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The Key Path of the Shape Optimization Design of Isotropic Material Pressure Vessels

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Abstract

An optimization design was conducted for the shape of the pressure vessel with a thin-shell shell. During this process, the optimization calculation was performed with the aid of the genetic algorithm toolbox included in Matlab. Firstly, through the parametric modeling function of APDL, models such as arc-shaped, parabolic, elliptical, and those generated by the fitting curve command were successfully constructed. Meanwhile, the relevant settings of material properties were accomplished, and the static analysis was conducted. Secondly, the optimization calculation process was initiated using the genetic algorithm toolbox in Matlab. Eventually, through analysis and judgment, the model generated by the fitting curve command was relatively superior within the category of the best shape.

Keywords

Optimization Design, Parametric Modeling, Thin-Shell Shell, Matlab, Genetic Algorithm Toolbox

1. Introduction

Sundeep Moyya [1] conducted in-depth research on the design and analysis techniques of pressure vessels through computer-aided design (CAD) and CAE tools. The combination of pre-existing materials and complex layered designs effectively alleviates pressure and enhances the safety and efficiency of pressure vessels. The results of this study are quite helpful for a comprehensive understanding of the design and analysis of pressure vessels, and the ultimate pursuit is to develop pressure vessels with higher safety and better efficiency in various industries. Hardi Mohammed [2] noticed that GWO performs well in developing the best solution, and used the WOA and GWO hybrid method called WOAGWO in the research. This hybrid model has two steps: First, the hunting mechanism of GWO is embedded in the development stage of WOA, which is a new situation related to GWO; Secondly, new technologies are added in the exploration stage to optimize the solution after each iteration.

Levend Parnas [3] developed an analysis program for the design and behavior prediction of fiber-reinforced composite pressure vessels. The elastic problem was solved through the classical lamination theory and the generalized plane strain model. Various factors were comprehensively considered, and the three-dimensional failure theory was used to obtain the optimal values of the relevant parameters of the pressure vessel, and the hygrothermal effect was also taken into account. F. Daghia [4]'s research shows that the mechanical response of pressure vessels to internal pressure is controlled by several key parameters, related to the structural geometry, the orientation and thickness of the composite layer. Simple models can understand the role and interrelationship of parameters in the early design stage, explore the design at low cost, and then use complex models to predict the detailed structural response. This article discusses the increasing model hierarchy, which is helpful for understanding the response of pressure vessels. M. Nebe [5] pointed out in the research that the industrialization of fuel cell electric vehicles requires an economically efficient hydrogen storage solution, and the gas storage technology of Type IV pressure vessels needs to be optimized. This study explored the influence of the stacking sequence of composite pressure vessels on the quality of laminates, etc. The laminates were studied by changing the stacking sequence. The specimen burst when pressurized to 166.11 MPa, and the deformation was tracked by 3D images. Experimental results: The burst pressure difference of the stacking sequence was 67%. Compared with the 3D elastic theory results, X-rays, etc. were used to provide insights. The results show that the stacking sequence has a significant influence. The 3D elastic method is useful, but there may be differences between predictions and experiments. The analysis and numerical strategies related to the transition effect should be considered. V. G. Belardi [6] proposed a closed-form analytical solution of the bending theory of composite material shells in the research, which is helpful for the design of composite material pressure vessels and promotes the development towards reliable structural configurations. The governing equations were derived and solved using the theory of thin-walled composite material shells to obtain the displacements and stresses at the joints. The analysis results were successfully compared and verified with the results of the finite element model. Different thicknesses of the container and other factors were considered to prove its accuracy. Cho-Chung Liang [7] studied the optimal design of the dome profile of filament-wound composite pressure vessels in his article. This design is subject to various conditions. The feasible direction method is used to maximize the shape factor, and the actual design example proposed by Fukunaga *et al.* is used to explore the optimal dome profile. S Sulaiman [8] covered the simulation work of carbon/epoxy fiber-reinforced polymer (CFRP) wrapped aluminum pressure vessels in his own research. The effect of winding angle on fiber-wound pressure vessels was explored through the finite element method (FEM). The burst pressure, maximum shell displacement and the optimal winding angle of the composite material container under the condition of pure internal pressure were determined.

Many researchers have conducted in-depth studies on pressure vessels. Sundeep Moyya used CAD and CAE tools to study its design and analysis techniques; Hardi Mohammed used a hybrid method of WOA and GWO to develop solutions; Levend Parnas developed programs to predict its design and behavior; F. Daghia pointed out that the mechanical response of pressure vessels is controlled by key parameters; M. Nebe explored the influence of the stacking sequence of pressure vessels; V. G. Belardi proposed an analytical solution of the bending theory of composite material shells; Cho-Chung Liang studied the optimal design of the dome profile; S Sulaiman carried out simulation work to explore the effect of the winding angle. These studies cover multiple aspects of pressure vessels and promote their development. However, these literatures lack research and discussion on the shape of pressure vessels. More researchers have focused on other aspects such as the lightweight and high performance of pressure vessels. There is relatively less research on the shape of pressure vessels. In this study, the parametric modeling function of APDL will be used to establish pressure vessel models of circular arc, elliptical, parabolic and those fitted by using the fitting curve command. By writing APDL code to apply force to the model and calculate, an equivalent stress value is calculated. Then, the genetic algorithm toolbox included in Matlab is jointly used for optimization calculation to obtain a relatively optimized target.

2. Establish a Model

2.1. The Establishment of the Parabolic Pressure Vessel Model

A parabola is the locus of points on a plane that are equidistant from a given point and a specific line. When the focus is on the focal line, it is a parabolic curve with a fixed angle. It has representations such as parametric equations and standard equations, and is important in applications in fields such as geometric optics and mechanics. As a conic section, it is obtained by the intersection of a cone and a plane with parallel generatrix, and can be regarded as the image of a quadratic function under coordinate transformation.

1) Parabola with the right opening:

$$y^2 = 2px \tag{1}$$

In the parabola with the right opening, p is the distance from the focus to the directrix and $p > 0$; the coordinates of the focus are $\left(p/2, 0\right)$; the equation of the directrix is $x = -p/2$; eccentricity: $e = 1$, Range: $x \geq 0$:

2) Parabola with the left opening:

$$y^2 = -2px \tag{2}$$

In the parabola with the left opening, p is the distance from the focus to the directrix and $p > 0$; the coordinates of the focus are $\left(-p/2, 0\right)$; the equation of the directrix is $x = p/2$; eccentricity: $e = 1$, Range: $x \geq 0$;

3) Parabola with the upward opening:

$$x^2 = 2py \tag{3}$$

In the parabola with the left opening, p is the distance from the focus to the directrix and $p > 0$; the coordinates of the focus are $(0, p/2)$; the equation of the directrix is $y = -p/2$; eccentricity: $e = 1$, Range: $y \geq 0$;

4) Parabola with the downward opening:

$$x^2 = -2py \tag{4}$$

In the parabola with the downward opening, p is the distance from the focus to the directrix and $p > 0$; the coordinates of the focus are $(0, -p/2)$; the equation of the directrix is $y = p/2$; eccentricity: $e = 1$, Range: $y \leq 0$.

In the parabolic pressure vessel model, the equation of the parabola can be derived by determining two points on it. In APDL, fixed point 1 $(x_0, 0)$ and fixed point 2 $(0.3, 0.3)$ are respectively created. Point 1 is the leftmost point in the entire model. Substituting point 1 and point 2 into formula (1), a parabola formula with the right opening and the vertex on the axis is obtained:

$$y^2 = \frac{0.09}{0.3 - x_0} \cdot (x - x_0) \tag{5}$$

Using the *DO loop command in APDL, one hundred key points are generated within the range from 0 to 0.3. Then, these key points are fitted into a straight line using Formula (5) and the BSPLIN command. This process is aimed at enhancing the appearance smoothness of the entire parabolic pressure vessel model. Through the above operations, a parabolic model with the right opening is obtained. As shown in **Figure 1**, it is the successfully fitted parabolic model with the right opening.

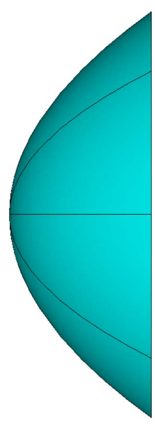

Figure 1. Parabolic model with the right opening.

The two key points of the parabola at the right end of the model are $(1.05 - x_0, 0)$, $(0.75, 0.3)$, Substitute these two key points into Formula (2), and by using Formula (6), a parabolic equation with the left opening and the vertex located on the x-axis can be obtained:

$$y^2 = \frac{0.09}{x_0 - 0.3} \cdot \left(x + x_0 - 1.05\right) \quad (6)$$

By generating one hundred points through the same method mentioned above, a parabolic model with the left opening can be obtained, as shown in **Figure 2**.

By connecting the key point 103 and the key point 104 in the model and applying the AROTAT rotation command, the pressure vessel model as shown in **Figure 3** can be obtained. Its left and right sides are parabolic in shape, and the middle is cylindrical. Combining them together forms the pressure vessel model in the parabolic shape.

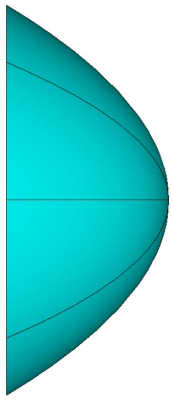

Figure 2. Parabolic model with the left opening.

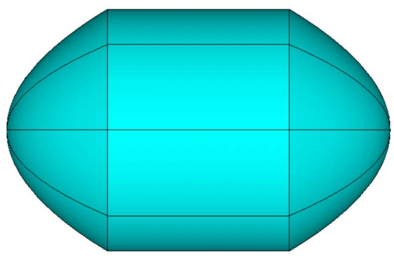

Figure 3. Parabolic pressure vessel model on both sides.

2.2. Establishment of the Circular Arc Pressure Vessel Model

A circle is a closed curve formed by rotating a certain length around a point, and the symmetry axis passes through the center of the circle. The entire model consists of three parts: the circular arcs on the left and right sides and the cylinder in the middle. The entire model is a closed and sealed pressure vessel model. Through the traditional formula of the circle, the expressions of the circular arc and the center of the circle can be obtained respectively.

1) General equation of a circle:

$$x^2 + y^2 + Dx + Ey + F = 0 \tag{7}$$

2) The formula of the center of a circle:

$$\left(-\frac{D}{2}, -\frac{E}{2}\right) \tag{8}$$

3) The radius of a circle:

$$r = \frac{\sqrt{D^2 + E^2 - 4F}}{2} \tag{9}$$

Among them, the condition that satisfies the equation of a circle in Formula (9) is: $D^2 + E^2 - 4F > 0$

By using the command LARC of the APDL parametric language:

LARC, PA, P2, PC, RAD

P1: The key point at one end of the arc line

P2: The key point at the other end of the arc line

PC: The center point of the circle corresponding to the arc line, the radius value is positive, and the PC point must not be placed at the straight line position of P1 and P2.

RAD: The curve radius of the arc.

The circular model is modeled through the LARC command. Two key points $(x_0, 0)$ and $(0.3, 0.3)$ are created in APDL, and by using Formulas (7), (8), and (9) to obtain the formulas for the radius and the center of the circle, the arc model can be created. As shown in **Figure 4**, it is the left part of the entire model, the circular arc model.

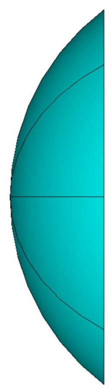

Figure 4. Left half model.

As shown in **Figure 5**, it is the right part of the entire model.

Connect the key point 3 and the key point 5, and use the AROTAT rotation command to generate a model with arc-shaped appearances on both the left and right sides and a thin-walled cylinder in the middle. Combining them together constitutes a complete circular arc pressure vessel model, as shown in **Figure 6**.

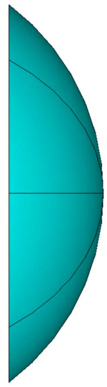

Figure 5. Right half model.

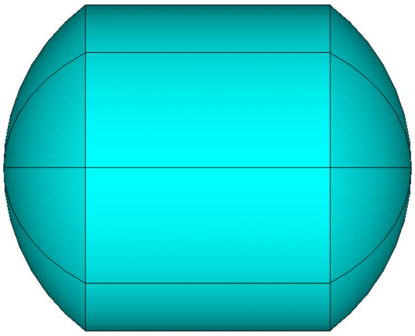

Figure 6. Circular arc pressure vessel model.

2.3. The Establishment of the Elliptical Pressure Vessel Model

In mathematical geometry, the sum of the distances from a point on an ellipse to its two foci is constant. It is a generalized form of a circle and its shape is represented by the eccentricity, with the range of the eccentricity being from 0 to less than 1. An ellipse is a closed planar curve formed by the intersection of a cone and a plane. Ellipses have similarities in many aspects with the other two conic sections, parabolas and hyperbolas, all of which extend infinitely. The section of a cylinder is elliptical unless it is perpendicular to the axis of the cylinder.

The standard equation of an ellipse has two forms:

1) The foci of the ellipse are on the *x*-axis:

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1\left(a>b>0\right) \tag{10}$$

Vertex coordinates: $\left(\pm a,0\right)$, $\left(0,\pm b\right)$

Symmetry axis: $x=0$, $y=0$

Focal coordinates: $\left(\pm e,0\right)$

Eccentricity: $e=\frac{c}{a}$ and $0<e<1$

Directrix equation: $x=\pm\frac{a^2}{c}$

2) The foci of the ellipse are on the *y*-axis

$$\frac{y^2}{a^2}+\frac{x^2}{b^2}=1(a>b>0) \tag{11}$$

Vertex coordinates: $(0,\pm a)$, $(\pm b,0)$

Symmetry axis: $x=0$, $y=0$

Focal coordinates: $(0,\pm e)$

Eccentricity: $e=\frac{c}{a}$ and $0<e<1$

Directrix equation: $y=\pm\frac{a^2}{c}$

It can be seen from Formulas (10) and (11) that there are two types of ellipses. In APDL, create Point 1 $(x_0,0)$, Point 2 $(0.3,0.3)$, and Point 3 $(0.3,-0.3)$. These three points can determine the elliptical arc model to be solved. Point 1 is the leftmost point of the elliptical model. Substitute the two points into Formula (10). The formula of the elliptical model with the major axis on the *x*-axis and the minor axis on the *y*-axis is:

$$\frac{y^2}{0.09}+\frac{(x-0.3)^2}{(0.3-x_0)^2}=1 \tag{12}$$

And use the *DO loop command in APDL to generate one hundred key points within the range of 0 to 0.3 using Formula (12). In order to make both sides of the entire pressure vessel model smoother, the BSPLIN command can be used to fit these 100 key points into an arc, and an ellipse with the major axis on the *y*-axis and the minor axis on the *x*-axis can be obtained. As shown in **Figure 7**, it is the left part of the required elliptical pressure vessel model. The two key points of the ellipse at the right end of the model are $(1.05-x_0,0)$ and $(0.75,0.3)$. Substituting these two points into Formula (11), an elliptical equation with a focus on the *x*-axis can also be obtained:

$$\frac{y^2}{0.09}+\frac{(x-0.75)^2}{(0.3-x_0)^2}=1 \tag{13}$$

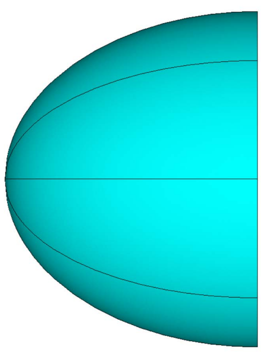

Figure 7. The left part of the model.

Using the same method mentioned above to generate one hundred points, the right part of the elliptical pressure vessel model can be obtained, as shown in

Figure 8. Subsequently, connect key point 104 and key point 103, and use the AROTAT rotation command to generate a model with elliptical shapes on the left and right sides and a cylinder in the middle, as shown in Figure 9. By combining these parts, an elliptical pressure vessel model is obtained.

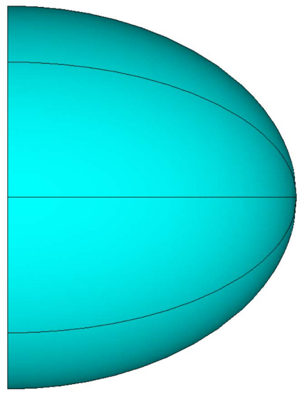

Figure 8. The right part of the model.

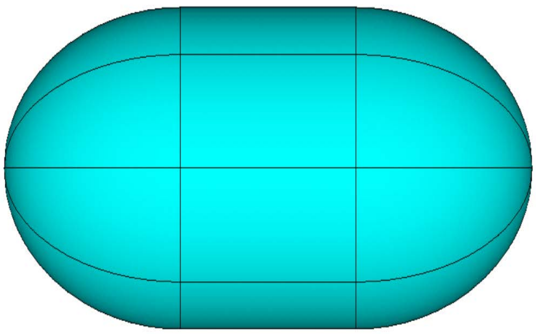

Figure 9. Elliptical pressure vessel model.

2.4. Establishment of the Fitted Curvilinear Pressure Vessel Model

In this subsection for modeling, the BSPLIN command in APDL is used for modeling. Firstly, create five points $(x_1,0)$, $(x_2,y_6/5)$, $(x_3,(2*y_6)/5)$, $(x_4,(3*y_6)/5)$ and $(x_5,(4*y_6)/5)$ respectively, and then create a fixed point $(x_6,y_6)=(0.3,0.3)$. These six points do not affect each other. The positional relationship of these six points is: $x_1<x_2<x_3<x_4<x_5<x_6$. The BSPLIN command in APDL is to generate a curve through spline fitting for multiple key points.

Its usage format is:

$$\text{BSPLIN, P1, P2, P3, P4, P5, P6, XV1, YV1, ZV1, XV6, YV6, ZV6}$$

Among them:

$\text{P1, P2, P3, P4, P5, P6}$: The key point numbers of the spline curve to be fitted are required, and at least two key points are needed. P1 can also be P.

$XV1, YV1, ZV1$: The positioning point of the outer vector tangent to the generated line at point P1, whose starting point is the origin. The coordinate system is the currently activated coordinate system, such as X corresponding to the cylindrical coordinate R, etc. The default value is zero.

$XV6, YV6, ZV6$: The positioning point of the outer vector tangent to the generated line at point P6 (if there are fewer than 6 key points, it refers to the last key point). The default value is zero.

When using this command, relevant matters should be considered. Generate a curve between the key point P1 and the last input key point. The line passes through each key point and should be used as little as possible in the toroidal coordinate system.

Among the settings of these six points P1 $(x_1, 0)$, P2 $(x_2, y_6/5)$, P3 $(x_3, (2*y_6)/5)$, P4 $(x_4, (3*y_6)/5)$, P5 $(x_5, (4*y_6)/5)$ and P6 (x_6, y_6), the values of the y coordinates are determined, and the values of the x coordinates change randomly.

Substitute these coordinate values into the BSPLIN command to obtain the fitted curvilinear model on the left side of the model. In order to make the curve smoother during fitting, set XV1, YV1, XV6, and YV6 in the command to 0, −1, 1, and 0 respectively. As shown in **Figure 10**, it is the left part of the model fitted by the fitted curve command. Similarly, for the coordinates on the right side of the model, they are set as: P7 $(x_6 + X\_LENGTH, y_6)$, P8 $(2*x_6 + X\_LENGTH - X2, y_6/5)$, P9 $(2*x_6 + X\_LENGTH - x_3, (2*y_6)/5)$, P10 $(2*x_6 + X\_LENGTH - x_4, (3*y_6)/5)$, P11 $(2*x_6 + X\_LENGTH - x_5, (4*y_6)/5)$, P12 $(2*x_6 + X\_LENGTH - x_1, 0)$. By using the BSPLIN command to select the above six points, the fitted curve model of the right part can be fitted. In order to make the curve smoother during fitting, the relevant data on the right side are set as $XV1 = 0$, $YV1 = -1$, $XV6 = -1$, $YV6 = 0$. **Figure 11** shows the right part of the model generated by the fitted curve command.

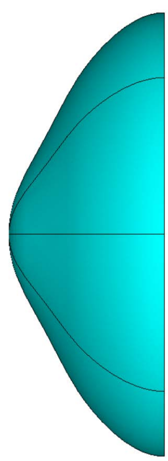

Figure 10. Left fitted curvilinear model.

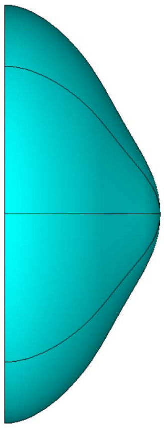

Figure 11. Right fitted curvilinear model.

Next, connect key point 6 and key point 7, and use the AROTAT rotation command to create the pressure vessel model as shown in Figure 12. Its two sides are models composed of fitted curves, and the middle is a thin-walled cylinder. After combining these parts, the fitted curvilinear pressure vessel model is generated.

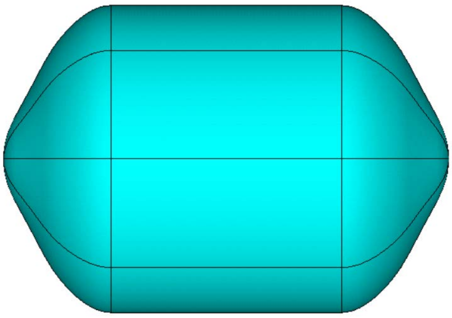

Figure 12. Fitted curvilinear pressure vessel model.

2.5. Model Material Properties

In the model of this study, it is a thin-walled pressure vessel model structure. In ANSYS, the element type is defined as SHELL181 element, and then the material properties of the isotropic material pressure vessel are defined. The material used for the pressure vessel is 7075 aluminum alloy.

7075 aluminum alloy is a cold-treated high-strength forged alloy, and its performance far exceeds that of mild steel. In 7075 alloy, zinc is one of the main alloying elements, and the addition of magnesium can significantly enhance the strength of the alloy. Compared to the aluminum-zinc binary alloy, 7075 aluminum alloy has a more significant effect after heat treatment. This alloy is widely used in aerospace, mold processing, mechanical equipment, and tooling fixtures, and is particularly suitable for aircraft structure manufacturing and other high-stress structural components that require high strength and corrosion resistance.

The material parameters of 7075 aluminum alloy need to be set in the finite element analysis, including Poisson's ratio, elastic modulus and density. These settings can be carried out simultaneously using the APDL parametric language command. The specific setting methods are as follows:

```
MP,EX,,71000E6
MP,PRXY,,0.3
MP,DENS,,2810
```

2.6. The Division of the Mesh

In APDL, the element shape can be achieved by means of the command MSHAPE, Key, Dimension. This paper covers the meshing work of circular arc-shaped, parabolic-shaped, elliptical-shaped and fitted curvilinear pressure vessel models. In the model, a freely divided mesh was adopted, and the element shape was divided into 2D tetrahedral elements for analysis. To ensure the efficiency and accuracy of the calculation, the element size of the model mesh in this paper is set to 0.009. Such a setting can avoid the problem of too long calculation time due to excessive number of meshes while ensuring the calculation accuracy. The meshing effects of each model are shown in Figures 13-16 respectively.

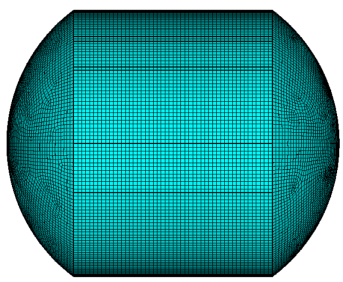

Figure 13. The overall meshing of the circular arc pressure vessel model.

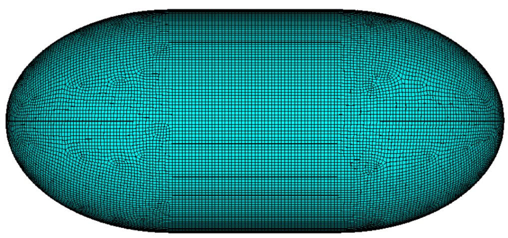

Figure 14. The overall meshing of the elliptical pressure vessel model.

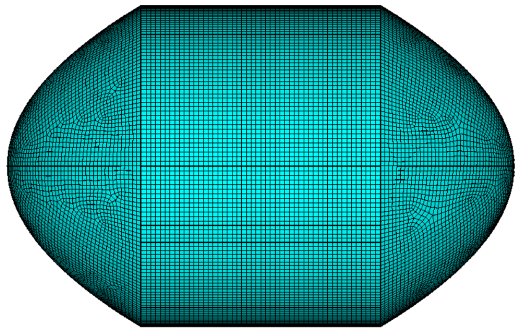

Figure 15. The meshing of the parabolic pressure vessel model.

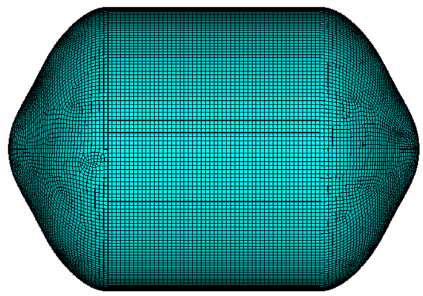

Figure 16. Meshing of the fitted curvilinear model.

3. Model Structure Strength Optimization Design Based on Genetic Algorithm

3.1. Operation Process of Genetic Algorithm

The operation process of the genetic algorithm belongs to a cyclic iterative process. At first, the initial population is generated through encoding to adapt to the actual problem. Next, genetic operations such as selection, crossover and mutation are carried out based on the fitness function, so as to screen out individuals with higher fitness and recombine to form a new population. This process is continuously cycled, and the search and optimization are carried out generation after generation until it converges to the optimal individual. The optimal individual is the optimal solution obtained by means of the genetic algorithm. The basic operation process of the genetic algorithm is shown in Figure 17.

3.2. Establishment of the Optimization Objective Function

For the circular arc-shaped, parabolic-shaped, elliptical-shaped and fitted linear pressure vessel models, this section will take their best shapes as the optimization goals.

The programs in APDL can automatically calculate the model. The equivalent stress magnitude of the calculation can be extracted through the following program:

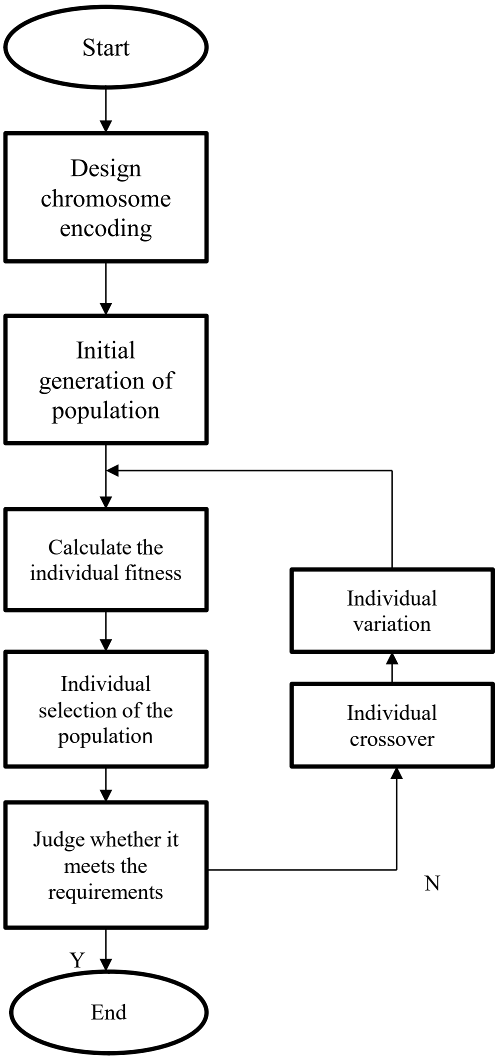

Figure 17. Flowchart of genetic algorithm.

```
/EFACET,1
NSORT,S,EQV,0,0,ALL
*GET,EQV1,SORT,0,MAX
*GET,EQV2,SORT,0,MIN
MAXEQV = MAX(ABS(EQV1),ABS(EQV2))
```

Output the result and write it to a file:

```
/POST1
SET,LAST
*CREATE,WOAINI,MAC
*CFOPEN,WOAINI,TXT
*VWRITE,MAXEQV
(1F20.6)
*CFCLOSE
*END
WOAINI
```

3.3. Determine the Constraint Conditions

For the constraint conditions of the model, they are mainly determined based on the value range of the independent variables. The constraint conditions that need to be determined for the four models are respectively:

1) The constraint condition of the circular arc pressure vessel model is Formula (14):

$$0 \le x_0 < 0.3 \tag{14}$$

2) The constraint condition of the parabolic pressure vessel model is Formula (15):

$$0 \le x_0 < 0.3 \tag{15}$$

3) Ellipses are divided into the cases where the foci are on the x-axis and the foci are on the y-axis. These two cases can be expressed together in Formula (12). The constraint condition in this case is Formula (16):

$$-\inf \le x_0 < 0.3 \tag{16}$$

4) The constraint condition of the fitted curvilinear pressure vessel model is Formula (17):

$$x_1 < x_2 < x_3 < x_4 < x_5 < 0.3 \tag{17}$$

3.4. Settings of Related Parameters

The Genetic Algorithm Toolbox is an optimization algorithm toolbox included in MATLAB. It has extremely powerful computing capabilities and a unique user interface, which can significantly reduce the amount of program writing. It is simple to operate and easy to use. Therefore, in this study, this toolbox is called for optimization solution.

When calling the toolbox for solution, a series of parameters need to be set, such as the call of the objective function, the number of variables, constraint conditions and boundary conditions, etc. When calling the genetic algorithm toolbox for calculation, some options need to be set. Among them, the population size is set to 20, the number of iterations is set to 10,000 generations, the size of the best fitness is set to: 1E−06, the feasibility of nonlinear constraints is determined as: 1E−3, and other parameters all use the default settings in the toolbox. When the genetic algorithm reaches the number of iterations or the optimized value is smaller than the size of the best fitness, the genetic algorithm will stop searching and find the best optimized value.

In this study, the APDL program was used as the fitness function and embedded in the genetic algorithm for calculation. Among them, the number of input variables for the fitted curvilinear pressure vessel model is 5, while the number of input variables for the other three models is 1.

3.5. Analysis Based on the Optimization Results of MATLAB

The optimization calculation was carried out using the MATLAB Genetic Algorithm Toolbox, with the best shape of the four models as the optimization goal.

The following presents the best solutions and equivalent stress values obtained through the optimization algorithm, as well as the corresponding model diagrams.

1) The optimal shape size and corresponding equivalent stress value of the parabolic pressure vessel model are shown in Table 1:

Table 1. The optimal data of the parabolic pressure vessel model.

x_0	Equivalent stress (Pa)
1.4901E−08	5.8692e+08

As shown in Figure 18, it is the model diagram after optimization by the genetic algorithm:

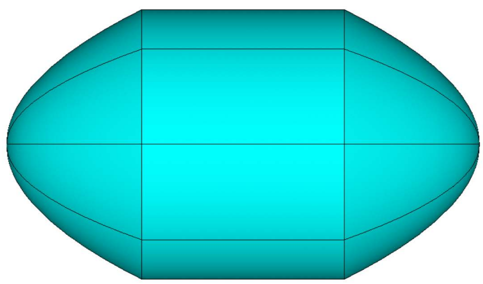

Figure 18. Optimal parabolic pressure vessel model.

Figure 19 is the optimization convergence graph formed when using the genetic algorithm. In Figure 19, the ordinate represents the fitness value, and the abscissa represents the number of iterations. It can be observed from the figure that it gradually converges from the tenth generation, and the fitness value gradually approaches 5.8692e+08 Pa.

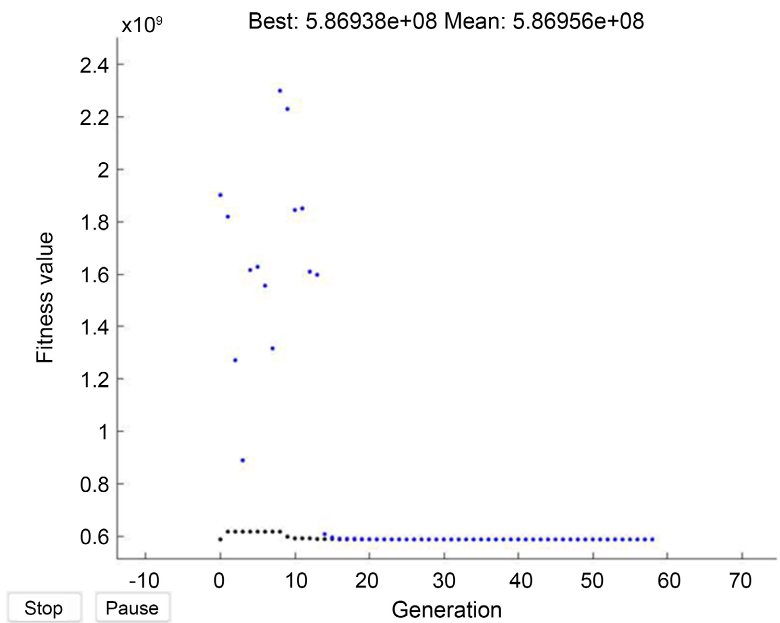

Figure 19. The optimization convergence graph of the parabolic pressure vessel.

As shown in Figure 20, it is the equivalent stress nephogram of the parabolic pressure vessel under the optimal shape size:

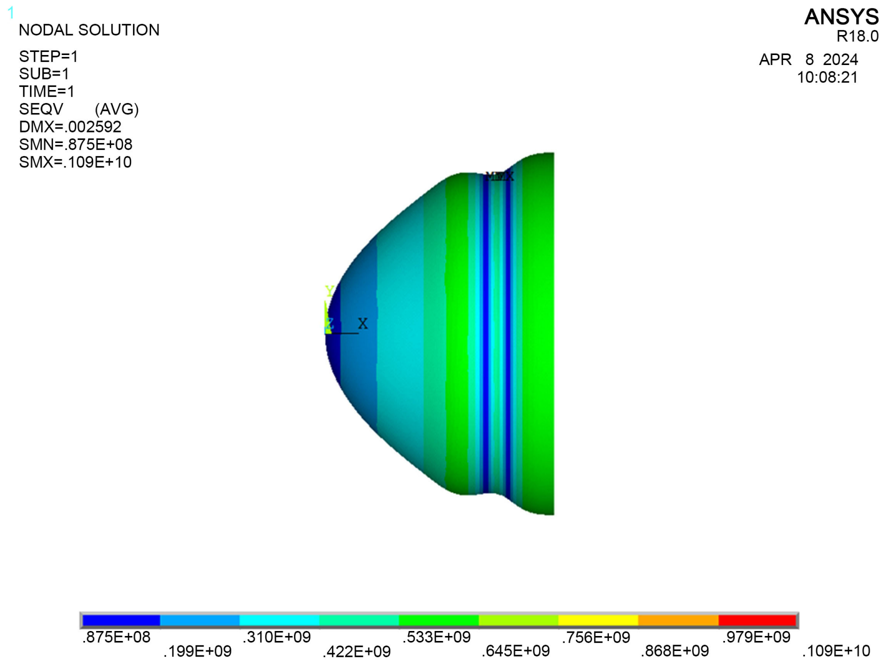

Figure 20. Equivalent stress nephogram of the parabolic pressure vessel model.

Through the optimization calculation of the genetic algorithm, the equivalent stress nephogram of the corresponding parabolic model in Figure 20 was obtained. It can be observed from the figure that the calculated minimum equivalent stress value is 0.861e+08 Pa, the maximum equivalent stress value is 0.109e+10 Pa, and the maximum deformation is 0.002592 m. The ratio of the two is 12.45, which indicates that the ratio of the maximum value to the minimum value is too large, and the expected equivalent stress effect has not been achieved. Through careful observation of Figure 20, it can be understood that the stress distribution of the parabolic model is extremely uneven. In view of this, among the four shape conditions studied and discussed in this article, the parabolic model fails to meet the relevant requirements.

2) The optimal shape size and equivalent stress value of the circular arc pressure vessel model are shown in Table 2.

Table 2. The optimal data of the circular arc pressure vessel model.

x_0	Equivalent stress (Pa)
4.4729e−04	5.3685e+08

As shown in Figure 21, it is the model diagram after optimization by the genetic algorithm:

As shown in Figure 22, it is the optimization convergence graph of the circular arc pressure vessel model obtained by using the genetic algorithm:

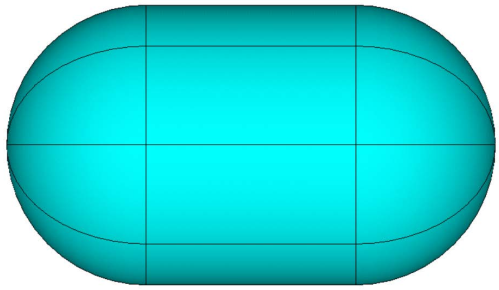

Figure 21. The best circular arc pressure vessel model.

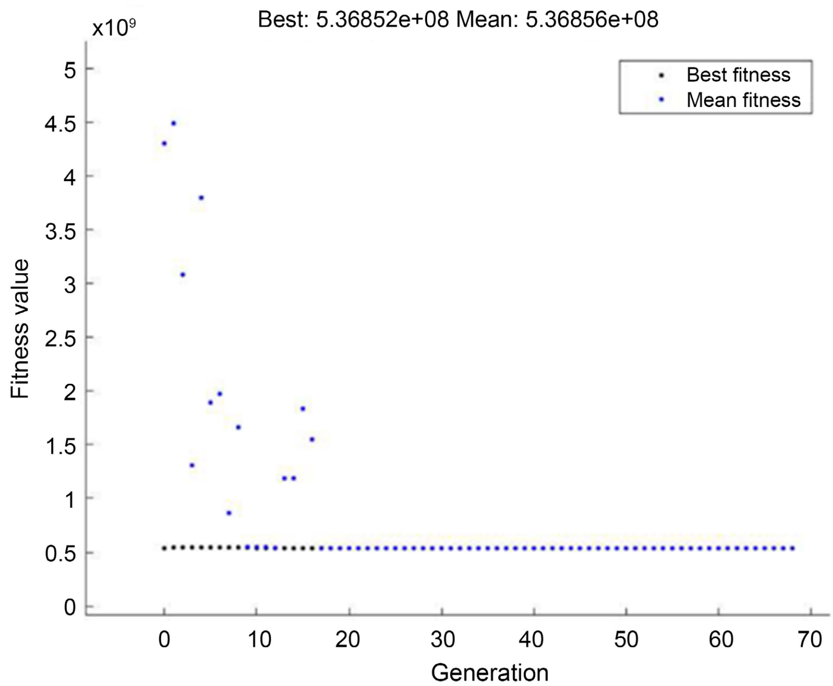

Figure 22. The convergence curve graph of the circular arc pressure vessel model.

By observing **Figure 22**, the ordinate represents the fitness value and the abscissa represents the number of iterations. It can be learned from the figure that starting from the tenth generation, the fitness value gradually converges to a fixed value. Eventually, at the 69th generation, the difference between the best fitness function value and the average fitness value is less than the set value, and the iterative calculation stops, obtaining the required value: 5.3685e+08.

As shown in **Figure 23**, it is the equivalent stress nephogram under the optimal shape size:

Considering the constraint conditions, after the optimization calculation by the genetic algorithm, the corresponding equivalent stress nephogram indicates that the maximum deformation of the circular arc pressure vessel is 0.002381 m, the minimum equivalent stress is 0.261e+09 Pa, and the maximum equivalent stress is 0.537e+09 Pa. It can be observed that the ratio of the two is 0.48, indicating that the ratio is moderate.

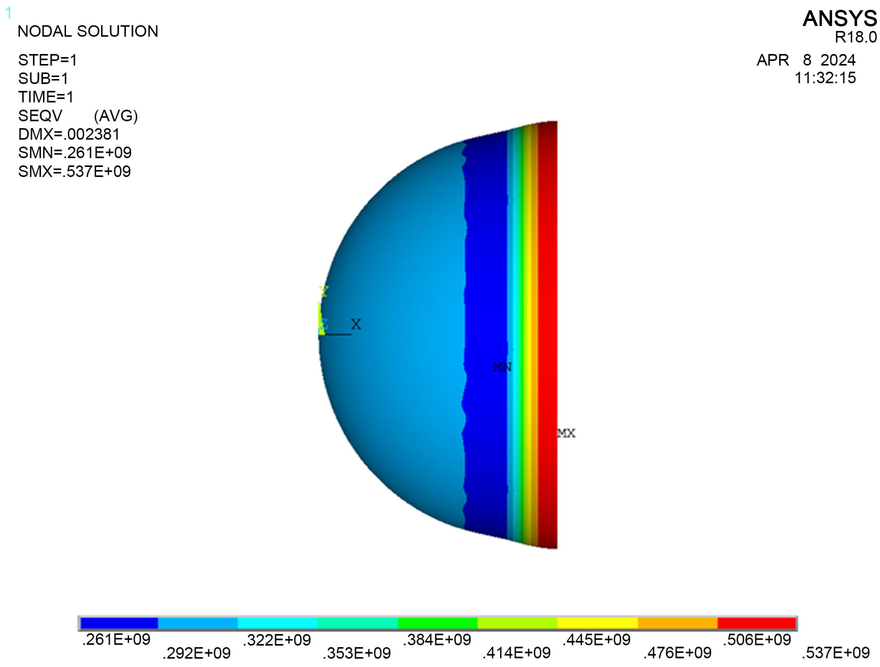

Figure 23. Equivalent stress nephogram of the circular arc pressure vessel model.

3) Elliptical pressure vessel model

The equation of the ellipse is divided into two cases where the focus is on the *x*-axis and the focus is on the *y*-axis. However, by using Formulas (13) and (14), both cases can be taken into consideration together, and the optimal shape size and the magnitude of the equivalent stress as shown in **Table 3** can be obtained under the relevant constraint conditions.

Table 3. The optimal data of the elliptical pressure vessel model.

x_0	Equivalent stress (Pa)
−2.7602	5.1969e+08

As shown in **Figure 24**, it is the optimization convergence graph of the elliptical pressure vessel model when using the genetic algorithm for optimization calculation. In **Figure 24**, the ordinate represents the fitness value, and the abscissa represents the number of iterations. By observing the chart, it can be found that the variation range of the optimal value is not significant. After iterative calculation, the equivalent stress values as shown in **Table 3** are obtained.

Figure 25 is the best model diagram after optimization.

As shown in **Figure 26**, it is the equivalent stress nephogram under the corresponding optimal shape. After the optimization calculation of the genetic algorithm, the equivalent stress nephogram shown in **Figure 26** is obtained. It can be observed from the figure that the total deformation of the elliptical pressure vessel model of isotropic material is 0.0044 m, the minimum equivalent stress value is 0.853e+07 Pa, and the maximum equivalent stress value is 0.519e+09 Pa. However, the ratio gap between the minimum equivalent stress value and the maximum equivalent stress value is too large. In addition, it can also be observed from Figure 26 that the stress distribution is uneven, and there is a situation that is very prone to damage at the junction of the stress. Therefore, the elliptical model does not meet the requirements.

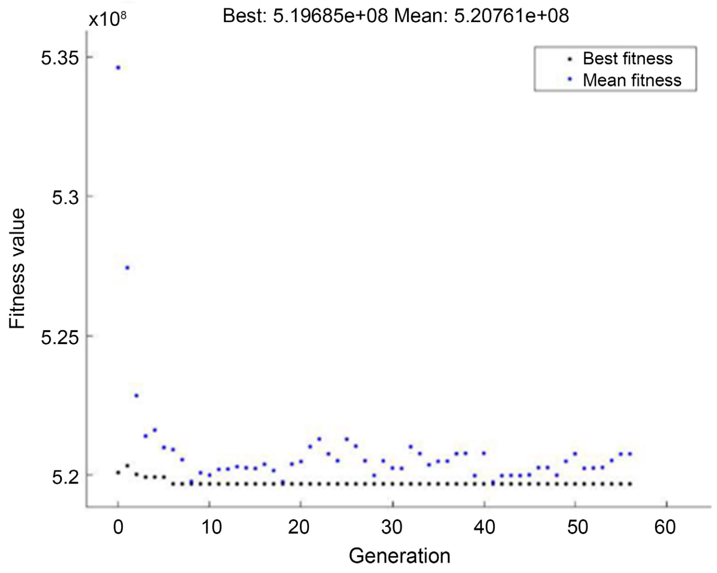

Figure 24. The optimization convergence graph of the elliptical pressure vessel model.

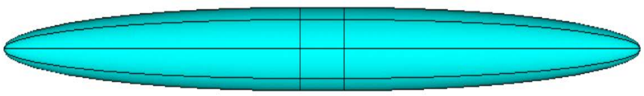

Figure 25. Model diagram of elliptical pressure vessel.

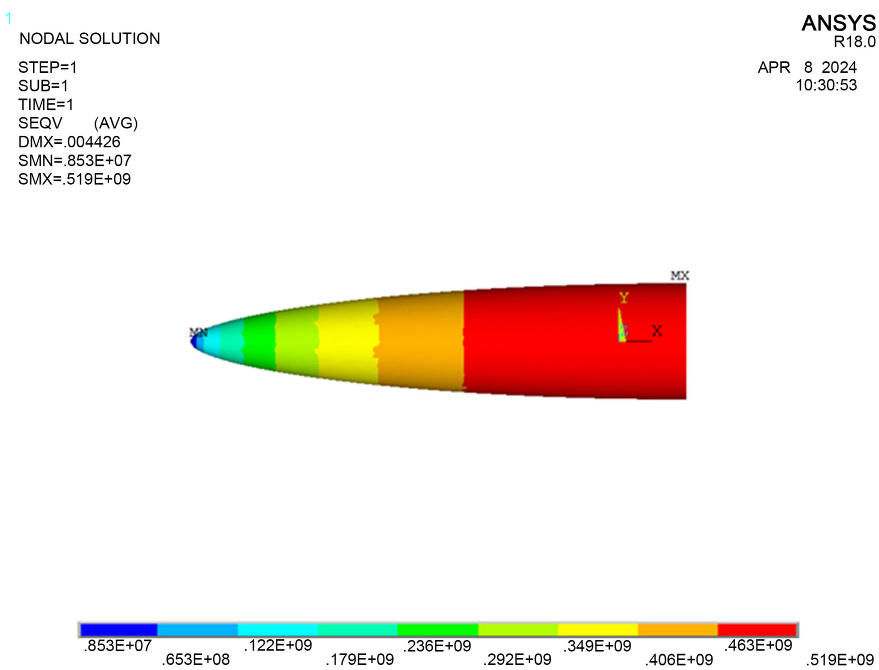

Figure 26. The equivalent stress nephogram of the arc-shaped pressure vessel model.

4) The optimal shape size and equivalent stress magnitude of the fitted curve-shaped pressure vessel model are shown in Table 4:

Table 4. The data values of the fitted curve-shaped pressure vessel model.

x_1	x_2	x_3	x_4	x_5	Equivalent stress (Pa)
0	0.006	0.025	0.063	0.121	5.37e+08

Figure 27 is the optimization convergence graph obtained when the genetic algorithm is used for the optimization calculation of the fitted curve-shaped pressure vessel model:

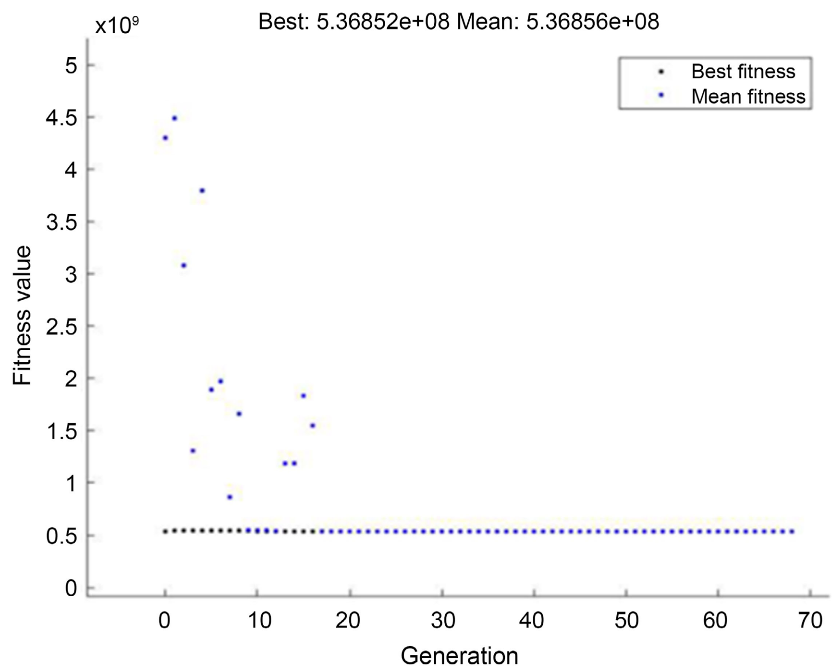

Figure 27. The optimization convergence graph of the fitted curve-shaped pressure vessel model.

As shown in Figure 28, the fitted curve model corresponding to the optimal shape:

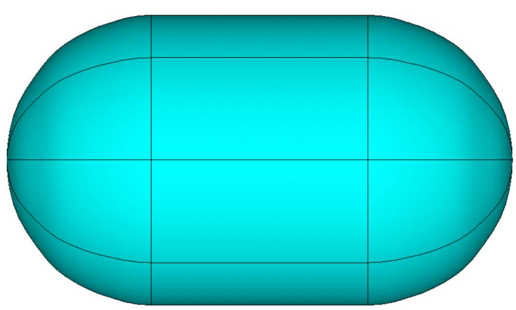

Figure 28. Fitted curve-shaped pressure vessel model.

As shown in Figure 29, it is the equivalent stress nephogram obtained after the optimization calculation:

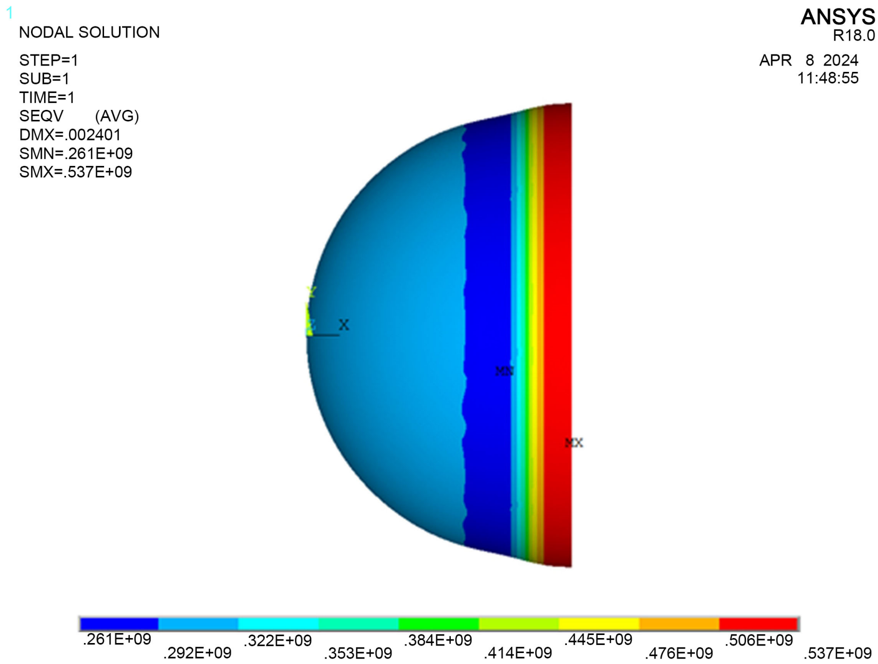

Figure 29. Optimal equivalent stress nephogram.

By observing Figure 29, it is known that the ratio of the maximum to the minimum equivalent stress values is moderate. In the equivalent stress nephogram, it is observed that the stress distribution is uniform, there is no stress concentration phenomenon, and the stress transition is uniform. Therefore, this model can be considered for use as the best model.

After comparing the parabolic, circular arc, elliptical and fitted curve-shaped pressure vessel models, it is found that the fitted curve-shaped pressure vessel model is more suitable among the uniform materials under the four shape conditions in this study. The fitted curve-shaped pressure vessel model can simulate any shape to a certain extent, which gives it a natural advantage compared to other models. Therefore, choosing the fitted curve model becomes the best choice.

4. Conclusion

In this paper, the core goal is to optimize the shape of pressure vessels. With the help of APDL parametric modeling technology, pressure vessel models of circular arc, parabola, ellipse, and fitted curve shapes have been successfully constructed. 7075 aluminum alloy is selected as the material, and relevant parameters are carefully set and meshing is carried out. Subsequently, the genetic algorithm is used to optimize the model, and the data shows that the optimal equivalent stress of the parabolic model is 5.8692e+08 Pa, but its stress distribution is extremely uneven, failing to achieve the expected effect and not meeting the requirements; the value obtained by the circular arc model after the 69th generation of iteration is 5.3685e+08, the maximum deformation is 0.002381 m, and the ratio of the minimum equivalent stress to the maximum equivalent stress is 0.48, which is relatively moderate; the stress ratio gap of the elliptical model is too large and the distribution is uneven; while the ratio of the maximum to the minimum equivalent stress values of the fitted curve model is moderate, the stress distribution is uniform, there is no stress concentration phenomenon, and it can be regarded as the best model. In general, under the four shape conditions in this paper, the fitted curve pressure vessel model performs better. Through detailed data and in-depth analysis, this paper provides a valuable reference for the design of pressure vessels and is of great significance for promoting the development of related fields.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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