Simulation and Optimization of a CFRP and a GFRP floating pontoon

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Abstract. According to the unique mechanical properties of composite materials, the replacement of the conventional materials like steel with composite materials is increasing in all fields. The low weight / capacity characteristics of composite materials make it possible to accommodate much more loads. Because of the great importance of the floating bridges for both military and civilian purposes especially in crises, the evolution of floating bridges is necessary. The traditional transportation steel ferry is composed of floating steel pontoons to accommodate the MLC-70 (Tank load) of weight equals (63.5 t). In this study, the steel floating pontoon is replaced with composite pontoon simulated for both carbon fibres polymers and glass fibres polymers with the laminate configuration [0°/90°/0°/…/0°]. The finite element analysis is performed using ANSYS software. The capacity of the ferry is increased to reach (90 t) instead of (70 t). The total deformation is determined under the applied load. The failure criteria is investigated for both composite models (Tsai-Wu, Tsai-Hill, maximum stress and maximum strain). The nonlinear buckling analysis is also investigated. The optimization process is designed and performed to get the optimum number of layers and angles orientation of the composite layers as well as possible.

Keywords: Floating; Pontoon; Composite; Optimization; Modelling

1. Introduction

Composites materials have been increasingly used in marine and civil engineering applications instead of conventional construction materials such as steel. [1, 2]. Many Studies conducted on the designing and optimization of composite structures using different types of materials [3-8]. Marin et al.[9], presented an optimization methodology for a geometric design of a composite stiffened panel, with optimum stacking sequence using static analysis and hydrothermal effects. Herath et al.[10], illustrated an optimization method to optimize a composite marine propeller blades using genetic algorithm and finite element approach. Costaetal [11], described an application of a genetic algorithm to a material and sizing optimization problem of a plate. Kim et al. [12], optimized a layup using genetic algorithm for composite wing and maximize the failure index of Tsai–Hill criterion. Akbulut [13], optimized a composite plates for weight minimization under in-plane loading. Hirono et al. [14], determined the vertical displacement of a floating bridge. There are many researchers considered the pontoon as a beam rested on elastic foundation subjected to applied loads [15]. Fu and Cui [16], studied numerically the hydro elastic responses of connected pontoons under dynamic and static cases of loading and introduced a numerical method for analysis of a ribbon floating bridge. Alnahhala and Aref [17],

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illustrated that the combination of FRP composites with concrete present a promising improvement in civil infrastructure applications additionally, the stiffness of the hybrid bridge was 35% higher than FRP-only bridge. Khalifa [18] investigated the floating bridge under eccentric static loads. Raftoyiannis et al. [19], studied numerically the dynamic response of floating bridges under moving load with constant velocity. Siwowski and Rajchel, [20], studied the structural performance of hybrid FRP composite concrete bridge girder for evaluating the strength, stiffness and the global safety of the girder. Wang et al. [21], investigated the dynamic response of floating bridge subjected to moving load. Panteleev [22], optimized a metallic sandwich structure for decreasing its weight. Abozaid et al. [23], investigated numerically the structural performance of pontoon with 70 ton capacity made of hybrid composite FRP. The results illustrated that the PVC foam has a great impact to reduce the web buckling and the weight. In this study, a numerical simulation and optimization of a CFRP and a GFRP floating pontoon is carried out to investigate the structural performance of composite pontoon to overcome the disadvantages of the traditional transportation steel ferry. Finite element model is constructed using ANSYS Composite Prep Post (ACP). The failure criteria are incorporated in the optimization process for composite models (Tsai-Wu, Tsai-Hill, maximum stress and maximum strain). The optimum number of layers and the best orientation of the angles are determined.

2. Composite Failure Criteria

Based on these failure mechanisms it can be more appropriate to consider the composite as a structure rather than as a material. Fibre failure is one of the simplest failure mechanisms to identify and quantify which occurs, when the loads applied to a composite structure cause fracture in the fibers. Matrix cracks are an intralaminar form of damage and involve cracks or voids between fibers within a single composite layer or lamina. Additionally, buckling is a structural phenomenon that occurs in compression or shear and though not necessarily resulting in failure. The large deformations, bending and loss of structural capacity involved to structural collapse [24]. A successful design of a structure requires efficient and safe use of materials. Theories need to be developed to compare the state of stresses and strains in a material to failure criteria. So, that one needs to use reliable failure criteria.

2.1. Maximum Stress Failure Theory

In this case, the principal stresses in each ply are compared with their corresponding strength values \( X_i, X_c, Y_i, Y_c, \) and \( S \). Where \( X_i \) and \( X_c \) are the longitudinal tensile and compressive strengths, respectively, \( Y_i \) and \( Y_c \) are those in the transverse direction, \( S \) is the ultimate in-plane shear strength. The failure index is defined as [25, 26]:

\[
I_p = \max \left\{ \frac{\sigma_{11}}{X_i} \text{ if } \sigma_{11} > 0 \text{ or } -\frac{\sigma_{11}}{X_c} \text{ if } \sigma_{11} < 0 \right\} \left(1\right)
\]

2.2. Maximum Strain Failure Criteria

The maximum strain failure criterion can be stated as:

\[
I_p = \max \left\{ \frac{\varepsilon_{11}^s}{\varepsilon_i^s} \text{ if } \varepsilon_{11} > 0 \text{ or } -\frac{\varepsilon_{11}^s}{\varepsilon_c^s} \text{ if } \varepsilon_{11} < 0 \right\} \left(2\right)
\]

Where \( \varepsilon_{11}, \varepsilon_{22} \) and \( \gamma_{12} \) are ply strains in the ply coordinate system (1 parallel to fibers and 2 perpendicular to fibers). Also, \( \varepsilon_i^s, \varepsilon_c^s, \varepsilon_i^y, \varepsilon_c^y \) and \( \gamma_{sy} \) are allowable strains in the corresponding direction and loading (tensile or compressive).
2.3. Tsai-Hill Failure Criteria

Tsai-Hill failure criterion is one of the most practicable criterions for the prediction of damage progress in laminates, which assumed that, there is an important interaction between longitude strength, traverse strength and shear strength in the damage progress. The criterion can be expressed as [6, 27, 28]:

\[
\sigma_{11}^2 / X^2 + \sigma_{22}^2 / Y^2 - \sigma_{11,22} / X^2 + \tau_{12}^2 / S^2 = 1
\]  

(3)

Where \(X\) and \(Y\) are the longitude strength and traverse strength, respectively whether tension or compression which is depended on the stress status in laminates.

2.4. Tsai-Wu Failure Criteria

The Tsai-Wu failure criterion is the most generalized criterion since it distinguishes between the compressive and tensile strength of a lamina and can be written as the following expanded form [29, 30]:

\[
I_F = F_{11}\sigma_{11}^2 + F_{22}\sigma_{22}^2 + F_{66}\tau_{12}^2 + F_{11,11} + F_{22,22} + 2F_{12}\sigma_{11}\sigma_{22}
\]  

(4)

Where the symbols \(\sigma_{11}\) and \(\sigma_{22}\) are the stresses in the longitudinal and transverse fiber directions, respectively, \(\tau_{12}\) is the in-plane shear stress.

3. Model definition

3.1. Steel ferry definition

The steel ferry is designed to accommodate the dynamic load of the tank (MLC-70) with capacity up to (70 t). The floating ferry configuration is composed of 16 repeated floating pontoons. These pontoons dimensions are 5.25 m length, 2.4 m width and 1.5 m height for every pontoon. The pontoons are separated from each other’s by a connection system separating every pontoon from the other one by 10 cm. As a result to this configuration the ferry has a total length of 21.3 m and a total width of 9.9 m. The ferry is as shown in Figure 1.

![Figure 1](image)

**Figure 1:** The configuration of the ferry composed of 16 pontoon

The floating pontoon is composed of longitudinal, transverse, and vertical stiffeners simulated as beam elements. These stiffeners have different cross sections as shown in Figure 2. The upper, lower and side plates are simulated as shell elements with different thicknesses.
The used material is steel 37 with the properties tabulated in Table 1. [18]:

Table 1: The properties of structural steel 37

| Property                      | Value                  |
|-------------------------------|------------------------|
| Density                       | 7850 kg/m³             |
| Tensile yield strength        | $2.4 \times 10^8$ (Pa) |
| Compressive yield strength    | $2.4 \times 10^8$ (Pa)  |
| Tensile ultimate strength     | $4.6 \times 10^8$ (Pa)  |

The steel ferry is supported with elastic supports that represent the supporting water. These elastic supports have stiffness value that depends on the stiffness of both the structure and the water. To calculate the elastic support stiffness for any structure, it is obligatory to draw a non-linear curve between the elastic support stiffness values and their corresponding effect to the draft of the structure under its own weight and then choose the elastic support stiffness that achieve the draft of the floating structure under its own weight from the analytical analysis [18]. In our case the stiffness is calculated as follows:

The ferry follows the floating principles and Archimedes law as it is a floating structure. This law states that the weight of the displaced water by the submerged volume of the floating body is equal to the weight of the floating structure [31].

$$W_w = W_F$$  \hspace{1cm} (5)

Where, ($W_w$) is the weight of the displaced water, and ($W_F$) is the own weight of the ferry. The own weight of the steel ferry ($W_F$) can be calculated so, ($W_w$) must be equal to that weight to follow Archimedes' law and make the ferry float. The weight of the displaced water ($W_w$) can be calculated as follows:

$$W_w = F_B \cdot F_L \cdot F_{SD} \cdot \gamma_w$$  \hspace{1cm} (6)

Where, ($F_B$) represents breadth of the ferry without connections (9.6 m), ($F_L$) represents the ferry length without connections (21 m), ($F_{SD}$) represents the submerged depth of the ferry in water which is still unknown for now and ($\gamma_w$) represents the density of water (1000 kg/m³). By substituting in equation (2), ($F_{SD}$) is calculated. So, the the elastic support stiffness ($k$) that makes the deformation of the ferry under its own weight equals ($F_{SD}$) is computed as follows:
\[ W_w = k * F_B * F_L * F_{SD} \]  
(7)

By substituting in equation (2)

\[ k = \gamma_w \]  
(8)

So, the elastic support stiffness \((k)\) is 9810 (N/m^3) for this simulation model.

4. The composite pontoon

The composite pontoon is simulated with the same exterior dimensions as the steel pontoon (5.25 m length, 2.4 m width and 1.5 m height) but, with different internal configuration. The stiffeners of the composite pontoon are designed to be shell elements. These shell elements are simulated to act as longitudinal and transverse stiffeners as shown in Figure 3. The simulation is performed using advanced composite programming (ACP).

Figure 3: The configuration of the composite pontoon

5. Boundary conditions

5.1. Loads and supports

The composite ferry is designed to accommodate a total dynamic load of (90 t). Because of the optimization process and the number of layers, it takes too much time to be simulated as a dynamic load so, the load is applied as a static load. The static load is increased by a factor (1.3) to represent the dynamic load so, the ferry is subjected to a static load of about (115 t). The equivalent static load that affect one pontoon is calculated to be a uniform load \((P)\) of (0.54 t/m^2). The pontoon is supported by elastic supports that represent water.

5.2. Validation

The elastic support stiffness is calculated to be (9810 N/m^3) as mentioned before. The verification is performed on the loaded pontoon.

\[ W_T = O.W + F_{app} \]  
(9)
Where, \( F_{\text{app}} \) is the applied load and \( O.W \) is the own weight of the composite pontoon which is calculated from the software to be equal (0.853 t) for the glass fiber-resin polymer (GFRP) model.

\[
F_{\text{app}} = P \times F_B \times F_L \tag{10}
\]

By substituting in equation (5), the total weight is calculated so, the draft can be calculated as follows.

\[
\Delta = \frac{W_T}{F_B \times F_L \times \gamma_w} \tag{11}
\]

Where, \( \Delta \) is the draft of the pontoon. By substitution \( \Delta \) equals (62 cm).
The pontoon total deformations is determined from simulation to be (63.6 cm) which is 97.5% matching with the analytical value noting that this difference is the deflection of the upper shell.

The total deformation is illustrated at Figure 4.

![Figure 4: The total deformation of the loaded composite pontoon](image)

6. Optimization

There are many techniques of optimization supported by ANSYS such as the screening method, non-dominated sorting genetic algorithm (NSGA), multi-objective genetic algorithm, non-linear programming by quadratic lagrangian, etc. The type of the technique is determined automatically in ANSYS according to the number of parameters, the objective function and the number of the constraints[32]. In our study the screening optimization is the most proper method to get the optimum weight of the ferry as well as possible. The Screening optimization method depends on using a simple approach based on sorting and sampling. The screening method supports multiple objectives and constraints as well as all types of input parameters. The screening method is the first process used in the new developed optimization strategy called the multiphase optimization strategy (MOST)[33, 34]. Usually, it is used for preliminary design, which may lead the designers to reach to the predicted results in a quick way instead of try and error methods.

6.1. The objective function

The pontoon is divided into 4 categories; the upper deck, the lower deck, the side transverse stiffeners and the longitudinal stiffeners. Each stiffener of these stiffeners is a composite laminate
The laminate is defined as a set of lamina oriented in a specific manner to achieve a desired result and this laminate's response depends on the mechanical properties of each lamina [35]. The objective function is to minimize the buoyancy factor (B F) which is defined as the ratio between the total weight of the structure to the weight of the displaced water by the full body of the structure as if it is fully submerged [36] as the following equation illustrates.

\[ \text{The buoyancy factor (B F)} = \frac{W_T}{V_t \times \rho_w} \] (12)

Where, \(V_t\) represents the total volume of the structure and \(\rho_w\) represents the water density. The objective function is defined in the following equation as follows:

\[ F_1(X): \text{minimize} \ B F = \frac{W_T}{V_t \times \rho_w} \] (13)

6.2. The design variables (Parameters)

The number of layers and the angle of orientation are the input parameters for the optimization process. The laminate parameters are defined as:

\[ W = [\alpha_1^\circ / \alpha_2^\circ / \alpha_3^\circ / \ldots / \alpha_n^\circ], (-90^\circ) \leq \alpha \leq (90^\circ), 1 \leq n \] (14)

Where, \((W)\) represents the laminate configuration, \((\alpha)\) represents the orientation angle of the layer, the subscript numbers beside \((\alpha)\) \((1,2,3,\ldots,n)\) represents the layer number not the number of layers used and \((n)\) is the number of layers for the laminate.

6.3. Constraints

The optimization process is constrained by the failure criteria (FC), the total deformations and the buckling load factor (BLF). Tsai-Wu, Tsai-Hill, Max. Stress and Max. Strain are used to determine the failure of the composite model. The buckling load factor (BLF) is the ratio of the critical buckling load \((P_{cr})\) to the applied load \((P)\).

\[ BLF = \frac{P_{cr}}{P} \] (15)

So, the constraints are defined as follows:

\[ g_1 = BLF = \frac{P_{cr}}{P} \geq 1 \] (16)

\[ g_2 = FC \leq 1 \] (17)

\[ g_3 = \frac{\Delta}{P_H} \leq 0.8 \] (18)

Where, \(g_1\), \(g_2\) and \(g_3\) represent the constraints and \((P_H)\) represents the pontoon height that equals \((1.5 \text{ m})\).

7. Composite models

7.1. The properties of the used composite materials

In this study 3 composite materials are used; Glass/Epoxy, Carbon/Epoxy and with the following properties [32] shown in Table 2.
Table 2: The properties of composite materials

| Properties                        | Glass/Epoxy (S - UD) | Carbon/Epoxy woven wet (230) |
|-----------------------------------|-----------------------|-------------------------------|
| Density (kg/m³)                   | 2000                  | 1420                          |
| Young's modulus X direction (MPa) | 50000                 | 61340                         |
| Young's modulus Y direction (MPa) | 8000                  | 61340                         |
| Young's modulus Z direction (MPa) | 8000                  | 6900                          |
| Tensile X direction (MPa)         | 1700                  | 805                           |
| Tensile Y direction (MPa)         | 35                    | 805                           |
| Tensile Z direction (MPa)         | 35                    | 50                            |
| Compressive X direction (MPa)     | -1000                 | -509                          |
| Compressive Y direction (MPa)     | -120                  | -509                          |
| Compressive Z direction (MPa)     | -120                  | -170                          |
| Shear XY (MPa)                    | 80                    | 125                           |
| Shear YZ (MPa)                    | 46.154                | 65                            |
| Shear XZ (MPa)                    | 80                    | 65                            |

8. The Glass/Epoxy pontoon

The pontoon is simulated using GFRP in ACP and the optimization process is performed and the results are as follows:

The configuration of the upper deck is the same as the lower deck arranged as \([0_2 / 22.5 / 45_2 / 90]_5\). These laminate is composed of 12 layer as mentioned in the configuration. Every layer of this type of fabric (single layer glass fiber) has a thickness of (0.2 mm) so, the total thickness of the upper deck is (2.4 mm) and the lower deck is (2.4 mm). The configuration of the transverse stiffeners is arranged as \([0_2 / 45 / 90 / 45]_5\). The total thickness of the shell is (2 mm) for the used 10 layers. The configuration of the longitudinal stiffeners is arranged as \([0_2 / 45 / 90 / 45_2 / 90 / 45 / 0_2]_5\). The total thickness of this stiffener is (4 mm) for the used 20 layers. The total weight of the glass pontoon is (804 kg).

8.1. Failure criteria analysis

The upper shell is found to be the critical shell to the stress generated from the applied load so, the failure index is higher than the other shells. The failure index for the first layer of the upper shell is as shown in Figure 5.
The failure index equals (0.75389) which is safe. If the load is increased till failure occurs, the failure will occur at the coincidence of the longitudinal stiffener with the transverse stiffener. The failure is determined for every layer and found that the failure is not of the same shape for every layer but, all layers are safe. The critical layer in the lower shell is the layer number (12) which is the upper layer connected to the longitudinal and transverse stiffeners. The failure criteria is safe and has a failure index equals (0.786) and will occur as shown in Figure 6.

The critical layer for the transverse stiffeners is safe with failure index equals (0.257) at the layer number (10). The critical layer for the longitudinal stiffeners is also safe with failure index equals (0.177) at the layer number (17). So, the critical shells that are affected with the stresses of the applied load are the upper and the lower shells.

8.2. Nonlinear buckling analysis
The nonlinear buckling analysis is performed as a constraints of the optimization process to be about (1.5) for military standards [37] noting that the minimum allowed value of (BLF) is (1). The buckling is illustrated as follows in Figure 7.

![Nonlinear Buckling Analysis](image)

**Figure 7:** The nonlinear buckling of the longitudinal stiffener

The (BLF) equals (1.44) which is safe for the model. The longitudinal stiffener is the critical laminate for this configuration and the (BLF) is the critical constraints that affects the results more than the failure criteria.

8.3. *The total deformation*

The deformation constraint is applied in the optimization process and the value is determined. The total deformation equals (63.67 cm) as shown in Figure 4.

9. *The Carbon/Epoxy pontoon*

The optimization is performed and the optimum number of layers and orientation angles are determined as follows to satisfy the constraints conditions of the failure and the buckling. The shell optimized configuration is \([0 \ 2/45 \ 2/90]_S\) with total thickness from those (10) layers equals (2 mm) for the upper lower and transverse stiffeners shells. The configuration of the longitudinal shell is \([0/90/0_{13}]\) with total thickness of (3 mm) from those (15). The total weight of the carbon pontoon is (583 kg).

9.1. *Failure criteria analysis*

The failure index of the upper shell is (0.233) at the layer number (10) as shown in Figure 8.
Figure 8: The failure criteria for the critical layer of the upper shell. The failure index for the lower shell is (0.24) and the same as the upper failure in the shape. The failure index of the longitudinal and the transverse stiffeners also are not effective.

9.2. The nonlinear buckling analysis
The buckling of the laminate is the critical constraints that affects the optimization results. The critical shell for the buckling analysis is also the longitudinal stiffener and the buckling load factor is (1.5). The nonlinear buckling is illustrated in Figure 9.

Figure 9: The nonlinear buckling of the longitudinal stiffener

9.3. The total deformation
The total deformation of the carbon pontoon equals (61 cm) as shown in Figure 10.
Figure 10: The total deformation of the carbon pontoon

10. Conclusion
In this paper the simulation of the composite materials is performed. The unique mechanical properties of composites make them candidate to replace the traditional materials. The pontoon is simulated for both GRFP and CRFP instead of structural steel. The capacity of the composite ferry is increased to be (90 t) instead of (70 t) of the steel ferry. The optimum number of layers and the best orientation of the angles are determined. The critical analysis of the composite pontoon is the buckling analysis. The failure criteria is effective for the loaded shells that are subjected to bending. The vertical stiffeners are the critical sections for buckling. The total deformations are determined for the different materials. The weight of the carbon pontoon is reduced by 27.5% from the glass pontoon that results in the reduction of the buoyancy factor. The reduction of buoyancy factor results in more increase in the capacity of the pontoon.

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