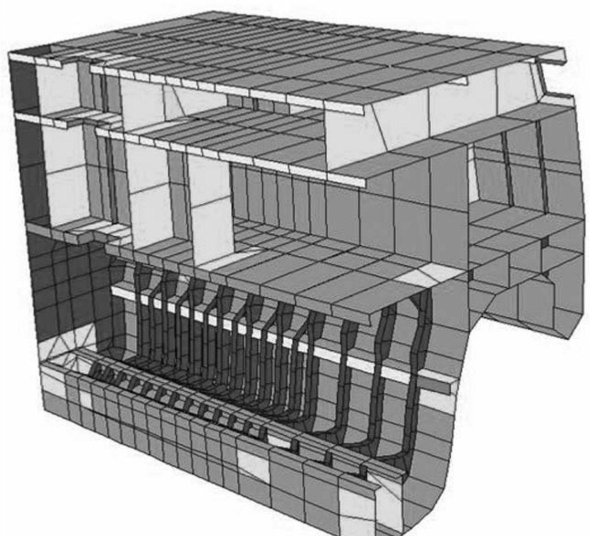
Any innovative design must be fully assessed by three-dimensional direct calculations, not only for the structural analysis, but also for the hydrodynamic behaviour. At the present state of the IZAR pentamaran project, hydrodynamic loads are been estimated by numerical com-



Figures 12 - Midship Section Long. Structure



Figures 13 - Outer and innr FE Model Views.



Figures 14 - Fore Engine Room Port Module

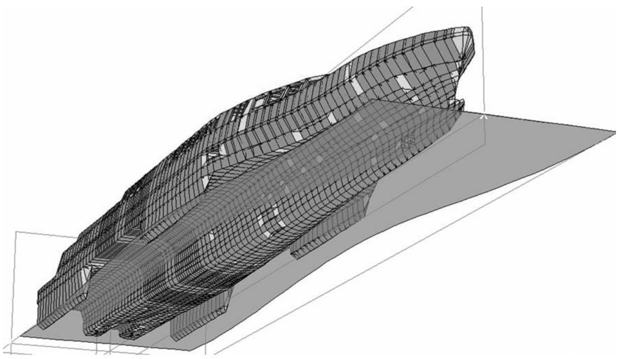


Figure 15.- Hogging Wave in the FE Model

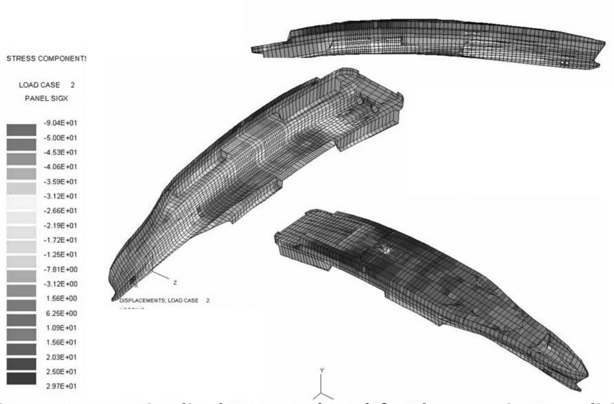


Figure 16.- Longitudinal Stresses (MPa) for the Hogging Condition. Deformed x 100

putation and results are not available yet. Future publications will include the whole design cycle.

Midship section is presented in Figure 12. The structure is longitudinally stiffened. Span between frames, as well as spacing between longitudinal stiffeners, has been analysed in an iterative process, in order to reach an optimum structural weight. Transverse reinforcement is half spaced in engine rooms and sponsons due to local vibrations and impact loads.

For an exhaustive 3D analysis of the structure, a finite element model (Figures 13 and 14) has been developed with MAESTRO software [ref. (a)]. This model corresponds to a slower version of the design, with smaller displacement and two waterjets, as required by the shipowner. It consists in 36 modules, with 44,000 nodes and 21,500 elements. Hull, decks, bulkheads, sponsons and transverse reinforcement under garage deck are modelled with 15500 plate (triangular and quadrilateral) elements. Deck girders and framing above garage deck are modelled with 6000 beam elements. Longitudinal stiffening is included in the strake plate element properties [ref. (b)]. More than 90 % of the weight of the structure has been finally modelled.

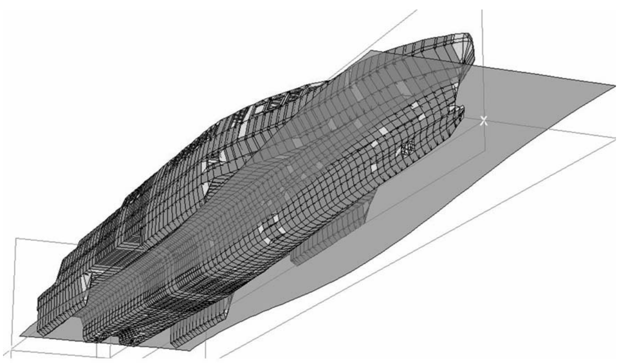


Figure 17.- Sagging wave in the FE model

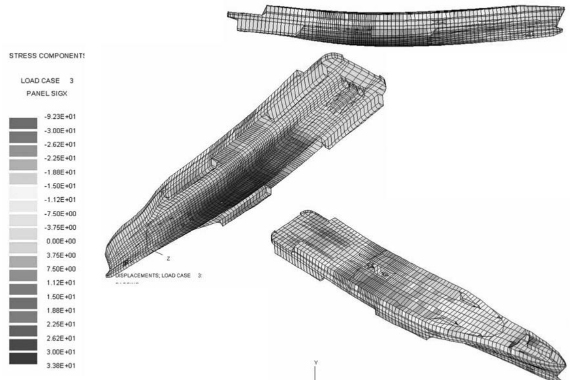


Figure 18.- Longitudinal stresses (MPa) for the sagging condition. Deformed x100

A wide range of loading conditions will be tested in the model, not only for head seas, but also for bow and transverse seas. Specific effects of this new design, such as behaviour of sponsons when submerged in oblique waves and transmission of loads from the fore end monohull to the wide pentamaran section, will be also analysed in detail in later stages, when the hydrodynamic loads are finally settled.

Once the model has been finished, a first set of computations for pure hogging and sagging loading conditions (explained in following paragraphs) have been carried out in order to check the global behaviour of the structure in terms of deformation levels, stresses ranges and significant effects induced at sponsons. The necessity of detailed FEM analysis in specific areas, such us engine rooms or transom, can be also evaluated with these computations.

5.1. Hogging Wave Condition

A wave 175 meter long with a height of 4 m and the crest situated in the midship section, has been selected for the hogging analysis (Figure 15). Deadweight has been introduced in the model and the static equilibrium is achieved with the Maestro balance tool.

Results are shown in Figures 16. First atypical effects can be observed. Aft sponsons contribute with weight but without buoyancy. Furthermore, they are providing a huge longitudinal stiffening to the aft part of the ship that causes a block deformation, bending the structure at the section in the forward end of the aft sponson with the corresponding stress rise of longitudinal stresses in decks and bottom.

5.2. Sagging Wave Condition

The model has been loaded in sagging condition with the same wave used for hogging, but with a trough in the midship section (Figure 17).

Results are presented in Figures 18 and show different global shape of stress concentration. Unlike in the hogging condition, stress concentrations are longer and located in a most forward longitudinal position. Aft sponsons are partially submerged and add their buoyancy force to the sagging vertical bending moment.

Therefore, sagging and hogging conditions show qualitative differences. Outer views of global longitudinal stresses in a hogging and sagging conditions highlight the fact that maximum values for decks and bottom do not coincide at the same section. This can be considered as one particular feature of a pentamaran design, caused by an specific flow of stresses through the structure.

5.3. Shear Stress Flow in Both Conditions

This basic analysis of the structure concludes with global views of shear stress flow in hogging (Fig. 19) and sagging (Fig. 20) conditions in order to check the correct behaviour of the design solutions adopted as a result of the initial iterations of this structural analysis.

From the figures below it can be observed how shear flow almost disappears from the hull side where connecting with the internal girder

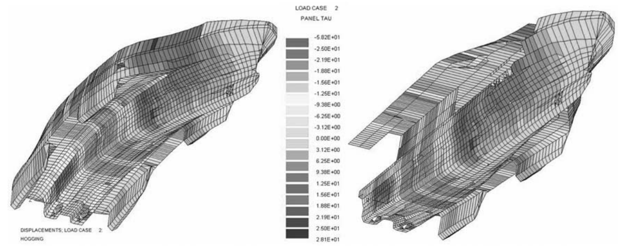


Figure 19.- Shear stress (MPa) for Hogging Condition outer (Def x100) and inner views

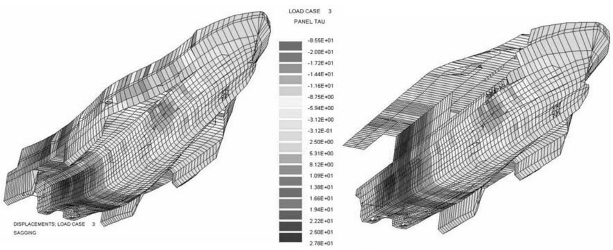


Figure 20.- Shear stress (MPa) for Sogging Condition outer (Def x100) and inner views

(figures on the left side) and how this shear stresses flow trough the longitudinal bulkhead (figures on the right side). These elements seem to be more effective in sagging condition than in hogging, although this effectiveness should be evaluated in a complete hogging-sagging cycle, since the phase angle of the wave is a relevant parameter for the global loading. The length of the internal structure is also a driving parameter.

Another effect observed in figures at left is how shear stresses flow through the transition area of the hull side from the fore end of the ship (which presents a transverse monohull section) to the central part of the length (which is a wider transversal section, although not yet a pentamaran section).

6.- Conclusions

- The structural behaviour of a pentamaran structure becomes now more clear for the designer. Iterative analysis has revealed several aspects of the way in which the load transfer is produced and the stress flow is built-up.

- Standard assumptions made for monohulls and other multihull designs are not always applicable. The limited extent of the sponsons induces that certain areas are atypically stressed, showing a stress variation that depends on the wave position with respect to the sponsons.

- Maximum stresses have been found out of the typical positions for monohulls. Navier bending theory is less evident than in other type of ships. The most concerned area with respect to primary loads is not limited to the central 30 % of the ship length but it is extended further forward and, especially, aft.

- Structural continuity between the central hull and the internal structure is more needed than ever. Sometimes it might be necessary to modify the upper part of the central hull in order to try to emulate a monohull behaviour.

- Longitudinal extent of the internal longitudinal structure (bulkheads or trusses) is critical and must be observed in relationship with the sponson extent.

- It is the concept that is new and not only the structural solution. Short term and long term response of the structure has to be clearly settled. Therefore, hydrodynamic numeric simulation and towing tank tests, taking into account the effect of the sponsons at different wave incident angles, should provide a deeper knowledge on the design load side.

- Maestro FEM capabilities have proven to be very useful for this type of innovative structural design. A large amount of information can be derived if the model is properly settled. Adequacy parameters indicating the ultimate capacity of the structure in different failure modes (buckling, yielding, fatigue…) is essential for an optimised design.

- Future analyses have been oriented together with its relative importance. A comprehensive knowledge of the primary loads is essential. Vertical and horizontal bending moment transfer functions as well as the torsional and transverse responses have to be settled. Impact loads in the forward wet deck should also be established based on towing tank results. Relationship of these functions and results with the main parameters of a pentamaran hull is also desirable.

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