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Multi-Objective Structural Optimization of a Large-Scale Spherical Public Aquarium Using FEM, ANN, and Genetic Algorithms

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Abstract


This paper discusses the design process and multi-objective optimization of a large public spherical aquarium with a cuboid inner viewing tunnel. The structural geometry of the space frame, composed of steel combined with acrylic panels supported by reinforced concrete, is modeled using the Finite Element Method (FEM). The hydrostatic pressure acting on the surface, the load due to visitors, and the dynamic force due to impacts from aquatic animals are accounted for in the structural analysis. To minimize computational cost, an Artificial Neural Network (ANN) surrogate model is created using Finite Element Analysis (FEA) output. After creating an ANN model, the problem is solved using a multi-objective Genetic Algorithm (GA), and the safety factor is maximized by minimizing structural weight. This research shows that the proposed hybrid FEM-ANN-GA model effectively determines the optimal acrylic panel thickness that meets the safety criteria. The optimal solution achieved has a total structural weight of approximately 9569 tons.

Keywords: Large-scale public aquarium, Structural optimization, Finite element method, Artificial neural network, Genetic algorithm, Hydrostatic loading, Acrylic structure.

1 | Introduction

Big public aquariums are multipurpose structures that provide not only leisure or touristic services but are also very useful for marine biology research, species conservation, and educational campaigns [1–4]. In addition to their educational and ecological missions, modern aquarium facilities are increasingly required to satisfy strict operational, maintenance, and research-related criteria associated with large zoological infrastructures [5].

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Moreover, the circulation systems and seawater treatment processes in aquaria are further constrained by engineering issues, especially in larger aquatic environments [6]. Over the past three decades, there have been significant advancements in structural and architectural planning for aquaria, from basic reinforced-concrete rectangular tanks to large-span structures with advanced geometry [2], [4].

In addition to the above changes, there have been significant advances in the materials used for aquarium construction. Traditional glass panels are increasingly being replaced by acrylic PMMA panels owing to their high optical quality, reduced weight, increased shock resistance, and durability under hydrostatic loads [7], [8]. Modern research indicates that large-span acrylic structural members exhibit favorable behavior under hydrostatic loads and do not exhibit creep; therefore, they are highly applicable for modern aquarium construction [8]. Large-span translucent acrylic systems have become increasingly popular for aquatic architecture due to technological advances [8]. Although this technology is now available, the engineering challenges of designing a large aquarium are significant, particularly when nontraditional geometries are considered.

Out of various geometric configurations possible, there is a definite structural benefit associated with the use of spheres, since the distribution of hydrostatic pressure in such geometric configurations tends to be more uniform, hence lowering stress concentration. Spherical aquariums can thus save on material requirements and increase rigidity compared to rectangular or cylindrical counterparts. Although several public aquariums use complex shapes, including curved panes, no study has been conducted on a completely spherical structure with a cubic tunnel inside.

To support such geometrically complex systems, spatial structures are considered among the most efficient structural solutions. Space-frame systems are three-dimensional truss structures capable of distributing loads effectively in multiple directions while providing high stiffness-to-weight ratios, excellent seismic resistance, and significant architectural flexibility [9]. Geodesic domes are better suited than any other spatial structure for designing spherical storage tanks because they accurately depict the spherical form, distribute forces uniformly, and are efficient in material use [10], [11]. Optimizations of geodesic domes and space trusses have been carried out in recent years, ranging from topological to structural optimizations [10-13].

In addition, generative design approaches and variable-frequency dome configurations have demonstrated significant potential for improving structural efficiency in large-span spatial systems [10]. The structural assessment of such structures subjected to hydrostatic load requires an advanced modeling method. This issue cannot be solved using classical methods because the problem statement contains multiple nonlinearities. For this reason, the Finite Element Method (FEM) is widely used today to analyze the behavior of acrylic panels and steel space frames under realistic loading conditions [8–11]. Finite Element modeling enables accurate prediction of stress and strain distributions within the structure. Nonetheless, FEM computations are rather costly, particularly when many design variables need to be analyzed.

To address these shortcomings, surrogate modeling using Artificial Neural Networks (ANNs) has been widely used in structural engineering optimization problems [14]. Finite element-based ANN models can accurately capture nonlinear structural responses while significantly reducing computational costs. Recently, it has been shown that deep learning neural network models can generate accurate predictions for nonlinear structural systems and could be used in the optimization process [14].

Once an appropriate surrogate model is created, optimization algorithms can be applied to optimize the structure design. One of several popular optimization methods used in structural engineering due to its ability to handle both discrete and continuous variables simultaneously, avoid getting stuck in local optima, and solve multi-objective optimization problems is the Genetic Algorithm (GA) [11-13]. Successful implementation of hybrid optimization strategies involving FEM, ANN, and GA was observed during the optimization of trusses, geodesic domes, and cable-supported spatial structures [13–16]. For instance, Lu and Ye [11] examined the optimization of space dome design with respect to buckling using GAs. At the same time, Lu and Ye [12] proposed a new guided GA approach to optimize space domes with discrete variables. On the one hand, Khodadadi et al. [13] presented a thorough review of metaheuristic optimization methods for large-

scale space trusses. On the other hand, Yücel et al. [15] proposed an innovative hybrid approach in optimizing the structure's weight under displacement and stress constraints.

While important progress has been made in the field of structural optimization and surrogate-assisted structural optimization [11-16], the problem of a combined analysis of a spherical public aquarium with a cubic tunnel using the FEM, ANNs, and genetic optimization has been neglected to date. The existing literature mostly focuses on either conventional dome shapes, instability control problems, or light-weight structural systems [10-13]. At the same time, little is known about the mechanical properties of the full-spherical public aquarium with hydrostatic pressure loads and construction materials such as acrylic glass panes, steel spatial members, and reinforced concrete supports. Another area that requires thorough investigation is the creation of reliable ANN surrogate models to predict nonlinear correlations between geometric design variables and structural response parameters, such as maximum stresses, displacements, and structural weight [14].

In addition, although GAs have been successfully employed for the optimization of truss and dome structures [11-16], their application to the simultaneous minimization of structural weight and stress in large-scale aquarium systems under hydrostatic loading conditions has not been reported. In addition, validation of optimized configurations through thorough analysis of full finite element simulations has received little attention in the existing literature.

Hence, the current research study aims to propose an integrated computing methodology for the design and optimization of a large-scale spherical public aquarium with a cubic tunnel within the spherical structure. The initial step would be to formulate a geodesic space-frame configuration, coupled with acrylic view panels and reinforced concrete support structures, to develop the finite element model. Hydrostatic and loading conditions would then be imposed on the structure. The geometry of the space frame and the addition of acrylic viewing panels and reinforced concrete support systems are first carried out to form an FEM model, followed by the application of loadings related to the hydrostatic environment and the structure's operation. The numerical results from extensive parametric finite element analyses are then used to train an ANN to approximate the relationship between the principal design variables and structural performance indicators. Furthermore, the trained surrogate model will be linked to a multi-objective GA to determine the optimal design parameters that achieve both structural safety and reduced material use. Lastly, the optimal design for the structure is validated through finite-element modeling analysis.

2 | Structural Modeling and Analysis

The spherical aquarium proposed herein is a massive spatial structure whose loads will primarily be determined by hydrostatic pressure and stability requirements. Because of the high stiffness-to-weight ratio and optimal force transmission associated with spatial systems, geodesic dome-like configurations are adopted as the primary structural forms. Spatial structures, especially geodesic domes, have been recognized for decades for their good stiffness-to-weight ratio, optimal force-transmission characteristics, and ability to handle multi-load directions within spheres [9–11]. New research proves that they also perform efficiently in multi-objective structural systems optimization [11-13].

First, the structure's geometry is created in CATIA and then imported into ANSYS Workbench for structural analysis. The complete layout of the structure is shown in *Fig. 1*, and its finite element model is illustrated in *Fig. 2*. The structure is located within a seven-story building used for commercial and administrative purposes. Every story is 3 meters high. Steel circumferential members are oriented with the floors.

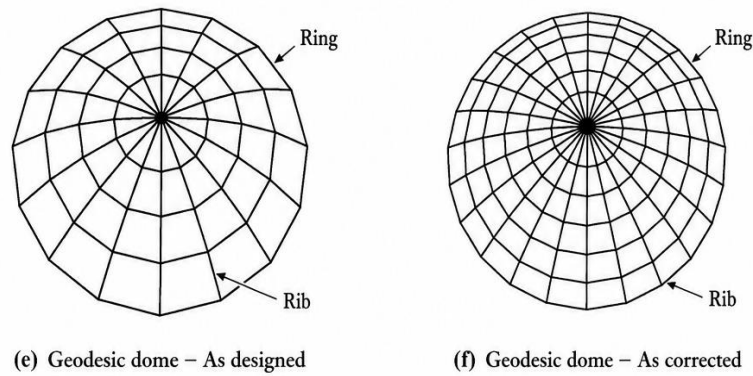


Fig. 1. e. Overall view of the designed ribbed dome structure, f. Geometric view of the designed spatial steel framework.

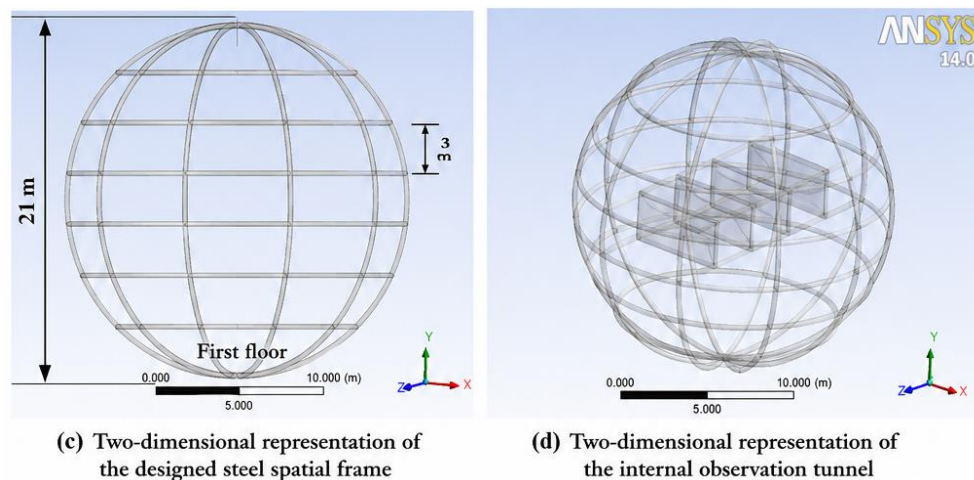


Fig. 2. Overall view of the designed steel space-frame structure.

The discretization of the sphere in terms of geometry was performed by splitting the surface into 10 equal angular sectors (36°). The inner observation passage of about 21 m long is split into five equal sectors to limit local deformations and enhance the stiffness continuity. The first level consists of a reinforced concrete base (8m x 8m) that serves as the main load-transfer component, accommodating hydraulic and mechanical systems. Acrylic panels enclose only the uppermost six levels of the sphere. The model configuration and assumptions are shown in Fig. 2.

To accurately consider the interaction between the structural elements, a hybrid finite element modeling approach is applied. Steel members are considered as beams (line bodies), while acrylic panels are modeled as shell elements. The reinforced concrete base is modeled using solid elements. This multi-material Finite Element Analysis (FEA) provides an adequate representation of the actual stiffness distribution and load-transfer processes under hydrostatic loading [7], [8]. The resulting finite element mesh comprises about 220,000 finite elements (Fig. 3).

2.1 | Mesh Discretization

Structural components undergo independent mesh generation to guarantee numerical stability and accuracy. Steel bars are automatically meshed using the beam method. Acrylic panels are discretized using mapped meshing to ensure an even distribution of elements and to achieve accurate stress predictions during pressure loading. The concrete base is automatically meshed using the tetrahedral meshing method.

Mesh refinement is performed in critical sections, especially at the interfaces between steel and acrylic bars, and between acrylic bars and concrete. The final mesh is shown in *Fig. 3b*. It comprises roughly 2.2×10^5 elements.

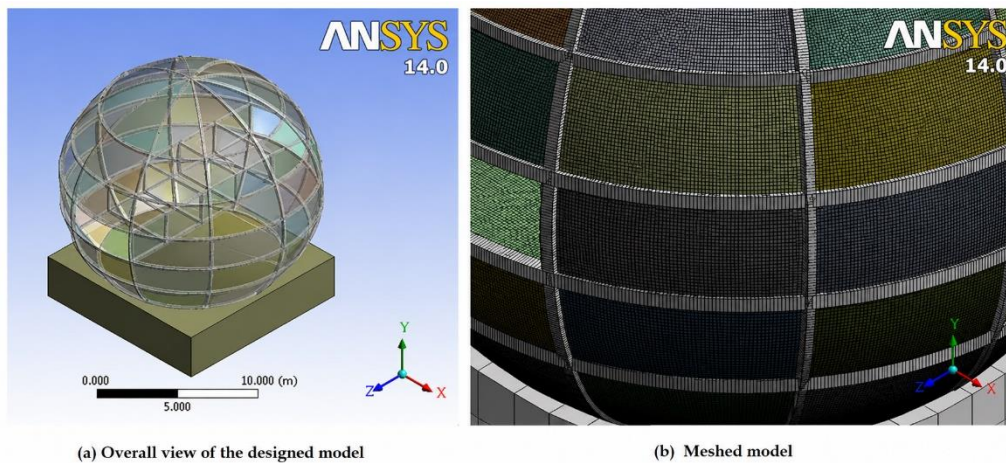


Fig. 3. a. Overall view of the finite element model, b. Meshed model of the proposed structure.

2.2 | Solution Process in Numerical Method

Once the structural geometry is established, meshing is performed, and all boundary conditions and loads are applied, the static structural problem is solved using the static structural solver within the ANSYS APDL environment. In the process, the analysis is completed in a single load step. At the same time, nonlinearities related to deformation are disregarded because the system's displacements will be small relative to the structure's size.

The structural integrity of the aquarium will be analyzed in accordance with internationally recognized recommendations for large public aquarium structures, which call for a factor of safety ranging from 6 to 6.5, depending on operating conditions. In this study, a minimum factor of safety of 6.5 is considered adequate for this analysis.

2.3 | Load Cases

Loads include hydrostatic pressure, live loads from people, and impact loads from aquatic creatures. In particular, hydrostatic pressure dictates the whole response of the structure.

2.3.1 | Hydrostatic pressure loading

Hydrostatic pressure loading is applied to the structure. Also, the analysis of flow-induced loads by CFD analysis in ANSYS Fluent and Gambit is carried out. For hydraulic balance purposes and to minimize turbulence, a constant mass flow rate of 0.36 kg/s is adopted at the inlet and outlet faces.

As shown in *Fig. 4*, the pressure behavior under hydrostatic loading conditions is observed, except at locations with turbulent flow. Turbulent flows occur at regions where a structural joint exists between the steel panel and the acrylic tunnel connection. Safety factors of 6.0 and 6.5 are used for the total region and the turbulent region, respectively [10].

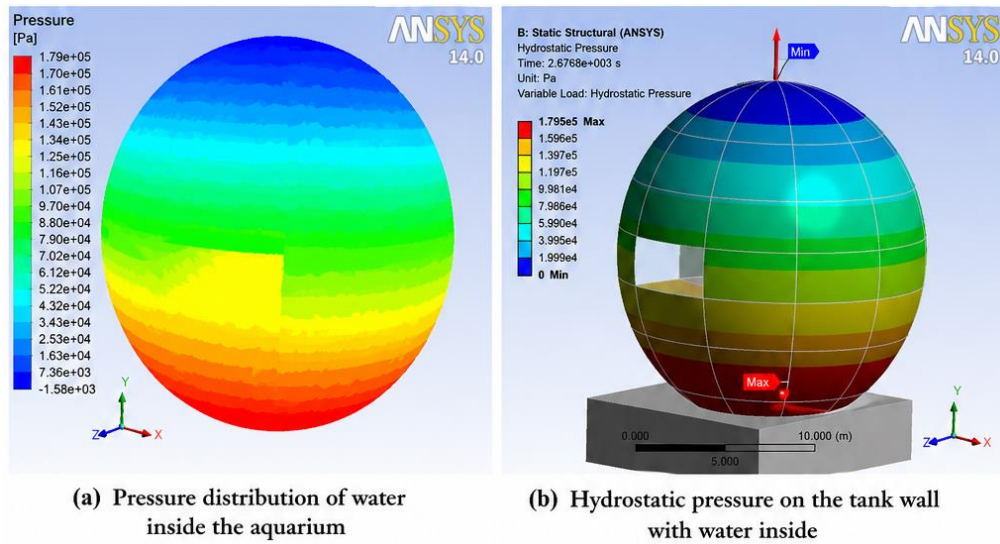


Fig. 4. a. Hydrostatic pressure contour inside the aquarium, b. Pressure distribution acting on the internal walls under static water conditions.

2.3.2 | Visitor-induced loadings on the inner tunnel

Apart from hydrostatic pressure, another source of load comes from visitors in the aquarium's inner tunnel. In assessing the structural safety of such a structure, it is presumed that the worst scenario, the maximum number of crowd loads, should be taken into account. The estimated value of this loading force is approximately 300 kg/m². Pedestrian movement is inherently dynamic; hence, an impact factor is needed to convert this load into a static one.

$$\begin{aligned}
 F &= Mg, \\
 M &= 300\text{Kg}, g = 10 \text{ m/s}^2, \\
 \Rightarrow F &= 3000\text{N}.
 \end{aligned}
 \tag{1}$$

It has been mentioned that the hydrostatic pressure inside the tunnel is about 120 kPa, which is close to 120 kN per square meter upwards. On the other hand, the crowd-induced loadings will act downwards (see Fig. 5). For this purpose, an impact amplification factor will have to be greater than 40 to compensate for this upward hydrostatic force and more than 80 to change the direction of this loading altogether. Such values cannot be physically justified. As a result, visitor load does not significantly affect the tunnel's critical dynamic response and can therefore be ignored relative to hydrostatic loading. Thus, the loading state that should be considered most important is when the tunnel is empty.

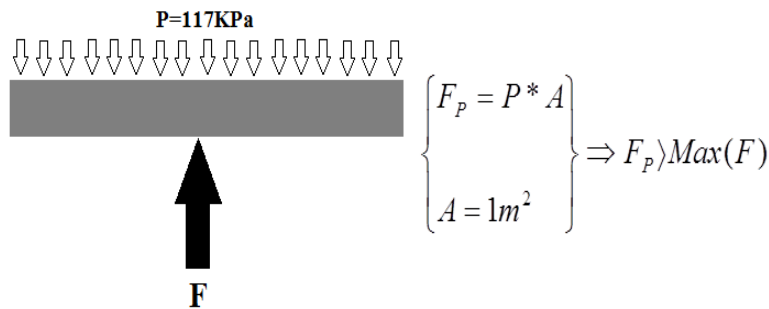


Fig. 5. Forces acting on the floor of the visitor observation tunnel.

2.3.3 | Dynamic impact loads caused by animals in water

The marine animals in the aquarium might produce dynamic impact loads from collisions with the acrylic plates outside the aquarium. In the current study, the limiting case would be a large shark weighing about 2 tons. The impact load caused by the collision is calculated according to the following impulse-momentum theory equation:

$$F = \frac{MV}{t}, \quad (2)$$

where (M) stands for the mass of the animal and (V) represents the velocity of the collision. Sharks are very fast swimmers and can achieve relatively high speeds even in enclosed areas. For the case when a large shark hits the acrylic wall at its top speed, with an assumed contact time of 0.01 sec, the resulting equivalent static impact load is expected to reach 400 kN.

3 | Structural Optimization

The most important optimization task here is to minimize the structure's total mass while maximizing the safety factor. Since the weight of the steel space frame remains constant throughout the optimization process, the total mass of the structure can be expressed as a function of the thickness of the acrylic panels. Therefore, three geometric parameters are selected as optimization variables:

- I. Thickness of the acrylic panels in the lowest level of the aquarium
- II. Thickness of the acrylic panels in the higher levels of the aquarium
- III. Thickness of the acrylic panels of the visitor tunnel

The system's response during optimization includes the structure's total mass and its minimum safety factor. To optimize the current structural configuration, a multi-objective GA will be coupled with FE simulations of the model. However, as there is no direct relationship between the input geometric parameters and the structure's performance, an ANN model must be created.

- I. Carrying out extensive finite element simulations for various combinations of acrylic thickness.
- II. Creating a dataset for structural responses such as stress, displacement, mass, and safety factor;
- III. Developing an ANN approximation of the nonlinear mapping of the input and output variables; and
- IV. Integrating the trained ANN with a multi-objective GA to identify the best design parameter values.

3.1 | Initial Database Creation via FEM

Based on the previous structural analysis, the acrylic thickness required to meet the minimum safety factor is presented in *Table 1* below.

Table 1. Initial acrylic thicknesses satisfying the minimum safety factor requirement.

Parameter	Thickness (cm)	Safety Factor
Bottom panels	27	6.5584
Upper panels	21	6.6167
Tunnel panels	29	6.5234

To generate the optimization database, the thickness parameters are varied within the ranges listed in *Table 2* using increments of 0.2 cm. Approximately 100 finite element simulations are performed in ANSYS Workbench for different combinations of acrylic thicknesses.

Table 2. Design variable ranges used in the optimization process.

Parameter	Minimum Thickness (cm)	Maximum Thickness (cm)
Bottom panels	27	32
Upper panels	21	25
Tunnel panels	29	34

The resulting FEM database is subsequently used for ANN training.

3.2 | ANN-Based Surrogate Model

As there is no explicit mathematical expression for the objective function, an ANN is used to model the relationship between the input variables and the structural response. Before training the ANN model, the masses are normalized to the range 0-1 to improve convergence. A multilayer perceptron with two hidden layers is chosen as the ANN model. Each hidden layer consists of 10 neurons, where the activation function used is hyperbolic tangent sigmoid. For the stopping criteria, there is no improvement in the error value for six successive training sessions.

3.3 | Multi-objective Genetic Optimization

After completing the training procedure, the ANN-based surrogate model is combined with a multi-objective GA to generate Pareto-optimal designs. Unlike single-objective optimization problems, multi-objective optimization problems often yield multiple non-dominated solutions. In the current case, there is a conflict between two objective functions: reducing acrylic thickness reduces structural mass while simultaneously making the structure less reliable. Hence, Pareto-optimal solutions for the current problem have been generated.

4 | Results of Optimization

The optimal structural solutions obtained from the GA are illustrated in the Pareto front shown in *Fig. 6*. Selected Pareto-optimal points are summarized in *Table 3*.

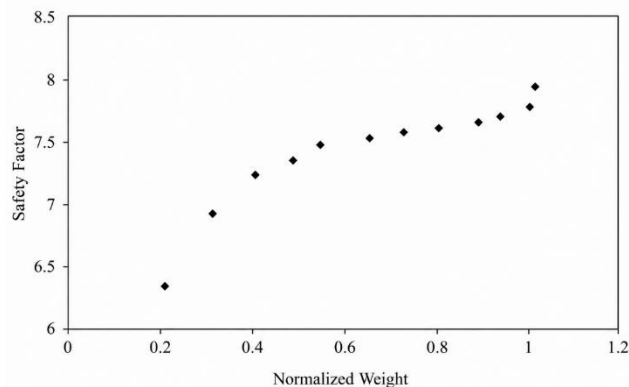


Fig. 6. Pareto-optimal solutions obtained from the multi-objective GA.

The optimization results indicate that increasing the thickness of the lower acrylic panels has a relatively limited effect on total structural weight because the number of these panels is comparatively small. However, this parameter significantly improves the safety factor in critical regions subjected to high hydrostatic pressure.

Conversely, the upper acrylic panels account for a large portion of the aquarium's total surface area. Therefore, reducing their thickness considerably decreases the total structural weight. The tunnel panels exhibit an intermediate influence on both structural mass and safety factor.

The optimization process further demonstrates that the hydrostatic pressure acting on the tunnel panels remains close to the static pressure distribution, indicating that slightly lower safety factors may still satisfy

the structural requirements without compromising reliability. The final optimized dimensions are 31.98 cm of acrylic thickness for the bottom panels, 21.54 cm for the top panels, and 30.46 cm for the tunnel panels. The respective safety factors are approximately 8.2, 6.81, and 7.18. Recalculating the optimized design against the full FEM design indicates that the total optimized structural weight is 9569 tons.

Table 3. Selected Pareto-optimal solutions obtained from the optimization process.

No.	Tunnel Thickness (cm)	Upper Thickness (cm)	Bottom Thickness (cm)	Safety Factor	Normalized Weight
1	31.243	22.573	31.983	7.354	0.489
2	31.400	23.046	31.983	7.599	0.786
3	31.667	23.234	31.983	7.644	0.872
4	31.130	22.543	31.983	7.498	0.540
5	33.638	24.999	31.983	7.925	0.984
6	31.282	22.954	31.983	7.563	0.718
7	32.027	24.827	31.983	7.760	0.978
8	31.135	22.917	31.983	7.520	0.647
9	31.626	23.483	31.983	7.680	0.916
10	30.993	22.657	31.983	7.374	0.406
11	30.460	21.540	31.983	6.920	0.310
12	30.554	20.311	31.983	6.340	0.220

The final optimized configuration corresponds to acrylic thicknesses of 31.98 cm for the lower panels, 21.54 cm for the upper panels, and 30.46 cm for the tunnel panels. The corresponding safety factors are approximately 8.2, 6.81, and 7.18, respectively. Reanalysis of the optimized structure using the full FEM model confirms that the total optimized structural weight is approximately 9569 tons and that all structural safety requirements are satisfied.

5 | Conclusion

In this research, an innovative computational methodology was formulated and applied for the design optimization of the structural system of a public aquarium sphere with an internal observation tunnel. Using FEM, an analytical model of a geodesic steel frame with acrylic panels and reinforced concrete supports was developed to study structural performance under hydrostatic pressure, the influence of visitor loads, and dynamic impact loads from marine animals. According to the simulation results, hydrostatic pressure was found to be the most critical loading condition affecting the structural performance.

To enhance the efficiency of the structural optimization process, an ANN model was built based on FEM simulation results. After training, the ANN model was employed together with a GA to optimize its structure, minimizing mass and maximizing the safety factor. The results of the optimization procedure showed that a hybrid computational approach involving FEM, ANN, and GA enables the determination of optimal acrylic panel thicknesses that satisfy all safety conditions.

The optimized design has safety factors above the required minimum, with a total structural mass of approximately 9569 tons. The results show that the proposed technique is an effective approach for designing and optimizing large-span aquariums and similar structural systems dominated by hydrostatic pressure.

Conflict of Interest

The authors declare that they have no competing interests.

Data Availability

The data supporting the findings of this study are available within the article.

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