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Stipe Plenča
E-mail: stipeplenca@live.com
NCP-Group, Obala Jerka Šižgorića 1, 22000 Šibenik, Croatia
Albert Zamarin
E-mail: zamarin@riteh.hr
University of Rijeka, Faculty of Engineering, Vukovarska 58, 51000 Rijeka, Croatia

Structural Design of a Composite Trimaran

Abstract

This paper presents a project of a composite trimaran structure, designed and built for competing at the *Hydro Contest 2016* competition at Geneva Lake. Concept of the contest is to raise the awareness of tomorrow's engineers, industrialists, opinion leaders and the public of what is at stake with regard to energy efficiency in the sea transportation of goods and passengers. In addition, to be the laboratory of tomorrow's boats, particularly enabling the most innovative ideas to be developed in collaboration with the industrial partners. Designed boats must have technological innovations enabling them to achieve the most efficient use of energy. Therefore, the goal was to design, construct lightweight structure, within simple closed rules, with a satisfactory stiffens, and strength as well as to strive for more efficient transport, which means higher speed with minimal energy consumption. An analysis of project variants was made with regard to the hull shape, material, and technology of the fabrication and for the adopted variant, a computer structure model was developed, and the *FEA* was carried out. The structure is divided into three main sections analysed individually: hulls, front wing and rear wing along with rudder. Calculation was made for the worst load case, i.e. mass transfer, while wings were analysed at the highest advancing speed. The boat has structurally met all requirements since there were no structural problems in testing and competing.

Keywords: *hydrofoil trimaran, hull structure, composites, FEA*

1. Introduction

The demand for high-speed sea transportation has increased dramatically in the last 15 years [1]. This statement of 15 years ago is still valid but with today's additional requirements on air pollutions restrictions and environment protection where the problem and solution is directed toward energy efficient ships. Since high speed is closely related to the weight of the vessel, to achieve these new speed requirements, designers began to use lightweight materials in place of steel. One of the most common materials used to achieve lightweight structures in small to medium size high-speed vessels are composites [2]. Higher speed also means additional loads to the vessel's structure. One of the most critical of these additional loads is slamming, which occurs when the vessel's motion causes an impact between her bottom and bow flare plating or cross deck structure in multihulls, and the water surface. For ships that use hydrodynamic lift as a basic mode of motion, minimizing the mass of vessels is of crucial importance because of the need for achieving higher speed as well less energy required to achieve it. Therefore, the use of composite carbon sandwich laminate is required for the structure of hulls and wings. The combination of all of these is a challenge for designers since it integrates several engineering areas; computational fluid dynamics, structural finite element analysis, novel composite materials usage related to advanced manufacturing technology and all connected with green propulsion systems. One way to bring fresh ideas is competition between naval architecture students with support of their faculties, departments and professors [3]. Besides bringing new innovative ideas to be developed in collaboration with the industrial partners, the concept of competition is also to raise the awareness of engineers, industrialists, opinion leaders and the general public of what is at stake with regard to energy efficiency in the sea transportation of goods and passengers. Therefore, designed boats must have technological innovations enabling them to achieve the most efficient use of energy. The goal is to design and construct lightweight structure, within simple closed rules, with a satisfactory stiffness and strength as well as to strive for transport that is more efficient. This means higher speed with minimal energy consumption [4]. This paper is dealing with finite element analysis of the hulls and wings with help of FEMAP-NASTRAN software, [5] and XFLR5 [6]. XLFR is analysis tool for airfoils, wings and planes operating at low Reynolds Numbers which includes XFoil's Direct and Inverse analysis capabilities and wing design and analysis capabilities based on the Lifiting Line Theory, on the Vortex Lattice Method, and on a 3D Panel Method.

2. Structural Design of a Catamaran

The design procedure involves the entire process from the initial concept to the final approved design [7] ready for fabrication/manufacture. An important part of this process is the design control, or structural analysis, to ensure reliability against structural failure. The design control consists of a number of steps, [8]:

- evaluation of environmental conditions,
- analysis of loads,
- analysis of response,
- evaluation of strength, and
- control of safety.

The analysis methods used may be based on theory, experiments or full scale measurements. An additional essential step in this development process is the calibration of the result against service experience. Conventional monohull ship structural design has, as its basis, about a hundred years of combined data and experience. This background allows the structural design of the hull to be pursued by relatively well proven design methods [9]. Within limits, one hull form is similar to previous hull forms, and the design is relatively forgiving to under or overestimation of the loads. Any radical departure from the normal hull forms would severely de-value the usefulness of accumulated expertise, as knowledge of the loads is essential for design of the hull structure. The key element in the development of design procedures for trimaran vessels is the prediction of the loads acting on the hull structure. In the absence of experimental data for trimarans, an initial emphasis must be placed on theory. Consequently, a level of conservatism must be applied in order to maintain an acceptable risk level. The vessel used for this analysis, Fig. 1 (left), was built within box rules of *Hydro Contest 2016* competition at Geneva Lake, [3]. Therefore, the loads applied are related with two worst load case according competition disciplines which are:

Load case 1 – mass transport of 200 kg cargo

Load case 2 – hydrofoil mode with maximum speed, v_{max} = 5 ms^{-1}.

Main characteristics of the trimaran are presented in Table 1.

Table 1: Trimarans main particulars

	Overall	Main hull	Side hulls
L_{oa}	2450 mm	2450 mm	2000 mm
B	2435 mm	350 mm	260 mm
D		500 mm	
T_{sprint}		57mm	
T_{mass}		160 mm	
V_{max}		5 m/s	
$V_{t.off}$		2,5 m/s	

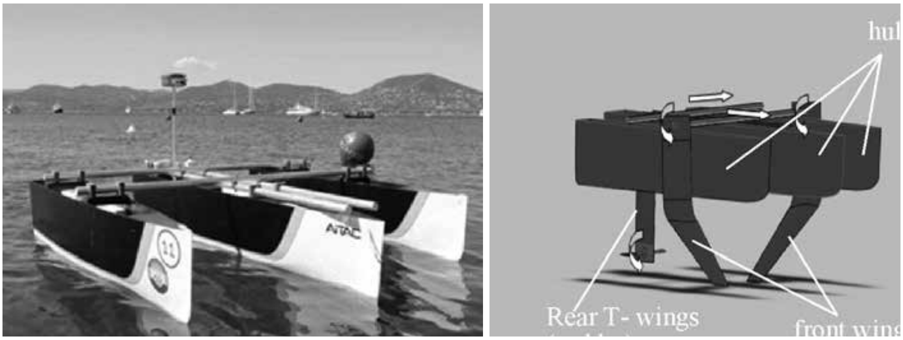

Figure 1. Designed trimaran at sea

When designing such a boat there is a conflict of design requirements because it is necessary to design a boat that carries 200 kg of cargo as well as to compete in a sprint race in hydrofoil mode with a load of 20 kg. Load represents standard steel profiles of the dimensions: 500 mm x 100 mm x 120 mm, where one such piece weighs 5 kg. When designing the initial concept, intention was to implement a straightforward guiding system at the start, which would allow the variable relative position of hulls and wings Fig. 1 (right). In other words, the front wings can be set to any length and width position at any incoming angle (thus adjusting the boat's pitch, roll and yaw). On the rear wing (stabilizer) the angle of incidence can also be changed.

3. FE Model

3.1. Hulls

Within initial phase, three possible configurations were taken into consideration for material [10], [11], 12] and production of vessel:

1. *Single skin* - 2x200 g/m^2 BIAX 0°/ **90°,** transverse frames of PVC foam core with thickness 10 mm and density 60 kgm^{-3} with laminate skin 2x200 g/m^2 BIAX 0°/**90°.**

2. *Sandwich* with PVC core – outer skin 200gm^{-2} carbon, 10 mm foam with density of 60 kgm^{-3}, inner skin 200 g/m^2 carbon.

3. *Sandwich* with NOMEX core, [13] (combined with TPT carbon)-outer skin 100 g/m^2 carbon, NOMEX core, inner skin 100 g/m^2 carbon, transverse frames with PUR foam core 60 kg/m^3 and laminate skin 2 x 200 g/m^2 BIAX 0°/ **90°.**

Table 2. gives material characteristics for hull and wing.

Table 2. Material characteristics

Characteristic	Material			
	Composite carbon-epoxy unidirectional	PVC FOAM	PLA polymer	Al
	linear orthotropic	isotropic	isotropic	isotropic
Young modulus, *E*, MPa	E_{11} = 12000 E_{22} = 6000	70	2000	70000
Shear modulus *G*, MPa	G_{12} = 4000 G_{13} = 4000 G_{23} = 4000	20	200	24000
Density ρ, kgm^{-3}	1600	60	1000	2700
Poisson ratio, *n*	0,255	0,3	0,3	0,3

Ultimate strength, tensile s_{ut}, MPa	long. 1437 transv. 32	-	-	275
Ultimate strength, compress. s_{uc}, MPa	long. 924 transv. 144	-	-	
Shear strength,τ, MPa	62	-	-	120

Hull structure and frames are modelled with *plate* elements. Goal is to generate flexible mesh for which would be easy to change parameters and have low computational time cost, Fig. 2. Transverse aluminium tubes are modelled as *beam* elements with 40 mm diameter and 2 mm shell thickness. Cargo is modelled with *mass* elements. In order to connect *mass* element with structure, *rigid RB3* elements are applied. Tubes are connected with hull structure with *rigid RB2* elements. This way all load carrying is done with frames and tubes in joint zone. Boundary conditions, Tab. 3, and loads, Tab. 4 differ for two load cases: mass transport (LC1) and hydrofoil regime (LC2). LC1 is unfavourable one and therefore is under scope further in this paper. Within LC2, load is generated by lift needed to start hydrofoil regime. When analysing hull, wings are not modelled and lift force is transmitted to structure with rigid elements.

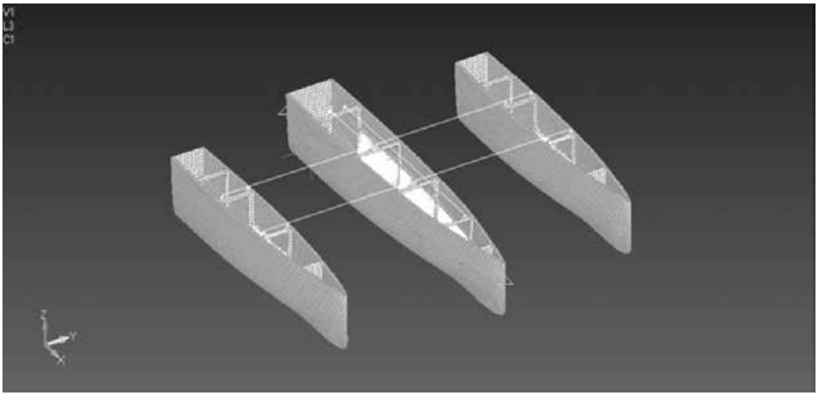

Figure 2. Hull model and mesh

Table 3. Boundary conditions

Boundary condition LC2 sprint	Translations per coordinate axes			Boundary condition LC1 mass transp.	Translations per coordinate axes		
	X	Y	Z		X	**Y**	Z
One node on left wing	free	free	fix	One node on ship bow	free	fix	fix
One node on right wing	free	free	fix	One node – right stern end	fix	fix	fix
One node on aft wing	free	free	fix	One node -left stern end	free	fix	fix
One node on tube end above outriggers right	fix	fix	free				
One node on tube end above left	fix	fix	free				

Table 4. Vessel load at LC1

	ρ, kgm^{-3}	*g*, ms^{-2}	*h*, m	*f*	Total, Pa
Hydrostat. press.	1000	9,81	0,2	1,3	2550,6
Cargo	Mass 1 , kg	Mass 2, kg	Mass 3, kg		Total, kg
Masses, hulls	60	60	20	1,3	78/78/26
Cargo		Mass (kg)			Total, kg
Masses, outriggers	30			1,3	39

3.2. Rear T-wing/rudder

This part of structure is the most demanding for analysis of all structure since it is composed of more different material and multiple joints as shown on Fig. 3 and Table 5.

Table 5. Geometry of T-wing/rudder

Geometry		
Height	570	mm
T-wing span	705	mm
Rudder chord line length	190	mm
Wing chord line length	95	mm
Profile NACA	63-412	

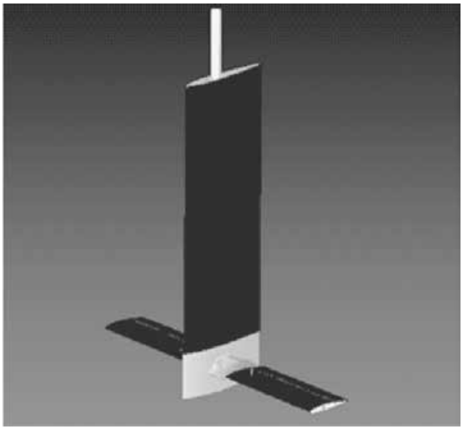

Figure 3. T-wing/rudder

Figure 4 and 5 shows elements made out of 3D printed PLA plastics (Table 2) for wing girder joint and their housing when positioned on rudder.

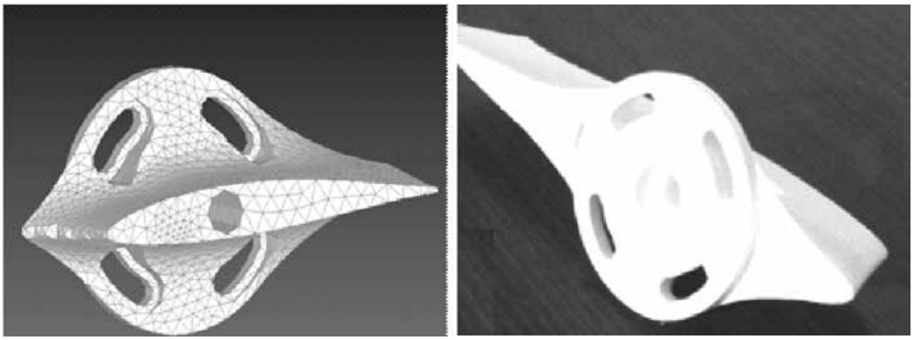

Figure 4. 3D printed wing joint: FEMAP model (left) and manufactured (right)

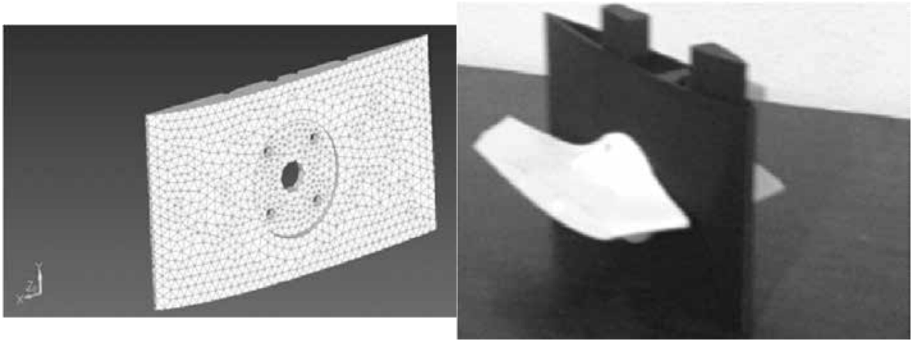

Figure 5. 3D printed housing: FEMAP model (left), manufactured part (right)

With aim to simplify analysis within acceptable calculations time regarding model, few assumptions and simplifications are made [14]. First, lift is modelled as evenly distributed load across wing while in reality most of lift is concentrated at approximately 1/3 of leading edge of wing. 3D effect is also neglected where in transverse plane lift distribution can be approximated as parabolic which is effect of tip vortex when fluid streams from high pressure to low pressure field. Final assumption is for drag, modelled as evenly distributed load along leading edge of wing. Geometry scheme is presented on Figure 6.

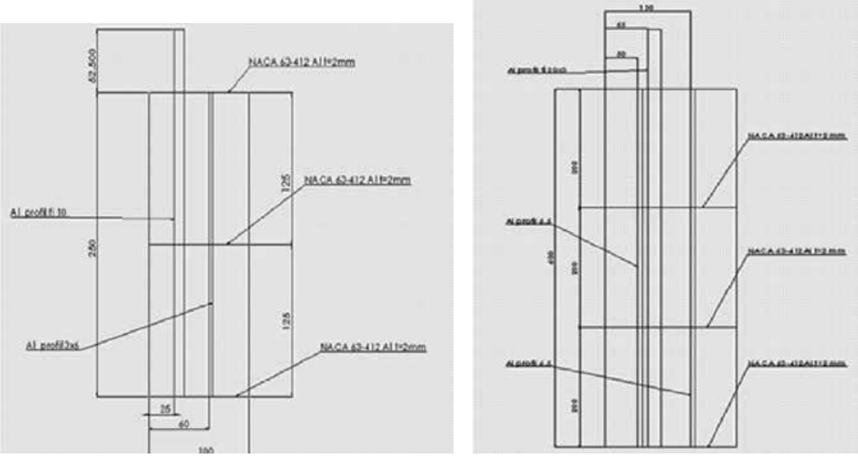

Figure 6. Framing scheme: wing (left) and rudder (right)

In order to function properly, wing must possess enough stiffness especially because rudder can be consider as vertically placed wing-console. Therefore, it needs to be fixed and strengthened with internal framing. Rudder is symmetric NACA profile modelled with triangular-parabolic *laminate* element. Components of rear wing/rudder along with corresponding elements are given in Table 6 while model is presented on Fig. 7.

Table 6. Rear T- wing / rudder element type

Component	Material type	Element type
Rear wing girders	Aluminium	SOLID – TETRAEDAR PARABOLIC
Rear wing frames	Aluminium	PLATE –TRIANGULAR PARABOLIC
Rear wing skin	Carbon	LAMINATE – 2D ORTOTROPIC
Rudder girders	Aluminium	SOLID –TETRAEDAR PARABOLIC
Rudder frames	Aluminium	PLATE-TRIANGULAR PARABOLIC
Rudder skin	Carbon	LAMINATE -2D ORTOTROPIC

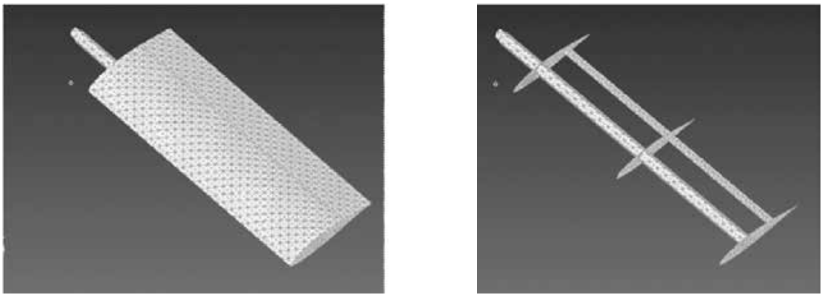

Figure 7. Rear wing mesh: skin (left) and framing (right)

Boundary conditions are presented in Table 7. and shown on Figure 8.

Table 7. Boundary conditions

Boundary conditions	Translations/Rotations per coordinate axis		
	X/XX	Y/YY	Z/ZZ
Rudder top skin prevent translations vertically into hull	/ /	fix /	/ /
Rudder axis	fix/fix	fix/fix	fix/fix

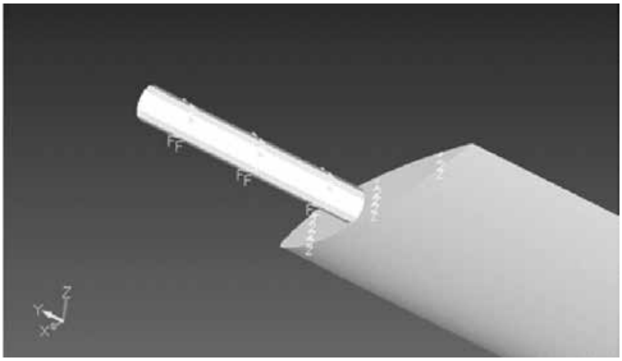

Figure 8. Boundary conditions on rudder

Lift is calculated using (1) while results are given in Table 8.

$$L = \frac{1}{2} \cdot \rho \cdot v^2 \cdot A \cdot C_L \cdot \sin\alpha \tag{1}$$

For calculating lift force following parameters are used: $v = v_{max} = 5\ \mathrm{ms}^{-1}$, wetted surface of rudder at maximum speed with maximum flying height of 300 mm above free surface; $A = 0.019\ \mathrm{m}^2$, $\rho = 1000\ \mathrm{kgm}^{-3}$, lift coefficient $C_L = 0.9$, maximum rudder deflection angle =30°. It worth to notice that lift coefficient is taken as very large number since rudder on this vessel is vertical wing on which lift and drag force occurs. When looking at 3D flow effects, lift coefficient C_L representing loss of lift because fluid transfer, from high to low pressure field, demonstrates as tip vortex. When vessel is in hydrofoil regime, on rudder is placed rear wing. This way rear wing acts as T-foil strut. Such configuration then represents barrier (rear wings) on lower part of rudder and acting as winglet on airplane wings.

Table 8. Forces on Rear wing/ rudder

	Load, N	Load increase factor	Total load, N
Rear wing lift	85.5	1	85.5
Rear wing drag force	10	1	10
Rudder lift	213	1	213
Rudder drag	10	1	10
Motor mass 3.8 kg	37.3	1	37.3
Trust force	320	1	320

It can be concluded that small part of surface, where lift on rudder occurs while in hydrofoil regime and flying at 300 mm above free surface, is zone of favourable lift conditions and that is why C_L is high. In addition, below rudder engine is placed, whose geometry also represents flow barrier. By setting C_L high, the total lift force would be higher, producing additional safety factor. Forces listed above are obtained by CFD analysis of rear wing-hull-front wing system.

3.3. Forward wing

Dihedral wing is used due to its effect on active stabilization in transverse plane, meaning control of roll. During vessel acceleration, while the wing is generating more and more lift, dihedral wing is emerging from water. Once it reaches enough speed dihedral wing won't generate more lift since it will start to loose wetted surface. In order to control pitch, it is necessary to have one stabilizing wing as rear stabilizator in form of T-wing which angle of attack is regulated also from the front wing as it affects trim of vessel and by that angle of incidence. Longitudinal wing girder, Figure 9., is modelled with *beam* elements, while girder –frame joint is ensured by *rigid* elements. Wing skin is modelled by *laminate* elements, Table 9.

Table 9. Laminate and foam of forward wing

	Material type	MATRIX	THICKNESS, mm
Wing shell	200 g/m^2 -KARBON UD	EPOXY	0,218
	200 g/m^2 – KARBON PLAIN +45°/ -45	EPOXY	0,218
Wing fill	PUR FOAM 60 kg/m^3	/	/

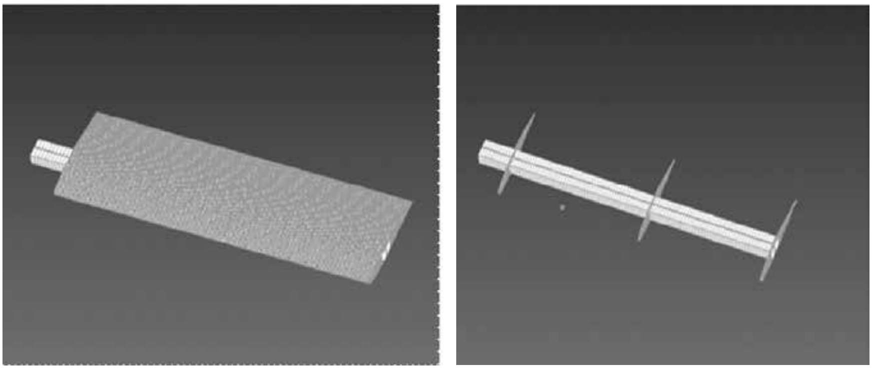

Figure 9. FEMAP mesh: wing plate (left), aluminium framing (right)

Due to large unsupported span between aluminium cross frames, it is necessary to fill wings with foam in order not to have loss of shape on wing caused by large local deformation, Fig 10.

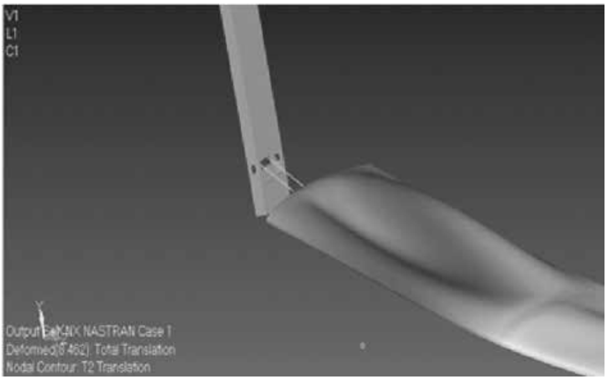

Figure 10. Example of shape loss on front wing near strut to wing girder joint

Framing of front wing is shown on Figure 11. Boundary conditions are relatively simple because in this load case model under consideration act as console girder and therefore rotation and translation in joint with hull are fixed. Base parameters are obtained from CFD analysis of hull-forward wing-aft wing system and shown in Table 10.

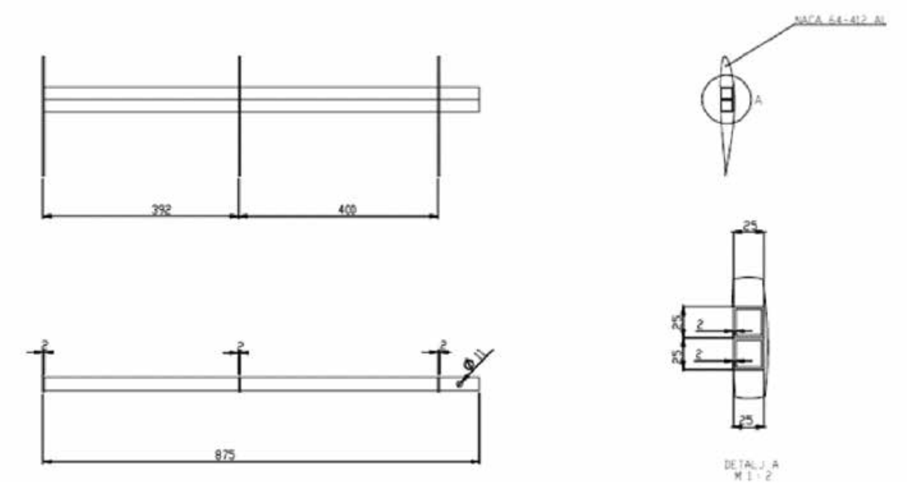

Figure 11. Forward wing scheme

Dihedral wing generates lifting force; when once equal to weight remain constant. The only parameter changed is wetted surface that is reduced with speed increase. Major problem with setting the lift force on element mesh is determination of wetted surface in order to position load as real as possible. Wing is analysed for most unfavourable case that is at maximum speed that produce total lift force of 171 N. Lift coefficient of 0,34 is obtained from 3D flow analysis using *XFLR* software. Applying (2) wetted surface A^* is calculated without taking into account dihedral angle at which the wing is set, therefore the real wetted surface is

$$A^* = c \cdot b^* \tag{2}$$

where b^* – length of immersed part of wing

Real length of wetted surface can be calculated using (3):

$$b = \frac{b^*}{\cos \Gamma} \tag{3}$$

Real wetted surface is: $A = c \bullet b = 46641$ mm^2

Once the wetted surface is calculated, all nodes belongs to wetted surface may be loaded with force F:

$$F = \frac{L}{n_{nodes}} \tag{4}$$

Table 10. Loads on front wing

	Force, N	Factor of load increase	Total force, N
Lift on forward wing	171	1	171
Drag on forward wing	27.5	1	27.5

4. Results and Discussion

4.1. Hulls

In case of LC1 increased stress is noted on frames, as expected considering it's a zone where loads are transferred between hulls due to the difference in displacement at mass transport (main hull takes 140 kg and outriggers 30 kg each). Global Von Misses stress on structure is low, Figure 12. Deformation of model for LC1 and for two different hull types are shown on Figure 13.

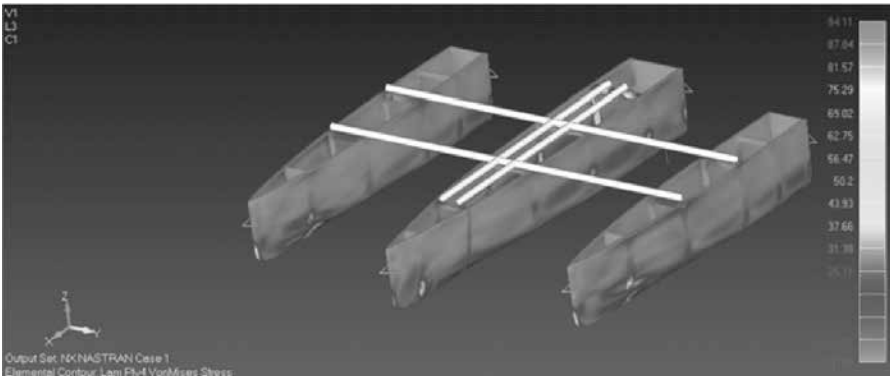

Figure 12. Von Misses stress in MPa

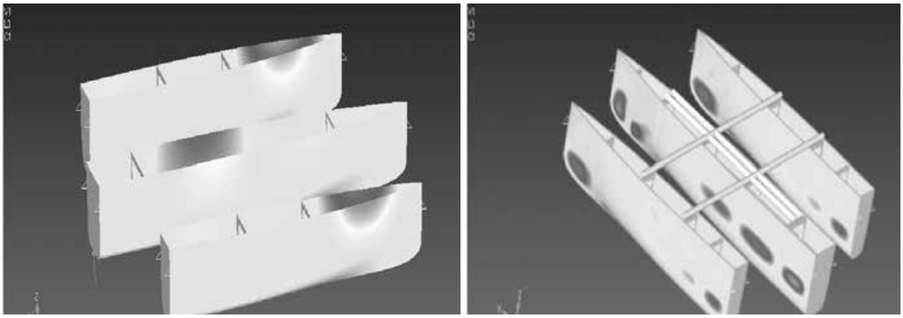

Figure 13. Deformation in global Y-axis (perpendicular on hull sides); single-skin (left) and NOMEX (right) in mm

Single skin is cheap and light, but need to be stiffened with longitudinal stiffeners which brings complexity in production. Sandwich type with PVC foam results with good stiffness, there is no need for longitudinals and therefore production is somehow easier then single skin. Regarding NOMEX, the hulls are extremely light with enough stiffness, but the price is much higher than in two previous cases. In final, single skin-sandwich combination with base laminate 2x200 g/m^2 BIAX 0°/ **90°** is chosen. This way, putting foam in hull sides, they get enough stiffness while single skin is placed at keel zone only. All masses, deformation and stress results are shown in Table 11. Hydrofoil load case is characteristic because the highest stress is expected in tubes while hull is low stressed. For simplicity the wing models in latter case are left over and rigid elements are placed to transfer forces in tubes according to Figure 14. Deformations are displayed for LC2.

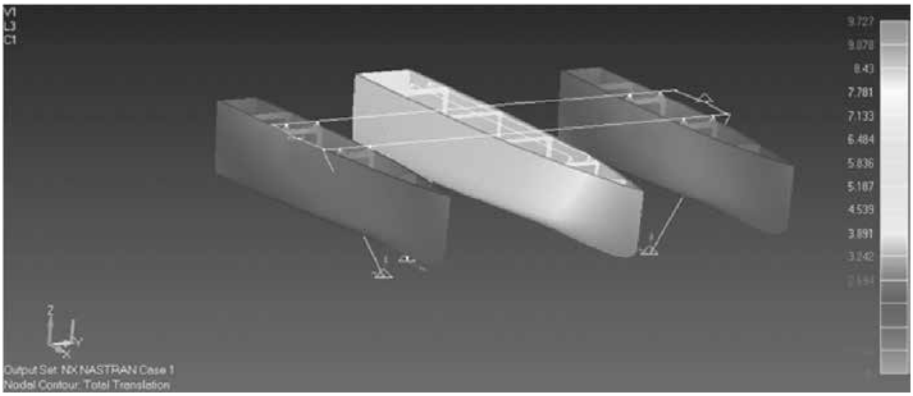

Figure 14. Total deformation in hydrofoil regime, mm

Table 11. Mass, max. deformation and max. stress for 3 types of hull structure taken into consideration at mass transport (LC1)

	mass, kg	max. transl, mm	max. stress, Nmm^{-2}
SENDWICH -NOMEX	4,04	4,29	58,78
SINGLE SKIN	6,5	4,5	94,11
SENDWICH - PVC	7,38	0,96	35,27

4.2. Rear T-wing/rudder

Results of analysis are shown as deformation Fig. 15., and stress Fig. 16.

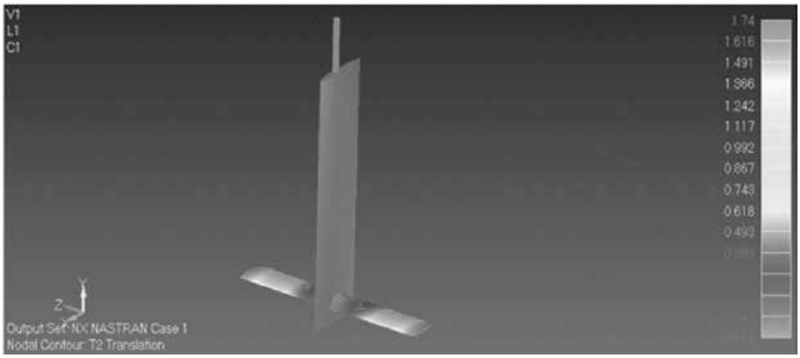

Figure 15. Deformation in global Y-axis, mm

From the results it can be seen that for given laminate schedule the structure itself is rigid enough with small deformations. There was no local loss of shape on wings and rudder, Von Misses stress are also within allowed limits with peak at 44.1 MPa. Total deformations on wing tip at 213 N loads are 16.6 mm. With further analysis, if rudder force is neglected and only lift force is applied on wings, with 85.5 N totals, the wing tip translations are then only 1.74 mm.

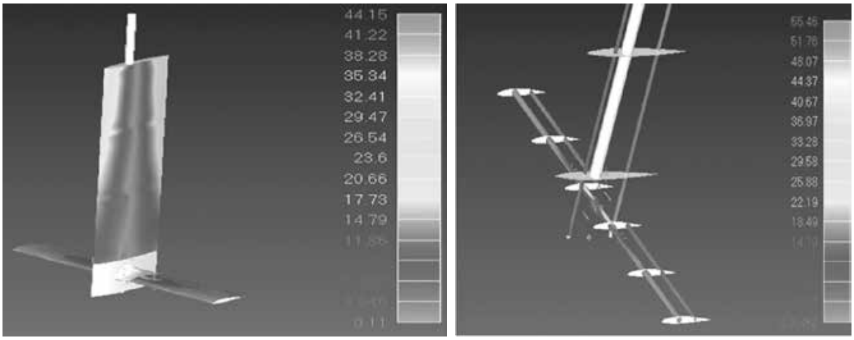

Figure 16. Von Misses laminate stress (left) and girder stress (right), MPa

Girder stress is higher in central joint of wing girders, which is expected since at that point the parts mentioned, are fixed, while on the other end there are free at wing tip. Everything stated leads to conclusion that with presented laminate schedule, construction will be rigid and light. Rudder and wing are hollow inside and there is no foam fill as no loss of shape is noted during analysis.

4.3. Forward wing

Analysis results are pointing on two basic aspects: wing stiffness and influence of deformation on whole structure. Therefore, model is made where strut to wing girder joint is fixed, Figure 17. Once, when translation of strut is neglected the same are reduced from 15 mm to 7.3 mm. In that case, vertical component (Y-axis) of deformation is only 1.8 mm.

Laminate is under low-stress with maximum at 91.2 MPa. Regarding translation analysis, the pre-determined allowable range is to be formed in order to define analysis goals. Small strut translation results in large wing translation, so the strut itself should have increased rigidity, but with increase in strut rigidity there is also a penalty of mass increase.

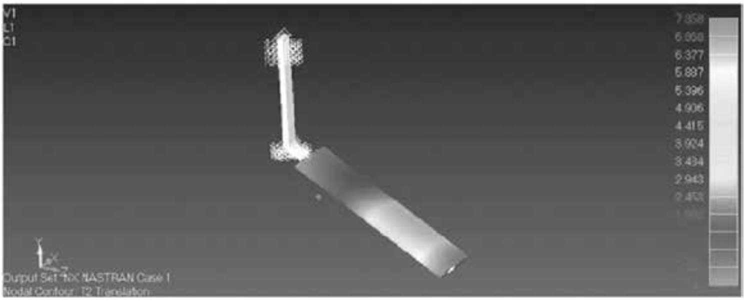

Figure 17. Translations in global Y-axis, mm

During the testing and competing there were no problems with translation, such could be due to wing tip vibration or loss of shape or structural failure. At targeted speed, the vessel achieved enough lift and hydrofoil regime. Additional, if only static vertical deformations are taken into account there have positive influence on lift (more) as they reduce dihedral angle Γ=30°. Analogy with this can be found on high speed special craft where wing produce enough lift, once, when under load influence (vertical translations) have enough wetted surface [8].

5. Conclusion

Within paper, project and structural analysis of hull and both wings, front and rear of composite trimaran, for different hull configurations and two load cases are shown. Since mass transport is the worst load case, more space is devoted on results for that particular load case. However, the sprint load case in hydrofoil regime is also important as one of the competition discipline. Therefore, the need for optimization between these load cases arises. For complete information of deformation influence of lift, it is necessary to perform hydroelastic analysis of such system in order to get whole picture of fluid-structure interaction, which will enable optimization of whole system.

Hull are made with goal of minimizing mass by incorporating available materials. It is possible to build even lighter construction with more advance/expensive materials or use single skin layout just for sprint races. A problem that arises and that have to be controlled is mass increase during production, because it influences hydrodynamic picture of vessel and if such increase is not in allowable limits, hydrofoil regime could become impossible to achieve. In addition, full composite construction should be goal for this purpose. Such building technology will produce structure that is more compact then aluminium-carbon one, which usually have bonding problems. In addition, wings can be designed and constructed as pure carbon material with pultruded carbon tubes positioned on pre-cutted wing frames. Those frames would be made of sandwich-carbon plate and shaped in order to fit inside the wing. These solutions are going to be implemented on new AHT vessel for Hydrocontest 2018 shown in Figure 18.

Figure 18. New vessel: IHC 2018

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Stipe Plenča, Albert Zamarin

Projekt konstrukcije kompozitnog trimarana

Sažetak

U radu je prikazan projekt konstrukcije kompozitnog trimarana, koji je projektiran i izgrađen sa svrhom natjecanja na takmičenju *HydroContest 2016*. godine na Ženevskom jezeru. Osnovni cilj takmičenja je podizanje svijesti budućih inženjera, gospodarstvenika, kreatora javnog mijenja i javnosti općenito o tome koji je ulog kod pomorskog prijevoza dobara i putnika s obzirom na efikasnost utroška energije, a ujedno da bude i laboratorij budućih inovativnih ideja i rješenja u suradnji sa privredom.
Projektiran i izgrađen brod stoga mora obuhvatiti tehnološke inovacije koje mu omogućuju efikasno korištenje energije. U okviru jednostavnih zatvorenih pravila, prikazano je idejno rješenje, projekt strukture i tehnologija izrade s ciljem što lakše konstrukcije, uz zadovoljavajuću krutost te čvrstoću i istovremenu težnju efikasnijem transportu, a što podrazumijeva veću brzinu uz minimalan utrošak energije. Napravljena je analiza projektnih varijanti s obzirom na oblik trupa, materijal i tehnologiju izrade, te je za usvojenu varijantu izrađen računalni model strukture i provedena strukturna analiza konačnim elementima. Struktura je podijeljena na tri glavne cjeline koje su analizirane zasebno a to su: trupovi, prednje krilo te zadnje krilo zajedno sa kormilom. Proračun je izvršen za najnepovoljniji slučaj prijenosa mase, dok su krila analizirana pri najvećoj brzini plovidbe. Plovilo je zadovoljilo sve zahtjeve budući nije došlo do bilo kakvih strukturalnih problema prilikom testiranja i natjecanja.

Ključne riječi: *trimaran na hidrokrilima, struktura trupa, kompoziti, MKE analiza*