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Design of a Quadramaran Vessel

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Abstract:
A new innovation in the world of multi-hull vessels has been proposed, by arranging the four spindle submarine type of hulls (A QUADRAMARAN) for higher stabilization and introducing new structural synthesis phenomenon which is a complete deviation from existing classification society approaches on structural design. A structural synthesis approach/method routinely used to design & build internally pressurized filamentary vessels is modified for application onto a radically different design of externally pressurized steel hulls. In the design process beginning with shell equilibrium, choosing geodesics as reinforcement directions, using Netting theory and integrating resulting ODEs, we arrive at a solution as demanded optimum shape rather than analyzing pre-determined shapes of hull body plan. That a zero hoop stress case of doubly curved rotationally symmetric pressure shells is same in composite and metallic design, this approach is adopted for steel. This consideration has lead to a corrugated/bellow/unduloid shape, more pointed on the outside than the inside. Very rigid structure resulted as expected through the composite route. FE analysis proves strength and stability of the resulting form.

1. Introduction

A new design with an novel design concept has been proposed with four spindle shaped quadra-maran hull form for vessel designs, where large deck area is a requirement. The application is not for a cargo vessel. For proving this design feature, a case study has been done on an existing proven design developed by Michigan University and the design is published. The vessel considered in this project is an Alaskan Arctic Research Vessel whose original design has been done by Michigan University, USA. The details of the design, parameters and developed drawings are available freely in their website with all the hydrostatics and hydrodynamics information also. This vessel is basically a catamaran hull form. All the design calculations were done based on the analytical approach. The weight estimates were calculated, scantling calculations have been performed using the classification rules by assuming the vessel to be built with four different materials. One being the standard ship building quality steel, second being the high tensile steel (AH36), third being the Aluminum and fourth being the FRP/GRP structures. See Fig.1(a) & 1(b) below for General Arrangement.

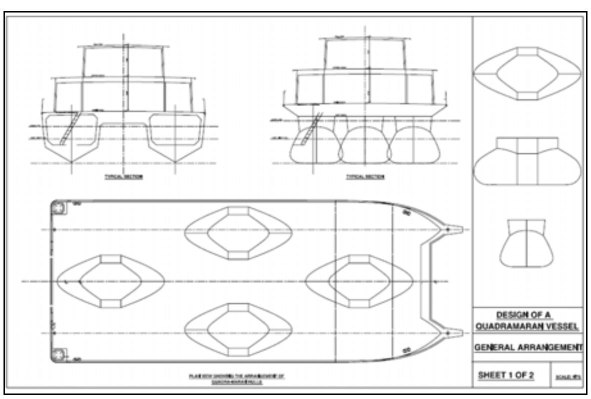


Figure 1(a): General Arrangement

These problems have been solved using standard empirical relations and governing differential equations and finding the solution within the domain and imposing the appropriate boundary conditions and solved a boundary value problem (BVP).

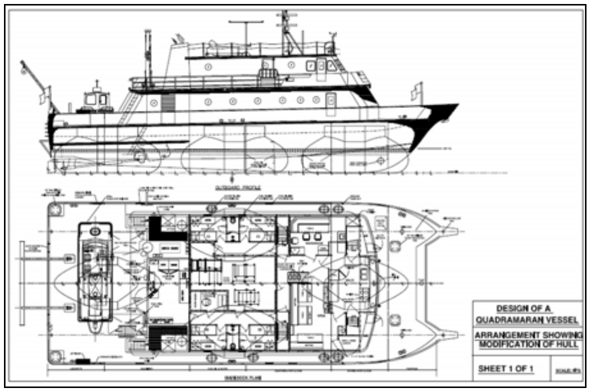


Figure 1(b): General Arrangement

One more important deviation in this design is an innovative approach in the shape of the hull. A deviation from the existing standard hull forms and approached through Geodesics and hull forms having stable negative curvature. Structural strength has been estimated using analysis based on Ansys FE analysis software. The analytical results are indicated in this paper in Fig.2 and in other figures also, where the reference is given elsewhere in this document.

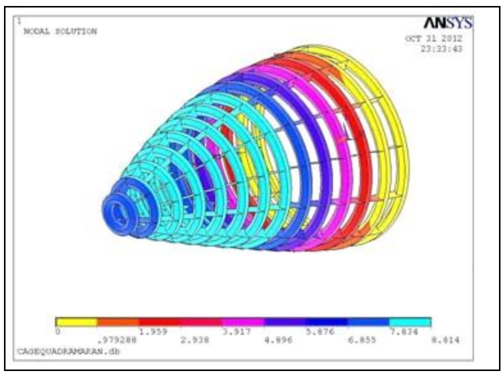


Figure 2: Ansys results of structure.

The hull form defined is of two hulls, one being external hydrodynamic hull and second is an internal pressure hull. Ref [1,2] at the end of this document gives analysis results for stable negative curvature shell, graphite reinforced plastic shell. First time that hyperbolic differential geometry (as far as first author believes) was brought to notice of structural / mechanical engineers for filamentary structural design application. This is because the word Bending conceptually common to mathematics and structural mechanics at the same time goes quite beyond ETB in shell theory. In Ref [3],TU Delft Netherlands handout points to same principles of isometric / in-extensional deformation where formulatively isolation between plate & shell in-plane and out-plane (bending) modes is hinted. Gauss Theorema Egregium gives Gauss curvature (product of principal curvatures) invariance in all in-extensional deformational modes. Simple logic: to protect against rain, we wear a cap on head, an umbrella to stay dry up to waist and a rain coat for entire body. To avoid buckling altogether, constant global Gauss curvature is a natural choice. It can be used to track bending in some patches of a shell as suggested in [3]. This avoids mid- plane extensions even by large deformations when laterally loaded, in- plane loads stay in a thin shell, somewhat like water under a mat, resulting retaining stretching strains are insensitive to bending. Correct direction of filaments is established by choice of appropriate geodesics (AG). The following Kármán's equations of compatibility link strains, curvatures and indirectly are global stability indicators.

A filament wound thin fiberglass shell fabrication and test made earlier in VSSC had given a near 99% compression failure, entirely avoiding buckling. This is a shallow shell, deeper CFRP sandwich shell made, not tested.

With this background, four hollow spindle shaped pods are assembled to form a single floating body for stability against listing and pitching in sea water during rough weather. Each of the spindle shaped hulls is made up of two hulls like a submarine, one hydrodynamic hull on outer side and a pressure hull inside. A near sinusoidal surface shape spindle of near constant total curvature is chosen for each outer hull. All the four hulls are connected to a common deck by means of struts as in a SWATH Vessel or a Hydrofoil craft. The shape is suitable for streamlining and stability against buckling.

For checking feasibility, we have analyzed a miniature model in CFD and FE analysis. The propulsion is given to the back three spindle shaped hulls and the forward spindle has no propulsion of its own. The FE model of the vessel configuration with four spindles is as shown in Fig 3 below.

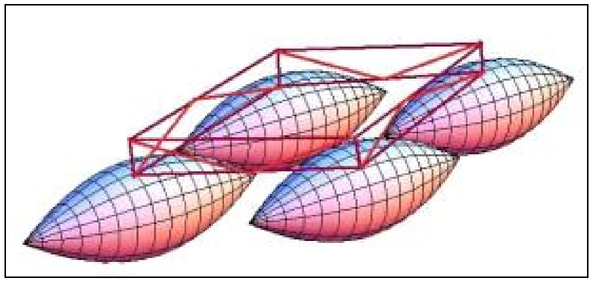


Figure 3: The assembled quadra-maran configuration with four spindles.

2. Internal Pressure Vessel Design

Pressure hull design presented here is an outcome of filament wound composite pressure vessels design method up to a point. The internal pressure geodesics are synthesized by adopting and winding high strength filaments (e.g., fiberglass, Kevlar, Carbon) according to following procedure: Pressure balance found between double curvatures and filament orientation from force equilibrium, netting theory that resolves stresses, and so defines curvatures as:

$N_\phi = N_s \cos^2 \psi, N_\theta = N_s \sin^2 \psi.$

$R_2/R_1 = 2 - \tan^2 \psi$

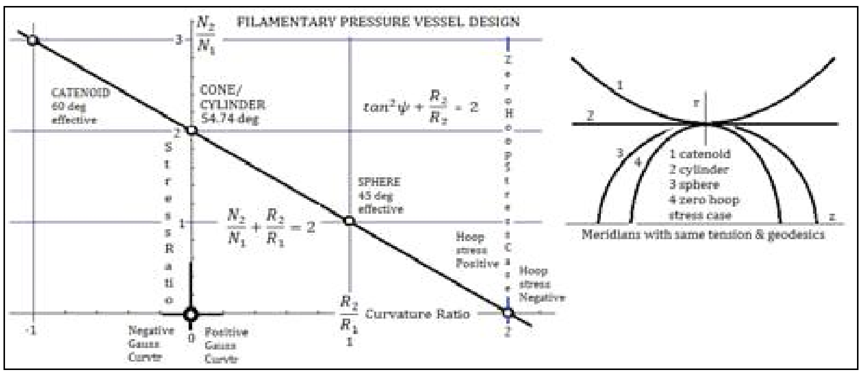


Figure 4: Pressure balance in filamentary vessels.

These "straight lines" on surfaces of revolution together define not only dish shapes, but also filament orientation. They are tangent externally to a boss circle radius r_0 minimum radius. A variety of "balanced "shapes above are possible from this approach. In the final steel isotropic solution here however, these filament directions are ignored.

When these convex vessels are wrapped with such geodesic windings, the mathematical invariant radius shows up at either end as minimum opening radius to which filaments are tangent.

Geodesic filaments are deposited between end closure dishes with opening diameters in accordance with slip- free trajectory Law of Clairaut $r_0 = r \sin \psi$. See Figure below.

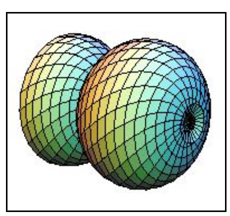


Figure 5: Geodesic / Non-geodesic windings

Composite vessel motor casings are often designed with different openings for attaching differently sized hardware (like igniter and nozzle). When this is tested, an interesting behavior is seen.

The dome shell is seen undergoing bending, witnessed as an associated new phenomenon. Stress-strain linearity is lost and it was a revelation of sorts that the shell can even axially contract under initial stages of pressure application. It can be fixed by improving geodesy and increasing dome thickness if geodesy improvement is not adequate.

So it appears that the geodesics to take pressure (in-plane loads) and geodesics to take bending (pressure loads normal to shell wall) have a different character. It is believed that there are no proper geodesic directions to take on in-plane introduced loads. This forms basis of present research interest. It is commonly known that a properly built internal pressure vessel cannot take even two percent of this internal pressure value when applied as external pressure. So much bending occurs and main cause of concern is shell instability.

Enquiry into factors that prevent achieving the same effect in case of external pressure vessels and thrust loaded shells where compression component of bending exists brings in rôle of hyperbolic geodesics. Large negative curvatures have to be applied with corresponding geodesy as an “appropriate geodesic”.

3. Initial Approach / Philosophy For Building Buckling Resistance In Shells

Buckling of thin shells had been and is a topic of extensive investigation. Metallic and composites shells prematurely transfer /bifurcate from membrane energy mode into bending mode when subjected to axial compression or external pressure.

On the other hand, internally pressurized composite pressure shells go neatly from unpressurized condition to full pressure, maintaining uniformity of unidirectional filament stress in a linear stress-strain relation. In its synthesis above Law of Clairaut is used but this invariant is no more applicable for external pressure as it is invalid for hyperbolic geometries and introduces bending.

When pressure as normal load is zero, equilibrium of forces normal to shell wall shows that, normal curvature is also zero:

$k_1 \cos^2 \phi + k_2 \sin^2 \phi = 0;$ hence $k_1 k_2 < 0$

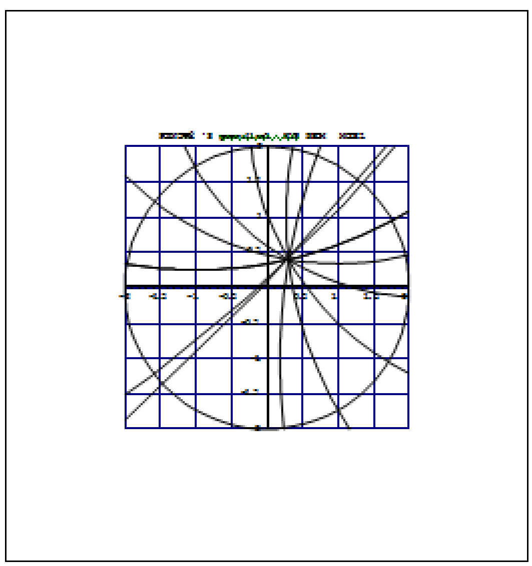
Accordingly, when more external pressure is applied, gauss curvature has to go even more negative. When external pressure is applied, structural synthesis demands higher negative Gauss curvature for in-plane loads to be incorporated and transmitted straight without bending. The search after appropriate geodesics, meaning those without any bending / stretching coupling is an important activity of structural mechanics and mathematics. Classical text books in Elastic Stability do not touch upon any aspect of preferred stress trajectory or reinforcement orientation for reducing stress concentration, as this came after advent of composites.

A radically different approach is needed here in building submarine pressure hulls and it has become evident that above geodesics have to be totally rejected in favor of more stable geometries and trajectory directions. Even the nature of geodesics has to qualitatively change;

Angle ψ_o inclination of geodesic lines with meridian should increase but not decrease with increasing radius. An important commonsense example is buckling behavior of a thin toroidal tube subjected to vacuum. Torus inside area does not buckle; however, the entire outside collapses and outer wall material buckles to the inside. It is a tell-tale for its wrong pre-buckling design configuration and also can be regarded as a clue / pointer to the designer to effect needed changes... to entirely eliminate the outer structural part... which does not seem to contribute at all….if you can help it, eliminate it in structural synthesis bringing in AG, appropriate geodesy.

Study and adoption of non-linear mathematical stability from hyperbolic geometry significantly away from current approaches [4,5] holds promise to eliminate the phenomenon of shell buckling. Figures 6 (below) is a Poincaré Hyperbolic Geometry Models.

POINCARÉ 'S generalized HYP GEOM MODEL 2



Figures 6: Poincaré Hyperbolic Geometry Models

However, there are two Poincaré models here, one Cartesian and other Disk model, even though in general a metric solution should be invariant to coordinate choice. There is another Klein model. Also David Hilbert proved that no analytical imbedding of the (entire) hyperbolic exists in R3 Ref [7]. Accordingly, some “temporary hyperbolic geodesics” have been adopted here.

In the ongoing study of pure mathematical considerations of for elastic instability, Poincaré’s models of hyperbolic geometry in the hyperbolic plane have been adopted as suitable geodesics to begin with. However, these internal contradictions have prompted the first author to temporarily settle with some approximation at least for surfaces of revolution using inversions indicated alongside forming basis of this paper. Strangely enough, sum of three angles of a hyperbolic red triangle is still π like the Euclidean case.

Author’s model using approximate hyperbolic geodesics

$re_H = r/\sin\psi$ are sketched alongside in Fig 6(a).

They are circles passing through the pole or origin suitable in polar coordinates and surfaces with axi- symmetry. It is difficult to accept hyperbolic geometry geodesics as "straight". The sum of three angles tallies as 180 degrees, as per classical Gauss-Bonnet requirement of pseudospherical deficit Pi- (A+B+C) = 0 for 2D flat case, but only after using hyperbolic geodesics shown here as more "appropriate" or suitable in 3D embeddings.

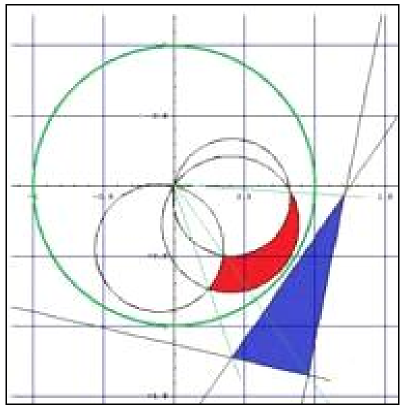


Figure 6(a): Hyperbolic Geometry geodesics, red triangle.

These are not adopted into engineering practice so far. They are drawn in Fig. 6(b) on circular torus on desirable areas of negative Gauss curvature of a circular toroid, similar to what may be adopted in isotropic/steel designs

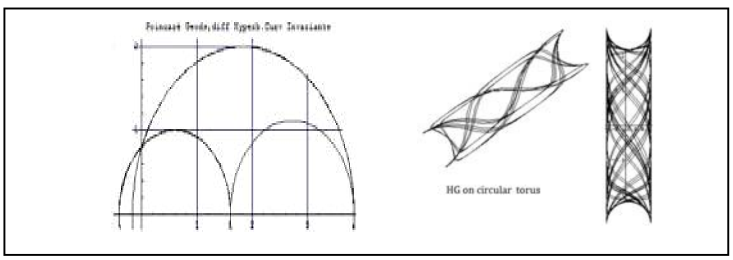


Figure 6(b): Hyperbolic geodesics on rigid parts of torus for external pressure.

4. Building A Miniature Sailing Craft

As a next practical step, we have planned to build a miniature sailing craft using above-mentioned pressure hulls with streamlined outer shell jackets placed to envelope a 5 meter elongated pressure hull structure as pod covering. Four such pods will be mounted in a diamond quadramaran configuration with equal moments of inertia, spaced 5 meters in x- and y- directions for same stability everywhere. Thrusters with 15 hp power run by diesel electric motors would provide propulsion. The miniature model of the vessel spindles planned to be constructed and tested is as shown in the Fig.7 below.

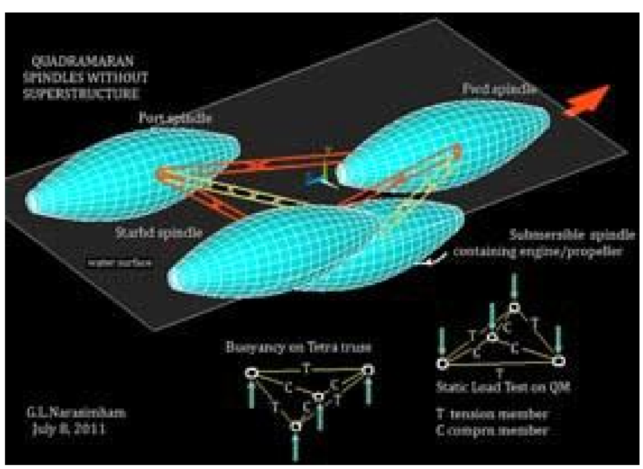


Figure 7: Sub-scale model to be constructed.

In the above outer hydrodynamic hulls/pods designed with a constant positive gauss curvature. Ring stiffened design with ABS code is also under consideration.

5.1. Pressure Hull Design

Integration of ODEs after combining equilibrium and appropriate geodesy has lead to wavy bellow meridians capable of taking external pressure. These results are as expected better structural forms seen in large GI culvert iron pipes resisting earth pressure as well in aneroid barometer bellow designs. See Fig.8 below.

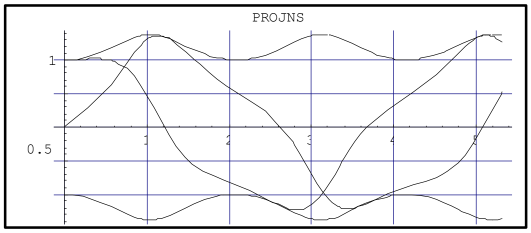


Figure 8: Filament projections of Bellow external pressure vessel.

There is like rounding of corners in a welded stiffener towards improved (less stress concentration) Finally after finding composite solution, specific filament or reinforcement direction can be ignored in steel design as equilibrium is satisfied in both, with compromise in steel because steel material is not directionally aligned as happens in filamentary composite monocoque stress flow. Figures 9 & 10 below indicates the stiffened pressure hull and composite shell before ignoring filament direction for steel.
curvature. Results are not as expected, under review.

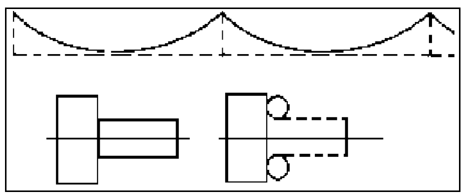


Figure 9: Spread-out stiffeners

6. Structural Analysis Results of Hydrodynamic Hull

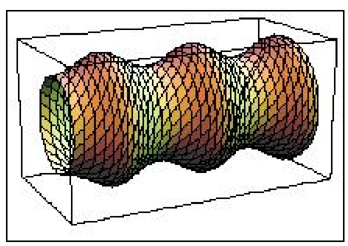


Figure 10: composite shell before ignoring filament direction for steel

5.2. Structural Analysis Results of Pressure Hull

Pressure hulls inside the hydrodynamic hulls are also analyzed using FE analysis (ANSYS software) and the results are found to be satisfactory for withstanding the hydrostatic pressures up to a depth of 20 meters. The deformation/stress of pressures hulls are shown in Figure-11 below.
The analyzed open steel shell has 2 meter diameter, 4 meter length, 3mm thickness, weighs 615 kg, full immersion displacement 10 tons approx. The maximum deformation found to be 0.7 mm, Von-Mises stress 4.0 kg/mm^2 and takes 38.4 bars external pressure, no shape change in Lanczos buckling.

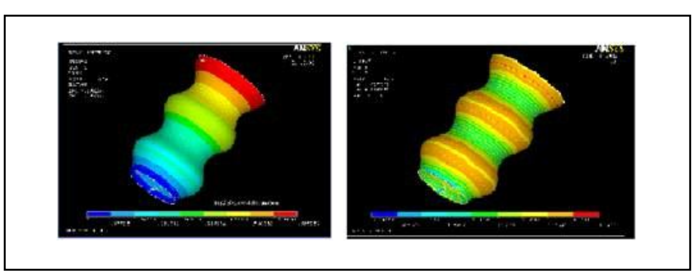


Figure 11: Pressure hull deformation and stress (FE Analysis)

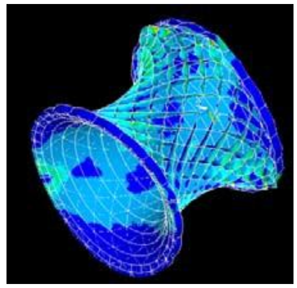


Figure 12: Skin/Helical stringer lightweight shell, positive K fully eliminated.

Another model of the pressure hull with skin/spiral stiffener design has also been designed/ analyzed, aimed to eliminate positive gauss The hydrodynamic hull of each of the spindle shaped hulls are designed to withstand only the normal wave loads and hydrostatic pressure which meets the rules and regulations of classification societies for construction and operation of the steel vessels. The hydrodynamic hull around the pressure is provided to have the streamlining effect of the water flow around the hull which imposes predominantly pressure drags.
Since the hull is immersed in the water, its wave making tendency is very low.

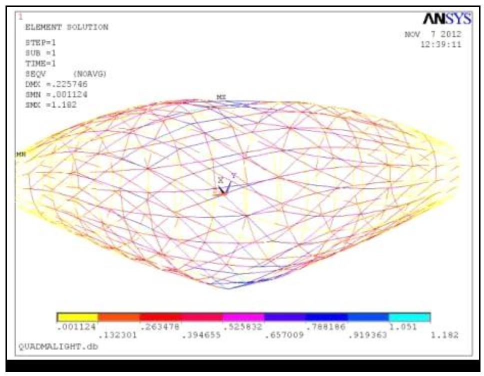


Figure 13: Reticulated HydroHull

In the second option above Fig. 13 constant Gauss curvature and preferred directions are shown for a Hydrohull (shown without sheets) designed with tube stiffeners (2” dia,1/8” thick), 5g self-weight with close two point support condition in dry dock. It weighs only
1.2 tons, max deformation and stress are 0.25mm and 1.2 kg/mm^2 respy. This is due to its rigid character.

7. Contemporary Trend in Certification

Recently ABS in Ref [8], in a guarded procedure enabled an alternate certification procedure without adherence to code in individual structural parts design for Siemens Company tourist submarine, considering it for certification only on basis of pure analysis and testing only. This relaxation in certification helps in furtherance of the State of Art. The fig.14 below indicates the ABS approved hull form which has a complete deviation from the standard structural designs and arrangements.

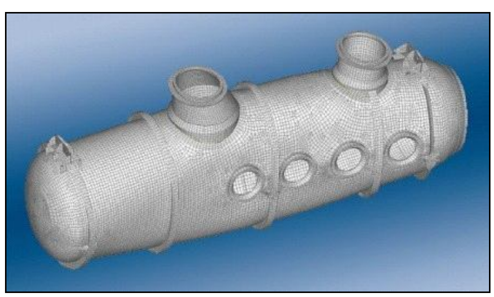


Figure 14: Reticulated HydroHull

8. Conclusions

Hyperbolic geodesics mathematical model choice and definition suitable for attention of mechanical/structural engineering adoption is in progress. Crude model is sufficiently encouraging. The search after appropriate geodesics is inconclusive at time of writing of this paper; however particular theoretical ANSYS analysis results have encouraged reporting them here even to undertake hardware development of critically loaded submarine hull.

9. Acknowledgements

First author recalls with pleasure encouragement given by Dr. S. Srinivasan, ex Director, VSSC/ISRO. Also am grateful to above students for faith reposed in new direction research risking their last semester as unreferenced work.

10. Nomenclature

AG	Appropriate Geodesic
ETB	Engineer's theory of bending
ICCM	International Conference on Composite Materials
R_1, R_2	Shell principal curvatures Filament-meridian angle Nc/, N_θ ,N_S Shell stress resultants r Shell radius
ε's, κ's	In plane strains, normal curvatures K, ΔK Gauss curvature and change
HP	Horsepower
MM	Millimetre
KG	Kilogram

11. References

i. Narasimham G.L. and R. Ramesh Kumar 'Ultralight Pseudospherical Shell' presented at International Conference of Composite Materials
ii. -ICCM12, presented at Paris, July 1999 , Paper 1362.
iii. Narasimham G.L, 'Stability of Reticulated Steel Shell Structures from Synthesis of Composites', Proc. of International Conference on Composites Engineering , ICCE7, Denver ,CO Edited David Hui, July 2000, pp 641-642.
iv. Inextensional deformation, Tech Univ, Delft, Netherlands. http://ebookbrowse.com/ct5143- handout-7b-pdf-d343793279
v. Anoop Abraham, J.P.Jacob,Riju Abraham, Shihad V.M., Static and Buckling characteristics of pseudospherical shells , Project Report, Rajiv Gandhi Institute of Technology, Mahathma Gandhi University, Kottayam , B.Tech Project Report. 1997. Project guide, G.L.Narasimham. VSSC/ISRO.
vi. Baiju Sasidharan, Design, Analysis and Fabrication of a Pseudospherical Shell as a Vibration Test Fixture, Master of Technology Thesis Report, Dept. of Ship Technology, Cochin