Dynamic Behavior of Steel and Composite Ferry Subjected to Transverse Eccentric Moving Load Using Finite Element Analysis

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Abstract: The most important problems confronted by designers of floating structures are minimizing weight and increasing payload to get proper resistance to the applied loads. In the present study, the structural performance of a ferry is analyzed using both metallic and composite materials as a result of the dynamic load of the Military Load Capacity (MLC) 70 (tank load). The model is composed of sixteen floating pontoons. Finite element simulation and dynamic analysis were performed using ANSYS software (analysis system software), considering a moving MLC70 (tank load). Both concentric and eccentric cases of loading are considered. Draft, deformation, and stresses are obtained and investigated. For the steel ferry, the von-Mises stresses are investigated, while for the composite ferry, the maximum principal stresses are investigated. Furthermore, buckling analysis is performed on the composite ferry and the buckling load factor is determined. The results of the dynamic analysis illustrated that the transverse eccentricity of the moving tank MLC70 must not exceed 0.5 m for a steel ferry while it may reach up to 1.5 m for the composite ferry. This research can also be a useful tool in the design of floating composite and steel ferries.

Keywords: pontoon; simulation; carbon fibers; ferry; steel; moving loads; eccentric

1. Introduction

The evolutionary demand of floating bridges and ferries are increasing continuously either for civilian purposes or military ones, as floating bridges are established over obstacles in a very short time. The history of floating bridges can be dated back to 2000 BC [1]. There are many main systems for floating bridges, depending on the environmental conditions such as wave velocity and shore bed conditions [2]. Moreover, there are many reasons making it obligatory to use floating bridges and ferries in war and peace times. As a result of the necessary need for floating pontoons, many researchers have studied floating pontoons. Sun et al. [3] investigated the dynamic response of floating bridge consisting of multi-modules. The motion, bending moment, and mooring force of the floating bridge model were discussed. Shahrabi and Bargi [4] developed a procedure to analyze the motions of floating piers comprised of several pontoons. These pontoons are modelled as rigid bodies and connected to each other by flexible and rigid connectors. Zhang et al. [5] studied the dynamic responses of two analytical models of floating bridges, continuous-pontoon floating bridge and a discrete-pontoon floating bridge subjected to moving loads for different water depths, and concluded that water depth has a minor effect on the dynamic responses of floating bridges. Furthermore, Hirono et al. [6] proposed a measurement system to determine the vertical displacement of a floating bridge. Other researchers
preferred developing a finite element model to get symmetric simulations, considering the pontoons as a beam rested on elastic foundations and subjected to the applied loads [7]. Ibrahim et al. [8] studied the influence of floating bridges on velocity distribution. Additionally, Fu and Cui [9] numerically studied 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. Khalifa [10] studied the performance of floating bridges under longitudinal and transverse eccentric static loads using finite element modelling. Raftoyiannis et al. [11] studied the dynamic response of floating bridges under the action of a moving load at constant velocity and introduced an equation that represented the effect of damping. Wang and Jan [12] investigated the dynamic response of floating bridge subjected to moving load. From the results, the vertical deflection in the entire bridge is shown to be caused by rotation at the hinge position. Also, Jun et al. [13] investigated a discrete pontoon floating bridge under moving loads. Nguyen et al. [14] introduced a numerical method to compute hydro-elastic responses of pontoon-type floating structures under moving loads and waves action. Dai et al. [15] presented a numerical study of a floating bridge with a total length of 4.6 km subjected to wave loads and supported by 35 pontoons along its full length. Kvåle et al. [16] studied the hydrodynamic modelling of pontoon bridges. The model relies on the finite element method and linearized potential theory. Taetragool et al. [17] investigated the optimal stacking sequence of plies in a laminated plate to maximize the first failure load using Tsai-Wu failure criterion [18,19]. The safety and crossing speed are two main features judging the success or failure of the pontoon bridges [20]. Safety insurance is not easy during loading of the ferries by the tanks, as many accidents occur due to the eccentricity. Figure 1 illustrates some accidents due to the transverse eccentricity of tank loads.

![Figure 1. Accidents due to tank loads eccentricity.](image)

The development of floating bridges requires the usage of new materials instead of traditional steel as the steel ferry has many limitations because of steel properties (relative low strength and large density in compare to carbon fibers). The low density and excellent mechanical behavior of composites (reinforced fiber polymers such as carbon fibers) make them candidates to replace metals for many applications [19,21–25]. Simulating composite materials is one of the most important topics to discuss, as it requires studying the failure criteria, buckling, and principal stresses. Composite materials showed better results than traditional materials (structural steel) in many structures such as submarines hulls, ships, and floating bridges. Helal and Fathallah [23] optimized an intersecting composite and steel elliptical pressure hull for maximizing buckling pressure and for minimizing weight. Mahdi et al. [26] investigated a stiffened plate structure of a ship subjected to truck wheels and calculated the plastic load carrying capacity. Abozaid et al. [27] investigated numerically the structural performance of pontoons made of hybrid composites (carbon fibers and glass fibers) and filled the voids between internal stiffeners with foam, which affects the reduction of web buckling and weight. Siwowsk and Rajchel [28] studied the performance of a hybrid fiber reinforced polymer (FRP) girder in a concrete bridge for evaluating the strength, stiffness, and the global safety of the girder. Botros et al. [29] used composite pontoons as piers for floating bridges and off-shore structures.
Blążejewski et al. [30] designed and fabricated a hybrid aluminum-composite pontoon bridge (from glass fibers) and concluded the importance of composite materials in floating bridges.

In this study, a floating ferry is simulated to accommodate the dynamic load of a moving tank with Military Load Capacity 70 ton (MLC70). The ferry is simulated from two different materials: structural steel and composite materials (carbon fibers). The study aims to avoid potential accidents by determining and improving the maximum allowable transverse eccentricity for MLC70. The concentric and transverse eccentric dynamic loads are studied for MLC70. The structural performance of the ferry is analyzed for both materials (structural steel and carbon fibers), and comparisons are performed between the two materials used: the structural steel and the carbon fibers. Additionally, the improvement in response and structural performance of the composite ferry is illustrated. The simulation of the studied ferry is performed as a transient dynamic analysis by using ANSYS software.

2. Finite Element Modeling of the Steel Ferry

This study is based on the stability of the floating structure theories under the overturning moment resulting from the eccentricity of applied loads. It is well known that the floating structure has a total weight equal to the buoyancy forces resulting from the submerged volume of this structure. When a floating structure is given a slight angular displacement or an eccentric additional mass, it starts to oscillate about a point called the meta-center point, which is defined as the intersecting point of the normal axis of the floating structure and the line of action of the buoyancy force [31–33]. The stability of the floating structures depends upon the location of the center of gravity, the center of buoyancy, and the meta-center. These factors determine whether the floating structure is stable, neutral, or unstable Figure 2 illustrates the ferry under stability conditions without eccentricity.

![Figure 2. The loaded ferry under stability condition.](image)

\((G_0)\) represents the original center of gravity of the ferry, and \((B_0)\) represents the center of buoyancy force. The transverse eccentricity of the mass (tank) over the floating structure (ferry) results in an additional overturning moment; Figure 3 illustrates the transverse eccentricity effect of the tank.

![Figure 3. The loaded ferry under stability condition (with transverse eccentricity).](image)
(M) is the additional moment due to eccentric load (overturning moment) and equals \((M = \Delta F \times S)\), where \(\Delta F\) denote the generated force from the additional submerged volume of ferry and \((S)\) denote the length arm of the coupled moment. The increase in the eccentricity results in an increase in the stability angle \((\theta)\), which causes the additional moment \((M)\) to increase. The additional moment \((M)\) makes the floating structure tilt around the longitudinal axis of the structure.

3. Model Definition

3.1. Geometry and Material

The ferry considered in this study is composed of sixteen connected pontoons, as shown in Figure 4. Each pontoon has a length of 5.25 m, width of 2.4 m, and a height of 1.5 m connected by both the upper and lower connection systems. The connection between every two pontoons is 0.1 m wide, and the ferry has a total length of 21.3 m and a total width of 9.9 m.

![Figure 4](image)

**Figure 4.** The configuration of the ferry composed of 16 pontoons.

The pontoon is composed of longitudinal, transverse, and vertical internal structural elements using different cross sections; three different equal angles (angle \(80 \times 8\), angle \(90 \times 9\), and angle \(120 \times 12\)), in addition to two main diaphragms using 2 different I-beam sections (IPE 160 and IPE 180), as shown in Figure 5. The angles and diaphragms are modelled using beam elements, while the deck sheet, round side sheets, and lower sheet are modelled using shell elements with different thicknesses (the deck sheet is six mm, and the other sheets are four mm). The material used for the metallic ferry is steel 37 with the following properties shown in Table 1. [34].

![Figure 5](image)

**Figure 5.** The isometric sections of one pontoon. (a) Internal stiffeners configuration, (b) Outer shell plates.
Table 1. The properties of structural steel.

| Properties                  | Value       |
|------------------------------|-------------|
| Density                      | 77 kN/m³    |
| Tensile yield strength       | $2.5 \times 10^8$ (Pa) |
| Compressive yield strength   | $2.5 \times 10^8$ (Pa) |
| Tensile ultimate strength    | $3.6 \times 10^8$ (Pa) |

3.2. Loads

The ferry is analyzed using transient dynamic analysis under the effect of moving tank (MLC70). The load of tank tracks is simulated on the deck of the ferry, where the dimensions of each tank track are considered 0.5 m width and 4.5 m length Figure 6 illustrates the dimensions of the military load capacity tank of MLC70.

![Figure 6. The tank dimensions. (a) Side view of MLC70, (b) Elevation of MLC70.](image)

Four cases of loading are considered in this study: in the first case, the load is centered (no eccentricity), while in the other three cases, the load is transversely eccentric from the center with values of 0.5 m, 1.0 m, and 1.5 m, as illustrated in Figure 7.

The eccentricity values are assumed according to the width of the tank track (0.5 m) to cover a wide range of transverse eccentricity with the whole possible cases of loading (the whole load of the tank is at the inner two pontoons; the whole load of the tank is at the inner two pontoon but eccentric; the whole load of the tank is over the separation between pontoons, i.e., the tank track acts on the edges of two adjacent pontoons; and the final case of loading is when the tank track acts on the edge pontoon). The behavior of the ferry can be divided into intervals from [0–0.5 m], from [0.5–1 m], and from [1–1.5 m].
Figure 7. The four cases of loading. Case (1) centered load (no eccentricity); Case (2) transversely eccentric from the center (0.5 m); Case (3) transversely eccentric from the center (1 m); Case (4) transversely eccentric from the center (1.5 m).

The dynamic load of the tank applied as a moving pressure calculated as follows:

$$ P = \frac{W}{2(B_T \times L_T)} $$

(1)

where \((P)\) denotes the applied pressure over the route of the tank, \((W)\) denotes the weight of the tank and equals \((623 \text{ kN})\), \((B_T)\) denotes the width of the tank track and equals \((0.5 \text{ m})\), and \((L_T)\) is the length of the tank track which equals \((4.5 \text{ m})\). The speed of the tank ranges from \(6 \text{ to } 10 \text{ km/hr}\) for crossing the floating bridges, so the tank is assumed to enter the ferry with a speed of \((8.1 \text{ km/hr})\). The periodic time of the moving tank \((T)\) is defined as follows:

$$ T = \frac{L_T}{V} $$

(2)

where \((V)\) denotes the tank speed. By substituting in Equation (5) \(T = 2 \text{ (s)}\), the tank crosses the ferry in \(12 \text{ s}\) to reach the end of the ferry.

3.3. Boundary Conditions

Following Archimedes law, the weight of the floating ferry equals the weight of displaced water by the submerged volume \([35,36]\). The simulation of water as a support is simulated as elastic supports with corresponding computed stiffness acting on the lower sheet of the ferry, while the home shore effect is simulated as a single hinged support at the mid-span of the lower shore side of the ferry.

3.4. Elastic Support Stiffness

Computing the stiffness for the elastic support varies according to the outer shape of the submerged structure, the stiffness of the floating structure, and its mass while the ferry is loaded in water:

$$ W_F = W_w $$

(3)
where $W_F$ denotes the weight of the ferry and $W_w$ denotes the weight of the displaced water. The own weight of the simulated ferry ($W_F$) is calculated using ANSYS software, while $W_w$ equals the following:

$$W_w = B \times L \times D_s \times \gamma_w$$  \hspace{1cm} (4)

where $B$ denotes the ferry breadth without connections and equals 9.6 m, $L$ denotes the ferry length without connections and equals 21 m, $D_s$ denotes the submerged depth of the ferry in water, and $\gamma_w$ is the density of water with value equals (9.81 kN/m$^3$). By substituting in Equation (7), $D_s$ is obtained.

The stiffness ($k$) is calculated as follows:

$$W_w = k \times B \times L \times D_s$$  \hspace{1cm} (5)

By substituting in Equation (8), we obtain the following:

$$k = \gamma_w$$  \hspace{1cm} (6)

The value of the elastic support stiffness is found to be equal 9.81 kN/m$^3$ for the considered model. Generally, calculating the stiffness value for any floating structure is obtained by plotting three graphs as discussed by Khalifa [10] in order to achieve the exact draft (submerged depth). As affecting load dynamically moves along the ferry, the general equation of motion introduced by Chopra [37] governs the model computations as follows:

$$F(t) = m \ddot{u}(t) + c \dot{u}(t) + k u(t)$$  \hspace{1cm} (7)

where $F(t)$ denotes the dynamic force at time $t$, $(m)$ denotes the mass of the structure, $\ddot{u}(t)$ denotes the acceleration of the structure at time $t$, $(c)$ denotes the damping coefficient, $\dot{u}(t)$ denotes the velocity of the structure at time $t$, $(k)$ denotes the stiffness of the structure, and $u(t)$ denotes the displacement of the structure at time $t$.

3.5. Convergence Study

In order to get the most proper meshing size according to the results and elapsed time during analysis processing, five element sizes are used, 0.15 m, 0.2 m, 0.28 m, 0.35 m, and 0.4 m, to illustrate the best result of the convergence study [38]. The corresponding numbers of elements are 52,236, 50,711, 17,904, 15,046, and 14,988, respectively. The results of these five models illustrate the accuracy of the analysis. Figure 8 illustrates the maximum total deformation results with every meshing size for the first case of loading.

The results illustrate that the difference between results is not significant. In our case, the difference between the minimum result from the coarse meshing and the maximum result from the fine meshing is 1.14%, which is not effective in comparison with the elapsed time in analysis. The difference between the analysis time between the fine meshing and coarse meshing is about 300%. The difference in the elapsed time between the 0.15 m meshing size and the 0.2 m meshing size is about 200%. These results are candidate the meshing sizing of 0.2 m for elements to be the most proper element size.
4. Validation

A verification analysis is performed to assess the accuracy of the analysis model. A numerical model is performed for a steel ferry under its own weight considering gravity acceleration; then, its result is compared with the reading measured at the field. The actual draft measured in the field is found to be 26.8 cm, as shown in Figure 9. The draft value can also be verified mathematically, where the weight of the ferry equals 562.5 kN; then substituting in Equation (7), the corresponding draft equals 26.6 cm. The maximum draft result from the numerical analysis is obtained as shown in Figure 10 and equals 26.6 cm. The numerical and the field result are found to be in good agreement with a ratio percentage of 99.3%.

Figure 9. The draft of the ferry under its own weight measured at the field.
5. Composite Ferry

The weight of ferries is the most critical factor; therefore, the designers strive for selecting a high-strength and low-density material. Decreasing the weight of the ferry allows increasing the pay load. Using composite materials is one of the most effective solutions available [36,39]. The mechanical properties of composite materials are very high compared with structural steel, which helps to reduce the weight of the used elements and sections. In this model, the material is proposed to be one of the modern widely used composite materials. Epoxy carbons woven and unidirectional are used as materials for the composite ferry model. All beam elements used in steel ferry model were implemented in composite model using the same cross-sectional area and were constructed from epoxy carbons woven. The thickness of the upper deck of the composite ferry differs from the steel ferry. The thickness of the upper deck in the composite ferry equals 10 mm, while the thicknesses of the other shells are the same as the steel ferry (4 mm). The materials properties and parameters are illustrated in Table 2. Avoidance of structural failure is a principal goal of all structural designers. Simulation of the composite ferry takes into consideration both material and buckling failure. In this study, the mechanical model is used to simulate the composite model as a worksheet and to lay up layers. The same geometry as the steel ferry is used. To simulate the layered section; it is obligatory to have 3 coordinate systems to adjust the direction of laying up the layers, as the layered sections are arranged in the +Z direction. The coordinate systems are assigned to the shells to make every shell in XY plane normal in the +Z direction. The first layer is on the top. Subsequent layers are added to the bottom, increasing in the +Z normal direction. The shell consists of a total of 5 layers with stacking sequence [(0/45)/90...]S but with a different layer thickness for every shell. For the upper shell deck, every layer has a thickness of 2 mm to get a total thickness of 10 mm, while for the other shells, every layer has a thickness of 0.8 mm to get a total thickness of 4 mm. Unidirectional carbon is used for shell elements, and woven carbon is used for the beam elements (internal stiffeners). The orientation of the composite laminate for the shell elements is illustrated in Figure 11. Every layer is placed and oriented according to its local coordinate system considering the layup of the layers in the +Z direction (normal to every shell). The orientation of every layer is defined according to the local coordinate system of every shell, and the angles of orientation are measured from + X direction for every shell.
Table 2. The material properties and strength parameters of epoxy carbon unidirectional (UD) and woven (230 GPa).

|                        | Epoxy Carbon UD (230 GPa) | Epoxy Carbon Woven |
|------------------------|----------------------------|--------------------|
| Density                | 14.62 (kN/m$^3$)          | 14.23 (kN/m$^3$)   |
| Tensile strength in X direction | 2231 (MPa)                | 513 (MPa)          |
| Tensile strength in Y direction | 29 (MPa)                  | 513 (MPa)          |
| Tensile strength in Z direction | 29 (MPa)                  | 50 (MPa)           |
| Compressive strength in X direction | -1082 (MPa)              | -437 (MPa)         |
| Compressive strength in Y direction | -100 (MPa)                | -437 (MPa)         |
| Compressive strength in Z direction | -100 (MPa)                | -150 (MPa)         |
| Shear modulus XY       | 4700 (MPa)                | 17,500 (MPa)       |
| Shear modulus YZ       | 3100 (MPa)                | 2700 (MPa)         |
| Shear modulus XZ       | 4700 (MPa)                | -(MPa)             |

Figure 11. The laminate configuration for lower and side shells.

Figure 12 illustrates the local and global coordinate systems for the different used shells. The load is the dynamic load of the tank (MLC70) similar to the steel ferry.

Figure 12. Coordinate systems.

5.1. Practical Validation for CFRP

A composite plate of dimensions (20 $\times$ 25 cm) with a thickness of 1 mm is manufactured in the lab to compare the real practical results to the numerical results from ANSYS. The plate is manufactured
from woven carbon fibers (230) with the illustrated properties in Table 2. The plate is designed from five layers with a sequence $[0]_5$ to get the required thickness. Figure 13 illustrates the manufacturing process. The manufactured composite plate is applied to the three-point bending test, and the maximum load and its corresponding deflection are determined. Figure 14 illustrates that the maximum load is 286 N and that the corresponding deflection at the critical section is 19.917 mm.

The simulation of the composite plate with the same characteristics as the manufactured one is performed with ANSYS software. The maximum load from the test is applied with the same conditions of the test, and the corresponding deflection is determined. The deflection is found to be 18.119 mm with a matching percent with the practical result of about 91%. Figure 15 illustrates the simulated composite plate with the applied load and the boundary conditions and then the total deformation result. The failure criteria are determined for the composite plate for whole layers. The upper layer designated as layer (1) and the additional layers were stacked from the top to the bottom. The critical layer is the lower layer (layer (5)). Maximum failure occurs at mid-span under the applied load. After that, failure occurs at the upper layer (layer (1)) and then layer (4), layer (2), and finally layer (3). Figure 16 illustrates the failure distribution for all layers. Failure of the manufactured plate is the same as of the simulated plate. The failure occurs at the mid-span in the top layer, as shown in Figure 17.
5.2. Nonlinear Buckling Analysis

The nonlinear buckling analysis of the model is investigated, and the Buckling Load Factor (BLF) is determined. To ensure stability, the critical buckling strength \( P_{cr} \) must exceed the actual load \( P_{act} \). The BLF is defined in ANSYS as the load multiplier, as shown in the following equation.

\[
BLF = \frac{P_{cr}}{P_{act}}
\]  

(8)

BLF must be \( \geq 1 \) to avert failure due to buckling. For military standards, BLF must be \( \geq 1.5 \) [40]. The nonlinear Eigen value buckling analysis is computed for one pontoon with an equivalent load of an adequate portion of the tank load accommodated by the ferry. The nonlinear Eigen buckling analysis in ANSYS is performed for static analysis. Therefore, the load of the tank (63.5 t) is multiplied by 1.3 to consider the dynamic effect [10]. The pontoon is loaded by 4000 Pa as a uniform load over the upper deck, which represents the ratio of the total load carried by one pontoon only. The study of buckling effect to detect which element could fail is essential. Figure 18 illustrates the buckling analysis and illustrates that the BLF is 5.3.
6. Results and Discussion

The steel and composite ferry are analyzed under four cases of loading. The achieved results were analyzed as follows:

6.1. Case 1

In this case of loading, the dynamic load of the tank (MLC70) is centered (i.e., no transverse eccentricity is considered). Figure 19 demonstrates the deformation distribution for both steel and composite ferries under the moving load of the tank (MLC70). The deformation distribution is symmetric at any time along longitudinal axis of the ferry as the load is centered. Figure 20 illustrates the maximum total deformation with time for both steel and composite ferries.

Figure 19. The total deformation distribution in case of loading 1.

Figure 20. The maximum total deformations with time for case 1.

Figure 20 shows the fluctuation of the deformation with time due to the dynamic effect of the tank over the ferry and shows also the damping effect while vanishing these fluctuations. The maximum value of the draft equals to 1.1291 m at t = 8 s for the steel ferry and 0.2335 m for the composite ferry at the same time (t = 8 s). Figure 21 illustrates von-Mises stress distribution for the steel ferry and the maximum principal stress for the composite ferry. The maximum principal stresses are investigated as the failure index is the most important criteria for the safety of the composite design.
The maximum affected elements are the elements around the tank tracks. Figure 22 shows the maximum values of stresses over the ferry with time for both materials. The maximum value of von-Mises stresses is $1.54 \times 10^6$ (Pa) for the steel ferry at $t = 2$ s. The maximum principal stress for the composite ferry is $3.47 \times 10^7$ Pa, which is lower than the principal strength of the used laminates; therefore, the failure index is <1. The composite ferry shows the same trend but with lower values. The low density of the composite material results in lower deformation values from the steel ferry, which is the reason for these lower values. The maximum deformations are found to be at $t = 8$ s where, the tank is about passing over the last pontoon. These values seem to be reasonable as the end of the ferry is the free end. The maximum stresses occur as soon as the whole tank enters the ferry with full capacity at $t = 2$ s which also, is reasonable.

![Stress distribution over the ferries for case 1.](image)

Figure 21. Stress distribution over the ferries for case 1.

6.2. Case 2

In this case, the dynamic load of the tank (MLC70) is applied with an eccentricity of 0.5 m away from the center of the ferry to the right direction (+X direction). Figure 23 illustrates that the deformations are unsymmetrical about the center of the ferry. The ferry is tilted towards the load position (about the Z axis). Additionally, the ferry is warped and the rotation at the hinged point at
the beginning of the ferry exists. This eccentricity results in an additional couple of moments which helps to overturn the ferry as the central gravity of the load is transversely shifted.

![Figure 23. The total deformation distribution in case of loading 2.](image)

Figure 24 shows the total maximum deformation values with time all over the ferry for both materials. The figure illustrates that the maximum total deformation values have the same manner as the previous case in Figure 20 but with higher values. The total deformation values are increased in this case of loading by 7% for the steel ferry and about 9.5% for the composite ferry from the previous case.

![Figure 24. The total deformations with time for case 2.](image)

The increase in deformation values in this case appears to be due to the eccentricity effect. Additionally, Figure 24 shows that the maximum deformation equals 1.2086 m at t = 8 s for the steel ferry and 0.2557 m for the composite ferry at the same time (t = 8 s). The maximum deformations occur at the same time as the previous case where the tank is about passing over the last pontoon. The distribution of the stresses is illustrated in Figure 25.
The stresses are increased for both ferries.

Additionally, the ferry is warped more than the previous case. The maximum value of stresses equals 2.2 × 10^8 Pa for the composite ferry at t = 8 s. The ferry is safe for both materials in this case of loading.

6.3. Case 3

In this case, the moving load is applied with transverse eccentricity equal to 1.0 m to the right from the center of the ferry (+X direction). Figure 27 illustrates that the deformations are unsymmetrical about the center of the ferry. The ferry is tilted towards the same load position (about Z direction) as the previous cases but with higher values as the rotational angle at the hinged point at the beginning of the ferry is increased. Additionally, the ferry is warped more than the previous case.
Figure 26. Stresses change with time for case 2.

The maximum value of stresses equals $2.2 \times 10^8$ Pa at $t = 4$ s for the steel ferry as in the previous case but, this value is very close to the yield strength of the used steel. The maximum value of stresses equals $1.49 \times 10^8$ Pa for the composite ferry at $t = 8$ s. The ferry is safe for both materials in this case of loading.

6.3. Case 3

In this case, the moving load is applied with transverse eccentricity equal to $1.0$ m to the right from the center of the ferry (+X direction). Figure 27 illustrates that the deformations are unsymmetrical about the center of the ferry. The ferry is tilted towards the same load position (about Z direction) as the previous cases but with higher values as the rotational angle at the hinged point at the beginning of the ferry is increased. Additionally, the ferry is warped more than the previous case.

Figure 27. The total deformation in case 3.

Figure 28 shows the maximum deformation values with time for the ferry for both materials. The figure illustrates that the deformation in this case has the same manner as in case 2 but with higher values due to the increase in the transverse eccentricity. The deformations are increased by about 12% for the steel ferry and by about 19.5% for the composite ferry from case 1.

Figure 28. The total deformations with time for case 3.

The maximum deformation is increased to $1.262$ m for the steel ferry and $0.279$ m for the composite ferry. The above results illustrate that the increasing in the vertical displacement is caused by the eccentricity effect. The stress distribution is illustrated in Figure 29.
In this case of loading, the von-Mises stresses are higher than the stresses in the previous cases. The maximum stress for this case of loading equals $1.58 \times 10^9$ Pa for the steel ferry at $t = 1.8$ s, which exceeds the ultimate strength of the used steel; additionally, the results illustrates its insufficient torsional stiffness to resist the twisting moment from the eccentric loading. Therefore, the steel ferry is not safe in this case of loading. For the composite ferry, the stress equals $1.62 \times 10^9$ Pa at $t = 2$ s, which is higher than the values in the previous cases of loading. The stresses curve is changed as the tank load is applied at the connections between two pontoons.

6.4. Case 4

In this case of loading, the load is applied with a transverse eccentricity equal 1.5 m from the center of the ferry to the left. The total deformation over the ferry is as shown in Figure 31. The figure illustrates that the deformations are asymmetrical and that the ferry is warped more than the previous cases for both steel and composite ferries.
Figure 31. The total deformation distribution in case 4.

Figure 32 demonstrates the maximum deformations with time over the ferry for both materials. The figure illustrates that the deformations in this case are the same as the previous cases but with higher values. The increase of the deformation values from case 1 is about 18% for the steel ferry and 30% for the composite ferry.

(a) The steel ferry 
(b) The composite ferry

Figure 32. The total deformations with time for case 4.

The maximum deformation in this case equals 1.3351 m for the steel ferry at $t = 7.8$ s and 0.30341 m for the composite ferry. Figure 33 illustrates the stress distribution.

(a) The steel ferry 
(b) The composite ferry

Figure 33. Von-Mises stress distribution for case 4.
The stress values exceed the allowable strength for the steel ferry. Figure 34 shows the stresses in case 4 for both materials.

![Figure 34](image)

(a) von-Mises stress for steel ferry  
(b) The composite ferry

**Figure 34.** Stresses change with time for case 4.

The stress values are slightly increased compared to the previous case, having a maximum value of \(1.65 \times 10^8\) Pa for the steel ferry at \(t = 2\) s and \(2.078 \times 10^8\) Pa for the composite ferry at \(t = 2.2\) s. The results assure that the increases in the vertical displacement and von-Mises stresses are caused by the increase in the transverse eccentricity of the applied load. The von-Mises results of the composite ferry for the whole cases are lower than the maximum stresses of the used composite materials, which means that the ferry is safe and that there is no failure according to the maximum stress theory. The maximum results for the four cases of loading for both materials are summarized in Table 3.

### Table 3. The results of the steel ferry and the composite one.

| Weight (kN)  | Case 1 | Case 2 | Case 3 | Case 4 |
|-------------|--------|--------|--------|--------|
| Steel ferry |        |        |        |        |
| Def. (m)    | 1.129  | 1.54 \(\times\) 10^8 | 1.2086 | 2.2 \times | 1.262 | 1.58 \(\times\) 10^8 | 1.335 | 1.65 \(\times\) 10^8 |
| Stress (Pa) | 562.5  | 1.297  | 1.49 \(\times\) 10^8 | 0.2557 | 1.49 \(\times\) 10^8 | 0.279 | 1.62 \(\times\) 10^8 | 0.3034 | 2.078 \(\times\) 10^8 |
| Comp. ferry |        |        |        |        |

These results make it possible to increase the capacity of the ferry to accommodate more than the tank load of (MLC70) or to reduce the cross-sectional dimensions to make the ferry more economic.

### 7. Conclusions

In this study, the dynamic behavior of a ferry is investigated using ANSYS software. The simulation of the ferry is performed for both steel and composite materials. The boundary conditions are simulated, and the applied load is assigned as a dynamic load of the tank MLC70, which equals 623 kN. The validation of the numerical model is checked by field measurement and mathematical results. The validation is performed for the draft of the ferry under its own weight, and the results from ANSYS are almost the same as the experimental results. Nonlinear buckling analysis is performed for the composite ferry to ensure the safety of the model. Furthermore, the study presents the expected modes of buckling and the methods of predicting their occurrence. The maximum stress theory which is used to predict the failure is safe for the composite model for all cases. For eccentricity of more than 0.5 m (i.e., for 1 m transverse eccentricity), the stresses are increased with a very high percentage to reach 9 times in steel ferry and 3.2 times in composite ferry. The results of the dynamic analysis also show that, if there is eccentricity, then the transverse eccentricity of the moving tank MLC70 must not exceed 0.5 m for the steel ferry, while may reach up to 1.5 m for the composite ferry with the same outer dimensions and stiffeners as the steel ferry. When the transverse eccentricity of the moving tank MLC70 is 0.5 m, the total deformation values are increased by 7% for the steel ferry and about 9.5% for
the composite ferry. Additionally, the stresses are increased by about 42% for the steel ferry and by about 4 times for the composite ferry. If the eccentricity exceeds 0.5 m for the steel ferry and 1.5 m for the composite, there will be an insufficient torsional stiffness to resist the twisting moment from the eccentric loading. The composite ferry shows that the buckling load factor is 5.3, which means that the capacity can be increased and shows also an improvement in weight/capacity ratio rather than steel ferry, as composite ferry weighs 29% of the steel ferry. The improvement in the weight/capacity ratio allows the increase of the permissible carrying load from a stability perspective. Additionally, the aforementioned results illustrate that the increasing in the vertical displacement is caused by the additional moment due to eccentricity.

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