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Research Article

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Comparison of offshore fish cage flotation systems designs using finite element method

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Highlights

- Finite element analysis of offshore structures
- Use of High-Density Polyethylene (HDPE) in cage systems
- Comparison of design geometries of floating collar systems

Abstract

Cage fishing is a sustainable production method that enables the controlled rearing of fish populations through cage systems established in inland waters or seas. Threats such as increasing environmental pollution, global warming, and irresponsible hunting negatively affect marine populations. This method offers significant advantages in meeting the need for seafood in a controlled and healthy way. To benefit from cage fishing effectively and healthily, the necessary conditions must be provided optimally, thus creating a suitable environment. However, the performance of cage systems is directly affected by environmental conditions, requiring designs to be analyzed under environmental effects. This study examined the designs of stable floating structures that ensure cage systems remain stable in the desired position and serve as a safe platform in situations requiring intervention. Floating structures with different geometric designs used in the application were analyzed using the finite element method under varying current speeds (0.5 m/s, 0.7 m/s, 1 m/s), and the results were compared. ANSYS Workbench, a software program based on the finite element method, was used during the analyses. In this context, it aims to provide information that can guide design decisions before implementation to prevent problems that may occur with the data obtained.

Information

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1. Introduction

Although not as ancient as land-based farming, the history of aquaculture dates back to 3000 years ago. However, it is less developed than as land farming and contributes less to production. With the development of technology, aquaculture, in other words cage fishing, has also developed in the last 50 years and has contributed to commercial changes and developments in aquaculture. It can be said that these changes and developments were caused by factors such as population growth, increased welfare, urbanization, and increased demand for aquaculture protein sources.

The development of cage systems has been progressively modernized over the last 50 years, along with the development of the salmon farming industry. In this regard, cages have been designed to create protected areas in onshore waters. The designed cages were made of wood steel, and plastic [1]. Cage fishing can be done in different environments, such as inland waters and seas. Factors such as wave amount, water temperature, current strength, and wind intensity vary in inland waters or seas. In this case, the cage and fastening systems to be installed must be designed carefully, considering the specified factors [2]. Today, cage systems used in aquaculture are generally seen as fixed, floating, submersible, and underwater systems. Each of these systems has its advantages and disadvantages. The most

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widely used system worldwide is the floating cage system due to its versatility and flexible design options [3]. Cage systems are used in different structures and different ways. Mesh net bags can be expressed in various ways, such as being flexible or rigid, the way the net is woven according to the shape of the taut net bag, or whether it is knotted. Depending on their swimming position, they are grouped into underwater swimming and surface floating cage systems. In addition, their applications and uses are common in circular, square, and polygonal shapes. The purpose of cage systems is to maximize the water mass in the existing resource storage [4]. The elements that make up truss systems generally consist of three main groups. These are: net cage, a net bag whose open part remains above the water; Floating collar, elements that provide swimming around the system; and Mooring systems, a mooring system that connects the system to the land or the bottom. These elements primarily operate under the influence of current.

There are many studies on cage systems. Some studies that have contributed to the literature are summarized below. Li et al. (2013) investigated the dynamic responses of floating fish cages to horizontal waves and currents using ABAQUS software and observed large geometric deformations and movements in the buoys and nets, and emphasized that the friction forces in the nets can significantly affect the dynamic movements of the buoy [5]. Liu et al. (2019) evaluated the structural strength and failure of the floating collar of single-point mooring fish cages based on the finite element method and stated that static analysis, vibration analysis and fatigue analysis of FEM can be preferred as reliable ways to evaluate the structural strength and failure for the floating system [6]. In their study examining fluid-structure interactions in cage-based aquaculture, Xu and Qin summarize studies showing how ocean environmental loads can affect offshore aquaculture cages and fish swimming behavior [7]. Chen et al. (2022) used numerical and experimental methods to study the fluid-structure interaction (FSI) problem of a wedge structure with stiffeners colliding with water during the free-falling water ingress process, and comprehensively analyzed the impact response results obtained by numerical simulation and experiments, including displacement, velocity, acceleration, impact pressure, deformation, structural stresses, and total forces on the wedge, taking into account the hydroelasticity effects under different free-fall height conditions [8]. Shaik et al. (2023) analyzed the hydrodynamic behavior of open-net offshore fish cages of single, double and quadruple cage systems exposed to regular sinusoidal waves with Ansys software. The analysis results concluded that the four-cage system performed better than other cage configurations [9]. Veigas et al. (2024) investigated the hydrodynamic behavior of a cage exposed to a steady current using a fluid-structure interaction model. As a result of the study, they stated that there were decreases in flow within the network and downstream, consistent with previous experimental findings and research, and that knotted networks gave better results than knotless networks in line with mechanical analysis [3].

The analysis of the behavior of the floating collars of the open sea fish cages, which are the subject of this study, when exposed to the current effect was made using the finite element method. The floating collars are connected to the mooring systems to ensure the net cage is stable in and above the water. Floating collars are produced in various shapes and sizes according to needs and design conditions. In general, the most common floating collar shapes are circular and angled. In the study, two different floating collar designs, circular and quadrangular, were made and modeled.

The data obtained as a result of the study is intended to provide valuable data to designers regarding the design of floating collars, one of the most important elements of cage fishing systems, and their positioning according to the direction of the current.

2. Materials and Method

This study conducted a Fluid-Structure Interaction (FSI) simulation using ANSYS Fluent. FSI simulation is a method that combines the effects of hydrodynamic loads on the model with structural mechanics. The loads calculated in Computational Fluid Dynamics (CFD) are transferred to the mechanical model (FEM) for this combination. This simulation (FSI) is an approach that integrates the effects of hydrodynamic forces on the structure with structural analysis. The forces obtained with the help of simulation were transferred to the Finite Element Model (FEM) used for structural analysis. Analyses of the systems were performed based on the finite element method.

The Finite Element Method (FEM) is an influential numerical analysis method used to perform complicated physical and mechanical problems in engineering applications. This method allows a system with a complex geometry to be easily analyzed by breaking it down into smaller and easier-to-solve finite elements. FEM is a method that has proven its reliability in terms of interdisciplinary analyses. Researchers have examined nanoscale analyses [10, 11], biomechanical studies [12-15], and complex engineering problems [16-18] with this method and presented their results to the literature.

Before analyzing the floating collar system with FEM, the model geometry must be created accurately in the digitized environment. In this stage, the most suitable geometry representing the system is created, and the most optimal finite element types are selected when creating the mesh structure. Specifying the appropriate finite element type and size greatly affects the correctness of the analysis results. The mesh structure is enhanced using the selected element types, and the material properties of the model are defined. Then, the loading and boundary conditions to be imposed on the system are specified. After all these steps are accomplished, the FEM analysis of the model is conducted. The findings of the FEM analysis enabled the detection of critical factors that should be considered in the design of Floating Collar systems and aimed to guide the pre-implementation process.

2.1. Geometry

The floating collars of the systems were designed with a height of 1 meter and a width of 1.11 meters to fit the grid element (Figure 1a). For the floating collars to act as a floating structure on the water, 4 independent hollow pipe geometries with a wall thickness of 2 mm were created. These pipes were connected with the help of another geometry on top, and a hollow structure was designed. A three-dimensional circular floating system was formed by rotating around a 5 m diameter axis. Similarly, a three-dimensional angular floating system was formed by moving it around axes of 5x5 m (Figure 1b, c).

To successfully simulate the flow of water in CFD analysis, a flow field surrounding the model must be defined. This flow area should allow water to move freely around the floating collar system. The correct application of boundary conditions in the analysis is also important to represent the physical behavior of the flow in the most realistic way (Figure 2).

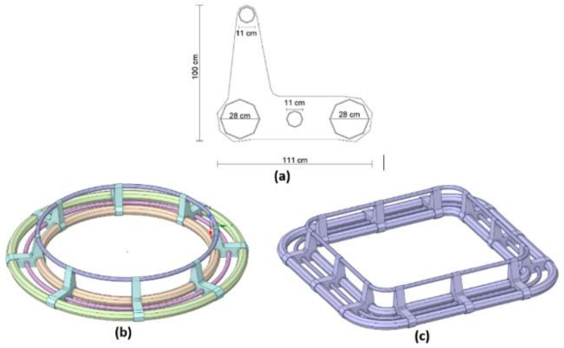

Figure 1. a) Cross section of floating collar models, b) circular floating collar system, c) angular floating collar system

2.2. Mesh structures

The models were transferred from AutoCAD to ANSYS Fluent for finite element analysis, and a separate meshing process was performed for each model. To obtain realistic and reliable results, great attention has been paid to correctly selecting the dimensions of the finite elements that comprise the mesh structure and using the appropriate finite element types. Each finite element is defined in this direction by a tetrahedral (tetrahedron) element with eight nodes for the mesh configuration. These finite elements suit displacement and rotational movements in the x, y, and z axes. The number of nodes and elements of each system are summarized as follows: The circular floating collar system has a total of 50633 nodes and 167616 finite elements, and the flow field designed by the geometry of the circular floating collar system has a total of 165929 nodes and 912552 finite elements (Figure 3). The angular floating collar system has 136863 nodes and 489283 finite elements; the flow field designed by the angular floating collar system geometry has 387075 nodes and 2128071 finite elements (Figure 4). Additionally, each mesh structure is modeled to have isotropic, homogeneous, and linear elastic properties.

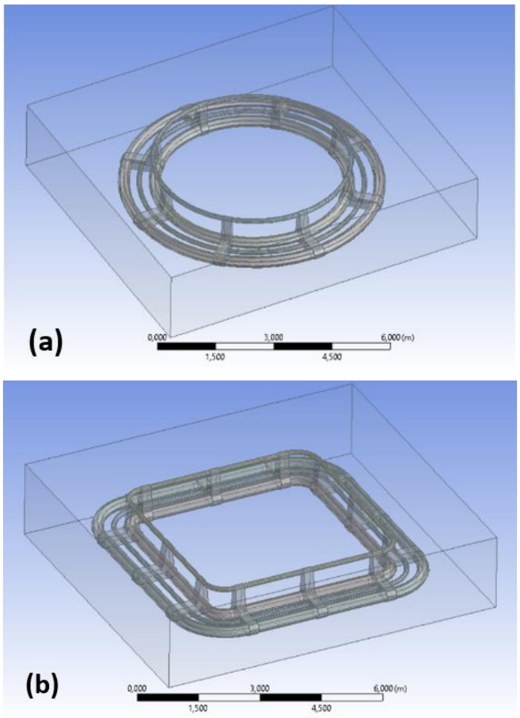

Figure 2. CFD analysis models a) circular floating collar system, b) angular floating collar system

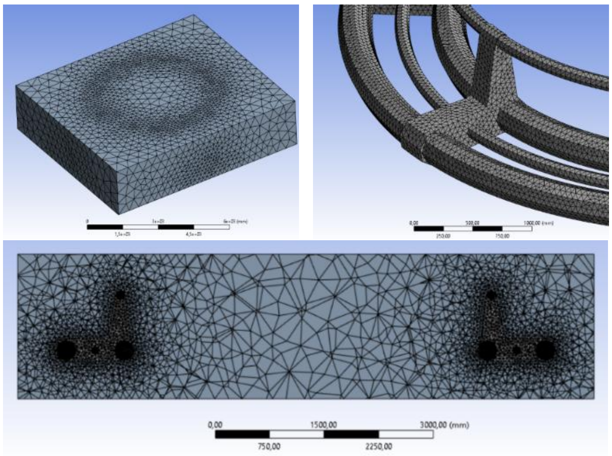

Figure 3. Mesh structures of the circular floating collar system and flow fields

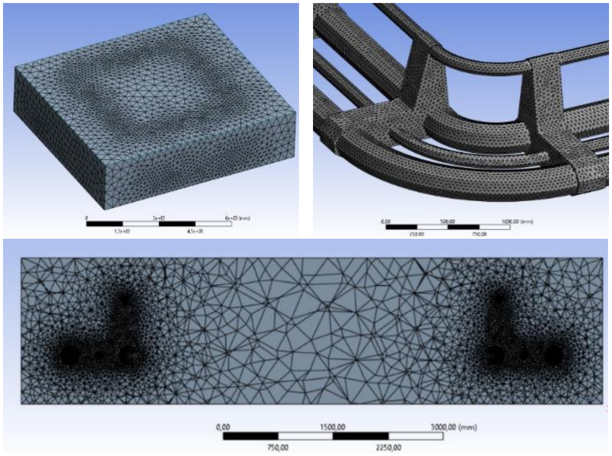

Figure 4. Mesh structures of the angular floating collar system and flow fields

2.3. Material properties, boundary and loading conditions

The mechanical properties of the materials for the floating collar systems and flow areas were specified in compliance with the literature. All the materials identified are such that they are isotropic, homogeneous, and have linear elastic properties, and were appropriately assigned to each site. The mechanical properties of the material used in the present study are provided in detail in Table 1.

Table 1. Material properties

	Density (kg/m³)	Young modulus (E) (MPa)	Poisson's ratio(v)
High-Density Polyethylene (HDPE)	950	1000	0.46

Before proceeding to the finite element analysis, the model's boundary conditions were determined, and simulations were performed for various loading scenarios. At first, CFD analyses were conducted to determine the pressure values generated by the fluid on the models. During the CFD analyses, no deformation analysis was conducted on the models; only the pressures generated on the surface of the models depending on the flow velocity were calculated. In the analyses, the "water-liquid" material was selected from the Fluent material database, and the constant viscosity for this material was defined as 0.001003 kg/(m-s), with a density of 998.2 kg/m³. Within the scope of the study, the models were analyzed under three different flow velocities (0.5 m/s, 1.0 m/s, and 5.0 m/s).

Analyses were performed under these defined boundary and loading conditions. The maximum stress and deformation values exposed to the floating collar systems were calculated and registered.

3. Results and Discussion

In this section, the results of mechanical analyses of floating collars designed in two different geometries under the boundary conditions explained in the previous section will be examined. As a result of the analyses, total deformation, equivalent (von Mises) stress, and equivalent strain values were obtained, and the obtained values were compared (Table 3-5). Images of the analysis results are given in Figure 6.

Table 2. Pressure magnitudes (MPa) obtained from CFD analysis and transferred to mechanical models

	0.5 m/s	1.0 m/s	5.0 m/s
Circular collar	0.00021509	0.00085873	0.021361
Angular collar	0.00022346	0.00088937	0.022065

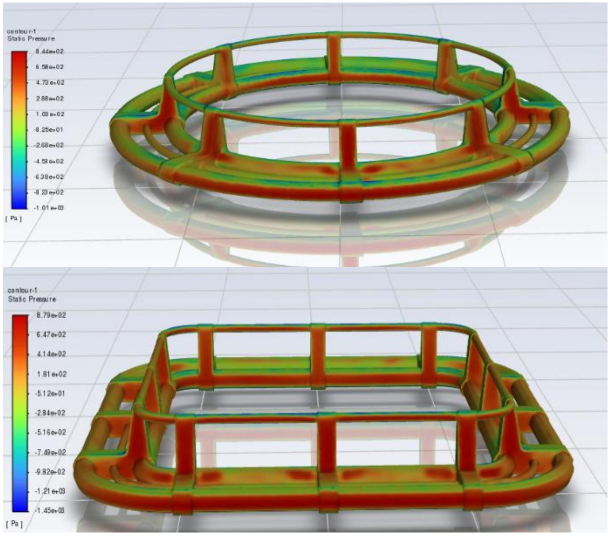

Figure 5. Pressure distributions calculated for 1.0 m/s flow velocity in CFD analysis

The CFD analysis calculated the pressure distributions formed by the fluid effect on the models, which influenced the models in the mechanical analysis. The magnitudes of the pressures obtained from the CFD analysis and transferred to the mechanical model are given in Table 2 and shown Figure 5.

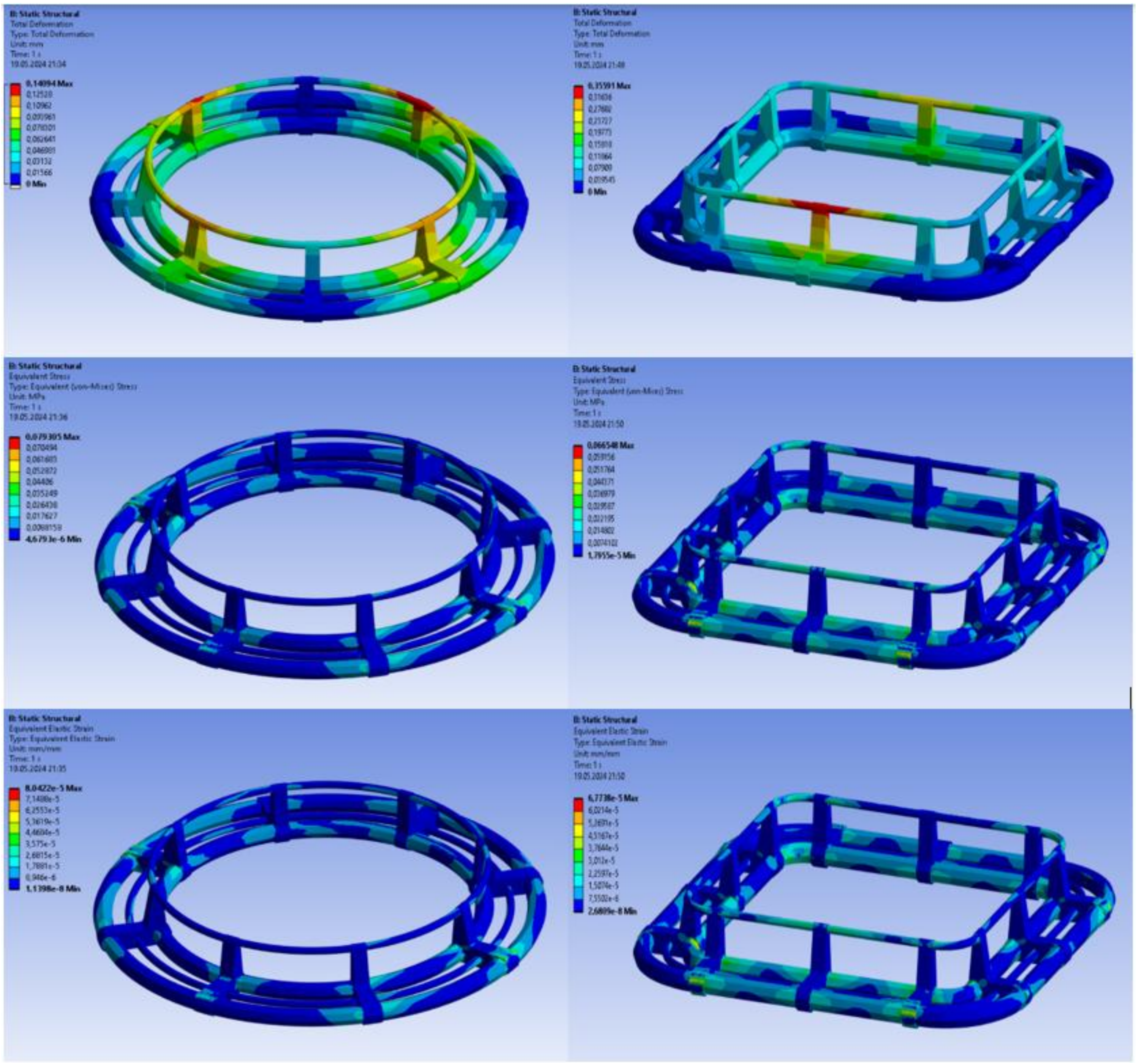

Figure 6. Analysis result images obtained from circular and angular floating collar under 0.5 m/s current speed.

Table 3. Total deformation values obtained as a result of the analysis (mm)

	Flow velocities		
	0.5 m/s	1.0 m/s	5.0 m/s
Circular collar	0.14904	0.56775	14.264
Angular collar	0.35591	14.237	35.996

When Table 3 is examined, the deformations occurring in both models increase as the flow velocity increases. The deformation occurring in the angular model was much larger than in the circular model. This difference can be explained by variations in the surface areas directly exposed to the flow and the fixation areas.

Table 4. Equivalent (von Mises) stress values obtained as a result of the analysis (MPa)

	Flow velocities		
	0.5 m/s	1.0 m/s	5.0 m/s
Circular collar	0.079305	0.31645	7.9069
Angular collar	0.066548	0.26639	6.6375

When Table 4 is examined, it is seen that the obtained stress values increase with the flow velocity. The stress values obtained for the angular collar are slightly smaller than the values obtained for the circular collar.

Table 5. Equivalent strain values obtained as a result of the analysis

	Flow velocities		
	0.5 m/s	1.0 m/s	5.0 m/s
Circular collar	8.0422×10^{-5}	0.00032092	0.0080186
Angular collar	6.7738×10^{-5}	0.00027116	0.0067562

When Table 5 is examined, it is seen that the obtained strain values increase with the flow velocity. The strain values obtained for the angular collar are slightly smaller than the values obtained for the circular collar.

4. Conclusions

As a result of the analysis, it was seen that there was no harm in the use of both models. The stress and strain values for the angular collar were slightly lower than those for the circular collar, indicating a slightly better performance. Angular floating collars placed perpendicular to the flow direction were subjected to more stress effects under liquid influence than circular floating collars. This situation can be solved by adjusting the position of the floating collar according to the flow direction. However, the deformation value for the angular collar was significantly higher, particularly in the upper parts of the collar. Despite this, it does not pose a threat to the overall structural integrity. Although both models show approximately the same reactions under loads, the angular model provides slightly more space, which makes it slightly more advantageous. In addition, the analysis results showed that the use of HDPE for collar production was quite suitable.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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