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Structural Performance of Hybrid Composite Pontoon Compared to Steel

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Abstract

Fiber reinforced polymer (FRP) composites have been increasingly used in civil infrastructure applications. They are a viable alternative to conventional construction materials such as steel and reinforced concrete due to their advantageous properties such as high strength-to-weight, corrosion resistant and durability. Several studies suggested the effective use of hybrid FRP composite sections to utilize the physical and mechanical properties of each of the used materials. Foam is most frequently employed as structural core material for composite laminates to improve the structural behavior in the transverse direction and reduce lateral buckling for laminates.Steel pontoon has disadvantages like rapid corrosion as it requires frequent maintenance and may require extensive repairs. It has heavy own weight which is deducted from the pontoon load carrying capacity.

In this paper, a numerical simulation study is carried out to investigate the structural performance of 70 ton pontoon made of hybrid composite FRP to overcome the disadvantages of steel pontoon and get benefits of composite materials. Finite element model is constructed using ANSYS Composite Prep Post (ACP) software version 15.0.

The design and factor of safety of the hybrid composite pontoon (HCP) is carried out according to EUROCOMP design code. The parametric study included different structural geometric configuration of the HCP, the option of using foam is considered in order to increase the structural capacity of the HCP and finally the influence of lamina orientation on the structural performance and load carrying capacity of the HCP is studied. The results of the parametric studies represented by different structural parameters is discussed and compared to its counterparts of the steel pontoon. The proposed HCP system is found to be structurally reliable as the pontoon draft is significantly reduced and it supports higher load carrying capacity compared to the steel pontoon and has the advantage of own weight reduction by 83.9 %.

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Key words

Composite material, steel pontoon, floating structures, Hybrid composite sections, Finite Elements.

1- Introduction.

Fiber reinforced polymer (FRP) composites have been increasingly used in civil infrastructure applications such as corroded bridge deck replacements, footbridges, and emergency vehicle bridges as well as military applications. They have attracted the interest of many researchers in the field of civil engineering since the 1980's. They are a viable alternative to conventional construction materials such as timber, steel, and reinforced concrete due to their advantageous properties such as high strength-to-weight, light weight, durable, readily transported, easily erected and corrosion resistant.
Several studies suggested the effective use of hybrid FRP composite sections to utilize the physical and mechanical properties of each of the used materials and to offset the disadvantages and deficiency of the others, in order achieve design requirements and economics.

Foam is most frequently used as structural core material for composite laminates to improve the structural behavior in the transverse direction and reduce lateral buckling for laminates, make as insulation, it is easy to handle, readily conforms to shapes, and can be bonded in layers to add thickness without adding weight.

Steel pontoon has disadvantages like rapid corrosion, and will rust over time when exposed to moisture and air. This leads to leaks and cracks, which requires frequent maintenance and may require extensive repairs. Another disadvantage of steel pontoon is its heavy weight, when designing a pontoon bridge; the civil engineer must take into consideration the maximum amount of load that it is intended to support. It has heavy own weight which is deducted from the pontoon load carrying capacity.

In the last decade, the research and development of all FRP structures in civil engineering has progressed substantially. Filling foam improved the longitudinal response of the GFRP deck and the strength was increased about 20% but the elastic modulus was not improved [1]. Alnahhala W. and Aref A. [2], found that a combination of FRP composites and concrete provide a promising advancement in civil infrastructure applications as the stiffness of the hybrid bridge was 35% higher than that of the FRP-only bridge. Hai, N. D. et al [3], studied hybrid beams made of CFRP and GFRP in the flanges and only GFRP in the web. The failure strength and failure mode of hybrid FRP beams were dependent on the carbon volume content in the flanges. It seems that when the higher carbon volume content is utilized, the extent of delimitation is greater resulting

in the lower failure load of beams. They found that the optimum carbon volume content in the flanges for the best hybridization of FRP beams was experimentally and numerically determined to be 25–33%. As compared to steel and aluminum military bridges, the load carrying capacity of composite bridges is relatively high when considering their strength-to-weight and strength-to-mass ratios. The weight and cost analysis of current composite bridges reveal that they weigh 75% of similar existing aluminum bridges however its cost is 10% higher [4]. Three hybrid composite beam (HCB) bridges were recently constructed in Missouri, USA. The study demonstrated that the HCB is promising technique in the highway bridge applications [5].
G.B. Maranan and A.C. Manalo [6] experimentally studied the structural performance of a sandwich-structured glue-laminated beam, named as hybrid FRP composite beam. They concluded that the stiffness of the hybrid beam was enhanced due to the addition of top and bottom GFRP plates. Even though the transverse shear strength of top and bottom GFRP skins are exceeded, the skins continued to resist stresses through its tensile strength. Khalifa, Y. A. [7] carried out finite element model for continuous type 70 ton steel pontoon using (ANSYS v. 11.0), as the traffic load capacity is assigned to 63.5 ton. The maximum calculated draft was 722 mm and the mass of the steel pontoon was (31625 kg). In addition, many studies cover a wide range of fiber and matrix types, fiber lay-up and stacking sequences, etc., which result in different structural behavior. Thus, additional investigations are required to enable the civil engineers to have confidence in designing of hybrid beams for real bridge application.

In this paper, a numerical simulation study is carried out to investigate the structural performance of 70 ton pontoon made of hybrid composite FRP to overcome the disadvantages of steel pontoon and get benefits of composite materials. Finite element model is constructed using ANSYS Composite Prep Post (ACP) software version 15.0.
The design and factor of safety of the hybrid composite pontoon (HCP) is carried out according to EUROCOMP design code. The parametric study included different structural geometric configuration of the HCP, the option of using foam is considered in order to increase the structural capacity of the HCP and finally the influence of lamina orientation on the structural performance and load carrying capacity of the HCP is studied. The results of the parametric studies represented by different structural parameters is discussed and compared to its counterparts of the steel pontoon. The proposed HCP system is found to be structurally reliable as the pontoon draft is significantly reduced and it supports higher load carrying capacity compared to the steel pontoon and has the advantage of own weight reduction by 80%.

2. Modeling of the Baseline Floating Steel Pontoon.

Three-dimensional FE analysis is carried out to investigate the structural performance of the continuous floating steel pontoon using ANSYS version 15.0. The codes assigned for such structure application limited the maximum draft as not to exceed 80% of the total height of the pontoon. Khalifa, Y. A. [7] developed and verified FEM of steel pontoon with load capacity equal to 70 tons. The inner pontoon is formed of 4 mm thick stiffened plates, the longitudinal ribs made of cold formed unequal angles 100×50×4mm spaced at 250mm with cross rectangular frames made of unequal angles 160×80×4 spaced at 900mms as shown in Figure 1. The analysis revealed maximum draft of 751mm. In the current paper, the FEM of the same pontoon is reconstructed for the same model parameters and configuration to serve as a base line for comparisons with the proposed pontoon made of composite materials.

2.1 F.E.M. of Floating Steel Pontoon.

The mechanical properties of steel used are listed in Table. 1. The upper, lower flange and the web plates are modeled using element SHELL181. The ribs and the cross rectangular frames are modeled using element BEAM188. The boundary condition to simulate water support of the lower pontoon surface is modeled as beam on elastic supports with ($k = 8$ kN/ m^3) [7]. The pay load of the pontoon is simulated as uniform pressure equal to (1.8×10^5 Pa) applied to limited area that simulates tank chain. The results showed good agreement with its counterparts acquired by Khalifa, Y. A. [7] in which the maximum draft found to be 750 mm and the total weight equal to 31625 kg. Figure 2 illustrates the deformation pattern of the 70 ton steel pontoon.

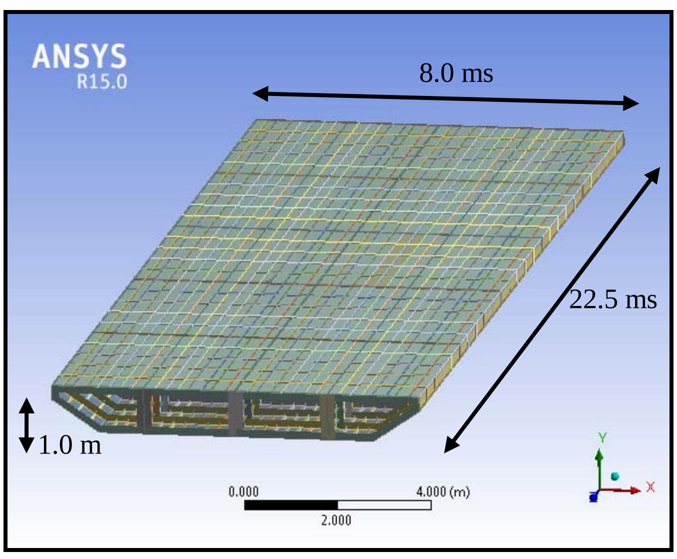


Figure 1. Geometrical dimensions and details of steel pontoon.

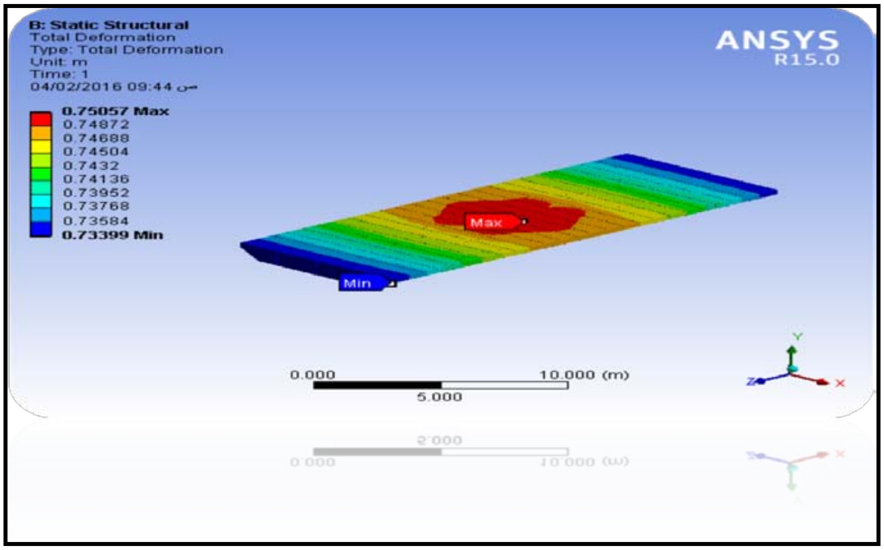


Figure 2. Deformation pattern of the 70 ton steel pontoon.

Table 1. Mechanical properties of materials.

Material	Steel	Epoxy_Carbon_UD _395GPa_Prepreg	PVC Foam
Density (kg/ m^3)	7850	1540	36
Compressive modulus (MPa)	2E5	209E5	26
		9450	
Compressive strength (MPa)	460	-893	0.25
		-139	
Tensile modulus (MPa)	2E5	209E5	44
		9450	
Tensile strength (MPa)	460	1979	0.48
		26	
Shear modulus (MPa)	7.7E4	5500	13
		3900	

Shear strength (MPa)		100	0.33
		50	

3. Proposed Hybrid Composite Pontoon (HCP).

In order to overcome the disadvantages of steel pontoon and get benefits of composite materials characteristics, floating pontoon made of hybrid composite FRP is proposed in the current study, named HCP. The proposed HCP has the same outer dimensions as that of the steel pontoon introduced in the previous section to keep the same draft limits. The structural configurations and systems of each HCP are listed in Table 2. The parametric studies included three structural geometric configuration of the HCP. The studies aimed to investigate the structural performance and determine the optimal web spacing and the weight. The structural configurations are illustrated in Figure 3. The deflection limits and the factor of safety for design is set according to EUROCOMP Design Code [9]. The upper, lower and web plates are selected to be Epoxy_Carbon_UD_395GPa_Prepreg with fiber orientation (0/90) as each lamina has a thickness of 0.5 mm.

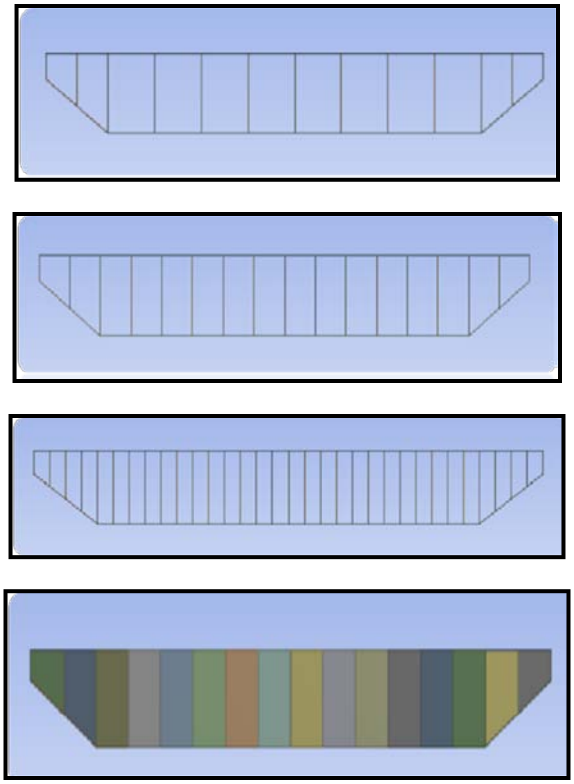
3.1 F.E.M. of HCP.

The modeling procedure is carried out using ANSYS Composite Prep Post ACP. The mechanical properties are listed in Table 1 according to ANSYS library [8]. Parametric numerical simulation studies are carried out to investigate the structural performance of 70 ton pontoon made of hybrid composite FRP. Finite element model is constructed using ANSYS Composite Prep Post (ACP) software version 15.0. The upper, lower flange and the web plates are modeled using element SHELL181. The boundary condition to simulate water support of the lower pontoon surface is modeled as beam on elastic supports with (k = 8 kN/ m3) [7]. The pay load of the pontoon is simulated as uniform pressure equal to (1.8×10^5 Pa) applied to limited area that simulates tank chain. The composite plates are meshed by element size equal to 20×5 cm. The total number of elements and nodes are variable with respect to each structural configuration.

Table 2. Dimensions of structural configurations of different HCP.

Configuration	**Thickness (mm)**			**Web Spacing (mm)**
	Upper Flange	**Lower Flange**	**Vertical webs**	
HCP (A)	32	6	4	750
HCP (B)	18	5	4	500

HCP (C)	10	5	3	250



Structural Configuration HCP (A)

Structural Configuration HCP (B)

Structural Configuration HCP (C)

Structural Configuration HCP (B)_foam

Figure 3. Structural geometric configuration of different HCP.

3.2 Effect of Foam Filling on the Performance of HCP.

In order to enhance the structural performance of the HCP, PVC foam is used as filling material to prevent web buckling. The mechanical properties of PVC foam are listed in Table 1. The parametric study was carried out on HCP (B), as listed in Table 3, as the new pontoon named (HCP (B)_foam) has the same web spacing as that of HCP (B). The FEM parameters are the same as HCP (B), in the addition that the bulk foam in represented using element (SOLID 186), in accordance with ANSYS Composite Prep Post (ACP) software version 15.0.

Table 3. Structural configurations of HCP (B) filled with PVC foam.

Configuration	Thickness (mm)			Web Spacing (mm)	Foam Filling
	Upper Flange	Lower Flange	Vertical webs		
HCP (B)	18	5	4	500	Non

HCP (B)_foam	5	4	3	500	Filled

Table 4. Structural parameters of HCP compared to steel pontoon.

Configuration	**Draft in (mm)**			**Pontoon weight (kg)**	**% Weight improvement**
	Max.	**Min.**	**difference**		
Steel Pontoon	751	734	17.0	31625	------
HCP (A)	844.66	804.23	40.43	12099	61.7%
HCP (B)	809.71	769.7	40.01	8673.4	72.6%
HCP (C)	793.79	760.18	33.61	7367	76.7%
HCP (D)	818.87	779.24	39.63	(4039) FRP. (5783) foam	68.9%

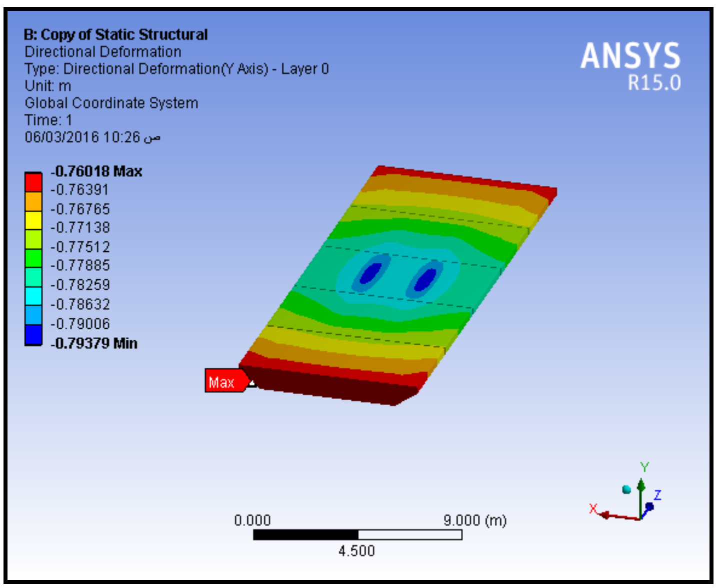


Figure 4. Differential draft for HCP (B)_foam.

4. Analysis Results and Discussion

4.1 Effect of web spacing on the structural performance of HCP.

In order to determine the optimum web spacing, three numerical simulation were carried out HCP (A), HCP (B) and HCP (C), such that the web spacing set to (750, 500 and 250 mm) respectively. The design factor of safety is set to (4) according to EUROCOMP Design Code [9]. The upper, lower and web plates are made of Epoxy_Carbon_UD_395GPa_Prepreg with fiber orientation (0/90) as each lamina has a thickness of 0.5 mm. The mechanical properties are listed in Table 1 according to ANSYS library [8]. The structural elements dimensions are listed in Table. 2. The maximum and minimum draft values for the three parametric studies are listed in Table. 4, from which it can be concluded that decreasing the web spacing to 250 mm, for HCP (C), resulted in remarkable improvement of the draft difference. This implies that the generated strains are decrease, however, the total weight is decreased as well and lead to the optimum percentage weight improvement compared to the steel pontoon.

4.2 Effect of Foam Filing on the performance of HCP

Aiming to reach a better structural performance, and optimum economic cost, the forth numerical simulation is carried out, (HCP (B)_foam), in which PVC foam is used as a filling material for HCP (B) configuration. It is found that the use of the foam as filling material would enhance the structural performance of the pontoon composite system as shown in Figure 4. The weight of the composite material significantly decreased by 53% compared to HCP (B). Although, the percentage weight improvement is decreased from 72.6% to 68.9% for HCP(B) and (HCP (B)_foam) respectively as illustrated in Table 4., but economically wise, the overall cost for (HCP (B)_foam) is less than HCP(B) because of the significant decrease in the weight of the composite material.

4.3 Effect of fibers orientation of the upper flange on draft difference.

The system HCP (C) is employed in the current parametric study as the reference system. The orientation angle of the fibers for layers of the upper flange is varied from 0^o to 90^o with step 10^o as (θ, - θ) with x-axis. The orientation angles for the web and lower flange are kept at (0^o / 90^o) as specified for HCP (C). Figure 5. illustrates the relation between the orientation angle and the difference in draft, which reached the value of (33.17 mm) as the orientation angle increase up to 90^o. The draft difference slightly improved by1.3% of the reference value for HCP(C) (33.61 mm).

4.4 Effect of fibers orientation of the lower flange on draft difference

Based on the result reached in the previous parametric study, the orientation angle of fibers of the upper flange set to 90^o and the webs as (0^o / 90^o). The orientation of fibers for the lower flange is then varied from 0 to 90 as (θ, - θ) with x-axis, as specified for HCP (C). Figure 6. illustrates the relation between the orientation angle and the difference in draft, which reached the value of (30.68 mm) as the orientation angle increase up to 90°. The draft difference insignificantly improved by 8.7% of the reference value for HCP(C) (33.61 mm), which still beyond the target enhancement.

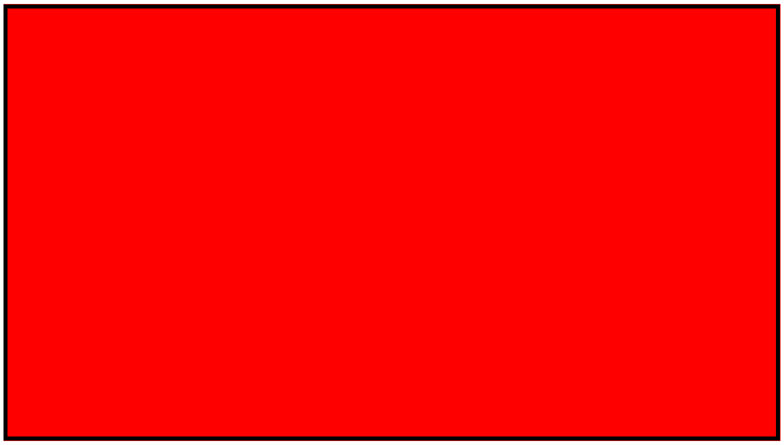


Figure 5. Effect of fibers orientation of the upper flange on draft difference.

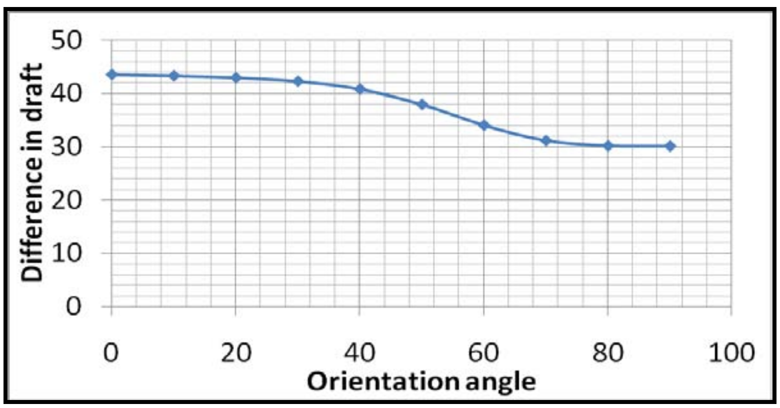


Figure 6. Effect of fibers orientation of the lower flange on draft difference.

4.5 Effect of fibers orientation of the web on draft difference.

Finally, based on the results reached in the previous two parametric studies, the orientation angle of fibers of the upper and lower flanges set to 90°. The orientation of the fibers of the webs is then varied from 0 to 90 as (θ, - θ) with y-axis, as specified for HCP (C). Figure 7. illustrates the relation between the orientation angle and the difference in draft, which reached the value of (21.86 mm) as the orientation angle increase up to 60°. The draft difference enhanced by 35% of the reference value for HCP (C) (33.61 mm). Consequently, the deduced strains are decreased w.r.t. the reference HCP (C) resulting in an increase of the load carrying capacity of the pontoon. At the same time, to keep the design safety factor at (4), it required to increase the thickness of the upper and lower flange and as well as the webs as illustrated in Table 4. Leading to a significant increase in the total pontoon weight compared to HCP (C). This can be attributed to the weakness in the transverse fiber direction since the composite material is an orthotropic material.

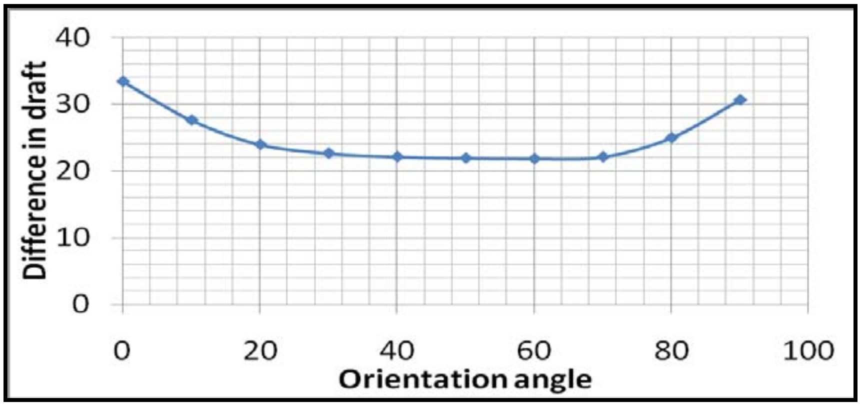


Figure 7. Effect of fibers orientation of the vertical webs on draft difference.

4.6 Simultaneous optimization of orientation angles of the fibers.

The parametric studies results reached in the previous sections lead to the conclusion that the orientation of the fibers for the all structural elements must be synchronized together to satisfy the stress distribution in each direction for each element. Also, for the same lamina, the fibers for successive layers should not have the same orientation angles. Consequently, in order to deal with this issue, the optimal configuration HCP (C) was optimized to get the best variation of fiber orientation. Many numerical simulations, as listed in Table 5., have been carried out to adjust the orientation of fibers in the upper flange, lower flange and web. The simulation analysis results lead to the following fibers orientations as: $[-45, 0, 90, 0, 45]_s$ for the upper flange, $[0, 45, -45, 45, -45]_s$ for the lower flange and $[45,-45]_s$ for the webs. The weight of the optimized pontoon reaches 5077.1 kg with weight improvement 83.9 % compared to the steel pontoon. The results are summarized in table 6. Figure 8. Illustrate the directional deformation of the reached HCP configuration that has a multiple orientation.

Table 5. Structural configurations of HCP (C) for different orientation angles.

Configuration	Thickness (mm)			Web Spacing (mm)
	Upper Flange	Lower Flange	Vertical webs	
0^o / 90^o	10	5	3	250
Single Orientation	28	25	4	250

Multiple Orientation	5	5	2	250

Table 6. Structural parameters of HCP (C) for different orientation angles.

Configuration	**Draft in (mm)**			**Pontoon**	**% Weight**
	Max.	**Min.**	**difference**	**weight (kg)**	**improvement**
0^{o} / 90^{o}	793.79	760.18	33.61	7367	76.7%
Single Orientation	879.95	869.21	10.74	17418	44.9%
Multiple Orientation	774.44	724.23	50.21	5077.1	83.9 %

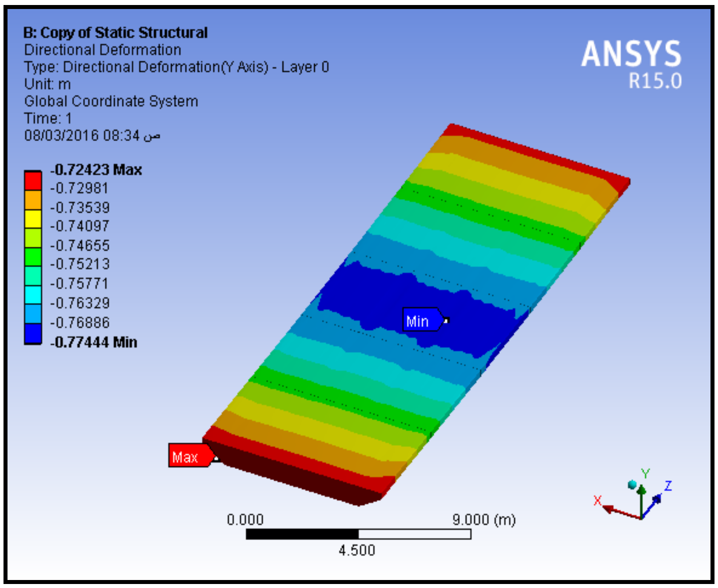


Figure 8. Differential draft for HCP with multiple orientation angles for fibers

5. Conclusions

The conclusions reached in the current study are limited to the proposed hybrid composite pontoon based on the numerical simulations carried out on FE model of the HCP. The results discussed in the earlier section led to the following conclusions :

(1) The proposed HCP system is found to be structurally reliable as the pontoon draft is significantly reduced and it supports higher load carrying capacity compared to the steel pontoon and has the advantage of own weight reduction by 83.9%.

(2) The structural configuration HCP (C) with web-clear distance (250mm) has the maximum weight improvement for both (0/90) pontoon and optimized pontoon by 76.7% and 83.9% respectively.

(3) The optimum fiber orientation to get the minimum difference in draft for upper surface, lower surface and webs are (90), (90) and (70,-70) respectively.

(4) Using multiple fiber orientation in the one laminate pass the disadvantage of the very low stresses in the transverse direction for the unidirectional orthotropic material. The lamina orientations found to be: $[-45, 0, 90, 0, 45]_s$ for the upper flange, $[0, 45, -45, 45, -45]_s$ for the lower flange and $[45,-45]_s$ for the webs. As the weight reduced from 17418 kg to 5077 kg for the same factor of safety.

(5) The use of the PVC foam as a filling material has a remarkable impact in reducing the web buckling and consequently reduced the weight of the composite material of the HCP, even with the total pontoon weight increase.

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