Structural Design of the Acrylic Vessel for the Jinping Neutrino Experiment

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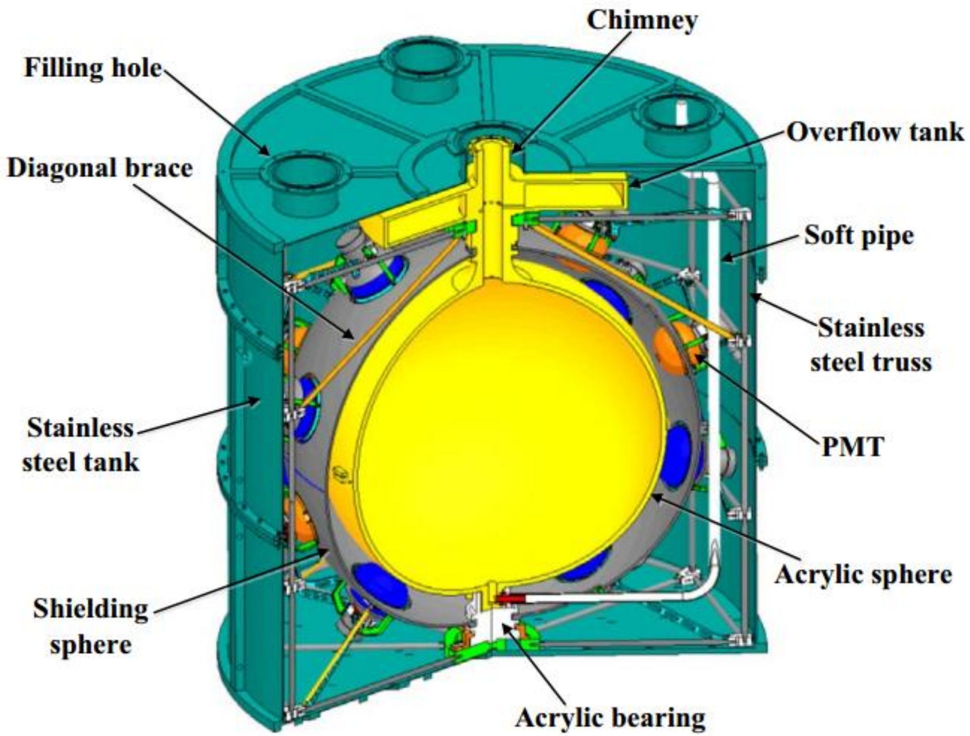
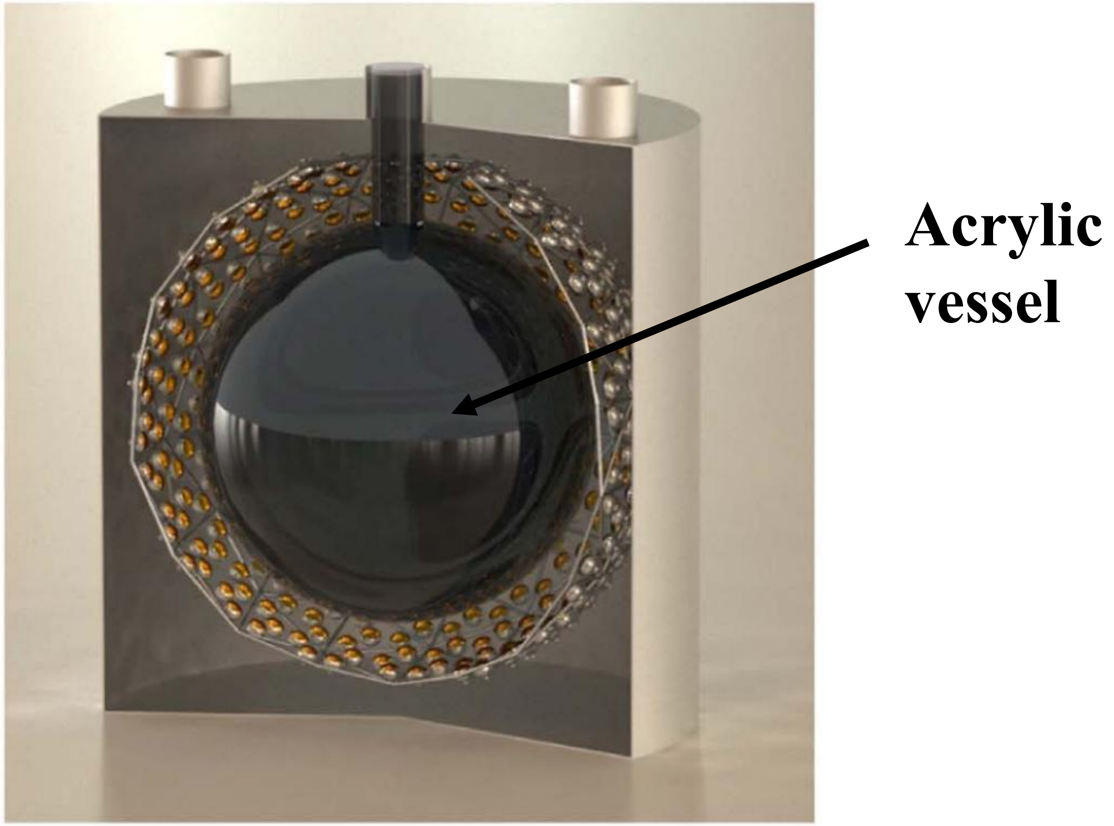
One-ton Prototype



Built in 2017, it has a diameter of 2 meters and a height of 2.09 meters, with an acrylic spherical shell thickness of 4 mm



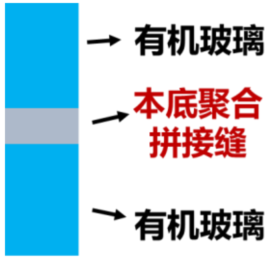
- The stress distribution on the spherical vessel is more uniform
- It better meets the spatial configuration requirements

The core vessel of the Jinping Neutrino Detector adopts an acrylic spherical structure

1. Characteristics of Acrylic

Acrylic is a transparent polymer, commonly known as polymethyl methacrylate (PMMA)

Characteristics		Details
Advantages	(1) No self-explosion issue	Outstanding advantage compared to glass; safety performance is guaranteed
	(2) Bulk polymerization	Similar to welding in steel structures, the "welded" joint is as transparent as the base material
	(3) High light transmittance	Acrylic has a high transmittance of about 91%~93%
	(4) Low density	Approximately 1.15~1.19 g/cm³, which is about half of glass
	(5) Aging resistance	Guarantees no yellowing after 20 years of outdoor use; it has the best aging resistance among plastics
Shortages	(1) Creep effect	Train continues to increase while stress remains constant
	(2) Poor fire resistance	Combustion properties are flammable; adding specific additives can improve fire resistance
	(3) Low surface hardness	Surface is prone to scratches; surface treatment processes can eliminate scratches



1. Characteristics of Acrylic

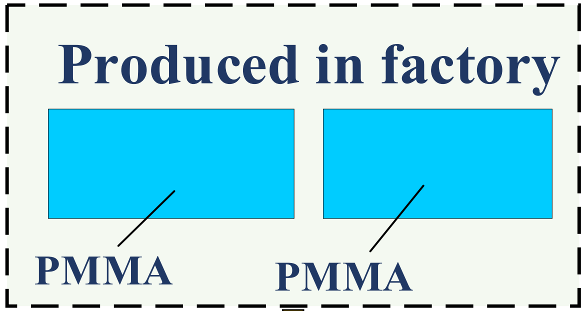
Large size sheets： Transported to the construction site for annealing and connecting

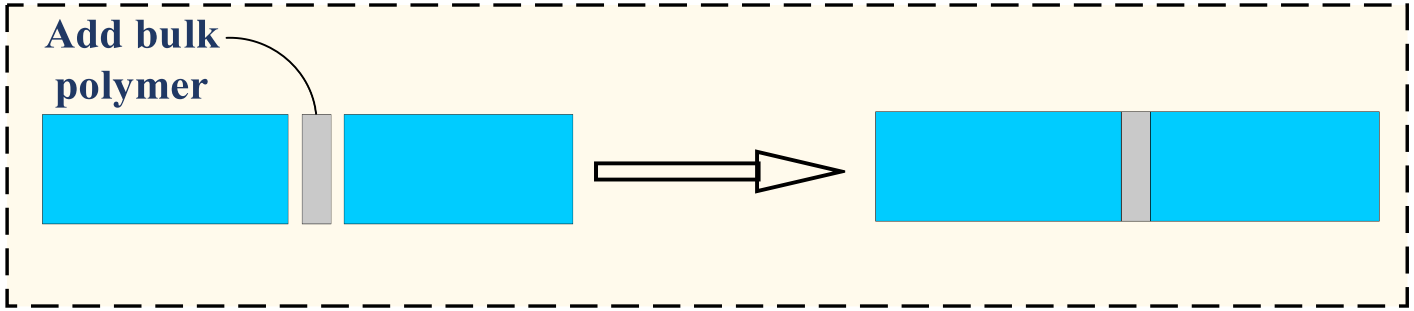
Large size sheets

Low temperature polymerization (20~30°C) for a few hours

Approximately closed environment

Difficult to maintain temperature at 85 °C





Small size sheets

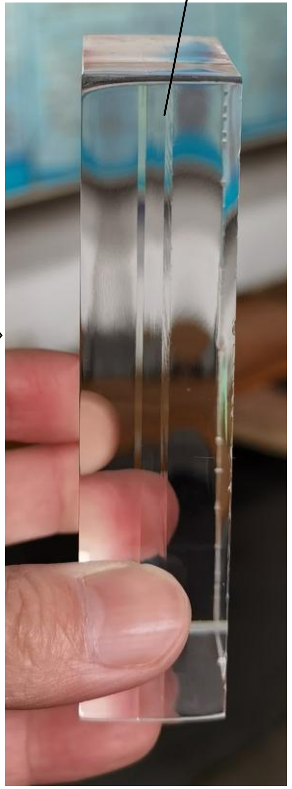
Low temperature polymerization (20~30°C) for a few hours

Closed environment

Annealing (85°C) for several hours

Small size sheets: Annealing and connecting in factory

Connecting seam



The connected seam and the acrylic base material almost has the same transparency

1. Characteristics of Acrylic

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Construction site of
Nanjing Future Garden

- Acrylic sheets were transported to the site and joined by on-site bulk polymerization.

1. Characteristics of Acrylic

Acrylic is currently widely used in various fields, including **aerospace, submarines, detectors, biomedicine, and aquariums**

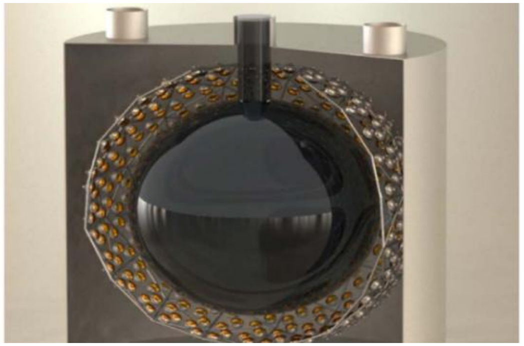
Aircraft Observation Window

Sightseeing Submarine

Aquarium

Translucent Projection Screen

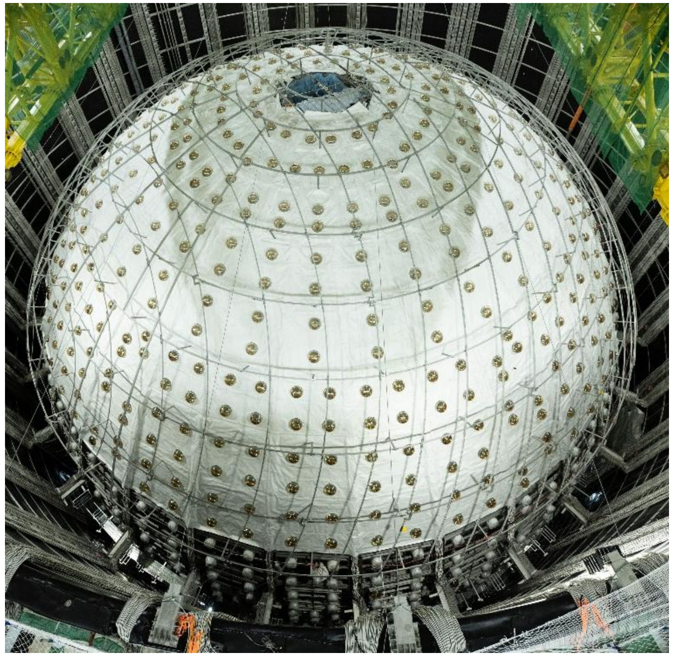
Medical Hyperbaric Oxygen Chamber



Neutrino Detector

Noise Barrier

1. Characteristics of Acrylic



Jiangmen Neutrino Detector

Year of Construction: 2024

Location: Jiangmen, Guangdong, China

Material: Transparent curved solid acrylic sheet

1. Characteristics of Acrylic

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Shenzhen Grand Water Feature

Year of Construction: 2025

Location: Shenzhen, China

Material: Solid transparent acrylic sheet

1. Characteristics of Acrylic

Nanjing Future Garden

Year of Construction: 2021

Location: Nanjing, Jiangsu, China

Material: Transparent acrylic roof panels and rib plates

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02 Material Properties of Acrylic

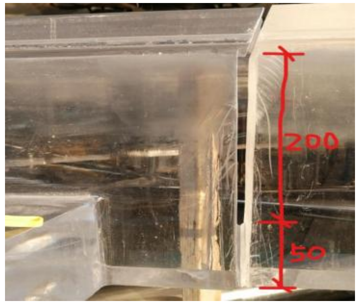
Why we should conduct these tests?

1. **Tensile test**

   Basic mechanical behavior; ultimate strength, Young's modulus, ductility

2. **Impact toughness test and fracture toughness test**

   Reflect the ability to resist cracking



3. **Rockwell Hardness Test**

   Acrylic is soft and prone to surface scratching

4. **Linear Expansion Coefficient Test**

   The larger the linear expansion coefficient of a material,

   the higher the stress of a structure under temperature variation

5. **Creep test**

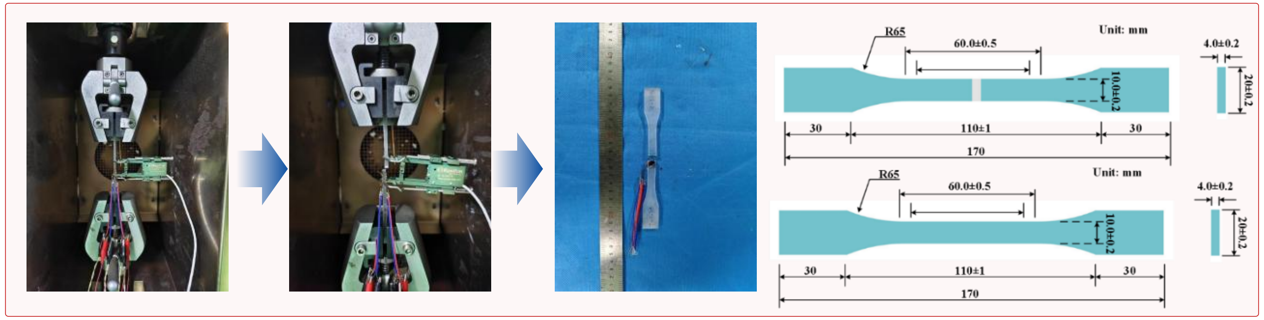
   The strain of acrylic structure subjected to a constant load may increase with time, and

   fracture occurs one day in the future

2.1 Tensile Test

Research Purpose

To investigate the static **mechanical performance and failure mechanism** of acrylic under various temperature conditions, so as to supply critical constitutive models and experimental data for the follow-up study on its **long-term creep behavior**



Test temperature

Base material coupon：-20°C、20°C、40°C、60°C

Connected coupon annealed at 85°C：-20°C、20°C、40°C、60°C

Connected coupon annealed at 65°C：20°C

Mean Values of Short-term Tensile Test Results

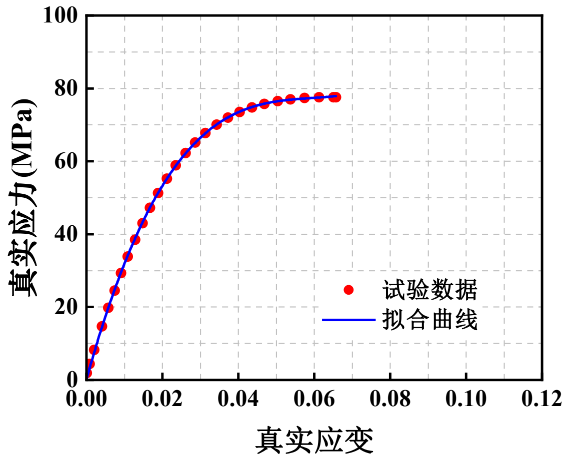
Coupon type	Test temperature	Ultimate load（kN）	Tensile fracture strain	True ultimate strength（MPa）	Tensile elastic modulus（MPa）
Base material coupon	-20°C	3.22	0.022	81	4674
	20°C	2.82	0.054	74	3362
	40°C	2.21	0.030	55	3010
	60°C	2.00	0.037	51	2510
Connected coupon annealed at 85°C	-20°C	2.90	0.019	73	4508
	20°C	2.52	0.032	64	3338
	40°C	2.38	0.037	60	3090
	60°C	1.88	0.031	48	2368
Connected coupon annealed at 65°C	20°C	2.07	0.022	53	3408

Tensile strength: Base material > Connected coupon (annealed at 85 °C) > Connected coupon (annealed at 65 °C)

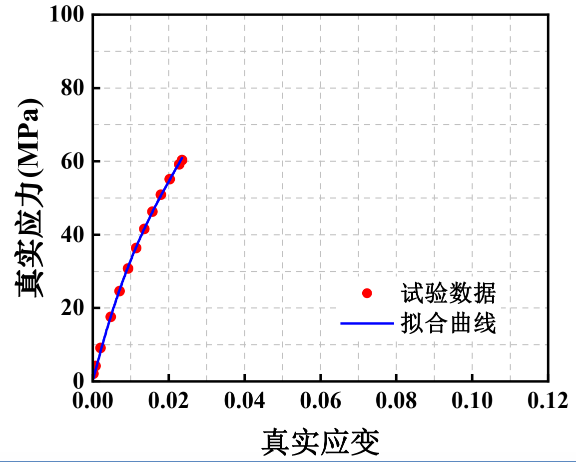
2.1 Tensile Test

Nonlinear elastic part of the ZWT model: $\sigma = E_0\varepsilon + \alpha\varepsilon^2 + \beta\varepsilon^3$

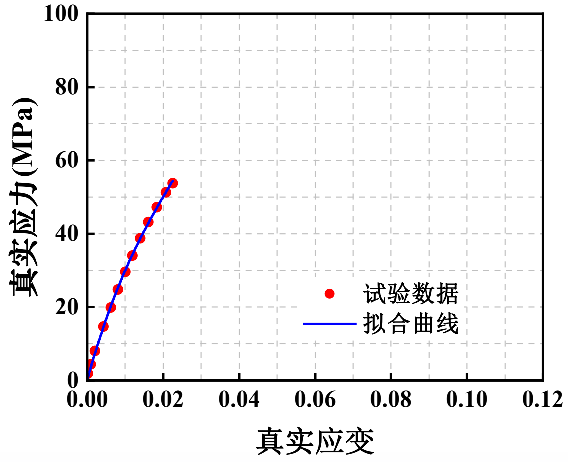
Coupon Type	Test Temperature	E_0	α	β
Base material coupon	-20°C	5054	-92338	1573699
	20°C	3937	-73544	554187
	40°C	2914	-27003	-274500
	60°C	3238	-73439	752784
Connected coupon annealed at 85°C	-20°C	5433	-152151	3837129
	20°C	3798	-74787	667167
	40°C	2976	-35072	-49110
	60°C	2861	-48211	200122
Connected coupon annealed at 65°C	20°C	4131	-128203	2432526



Base Material -20°C



Connected coupon annealed at 85°C-20°C

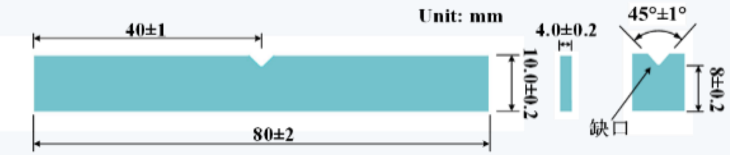


Connected coupon annealed at 65°C-20°C

2.2 Impact Toughness Test

Research Objective

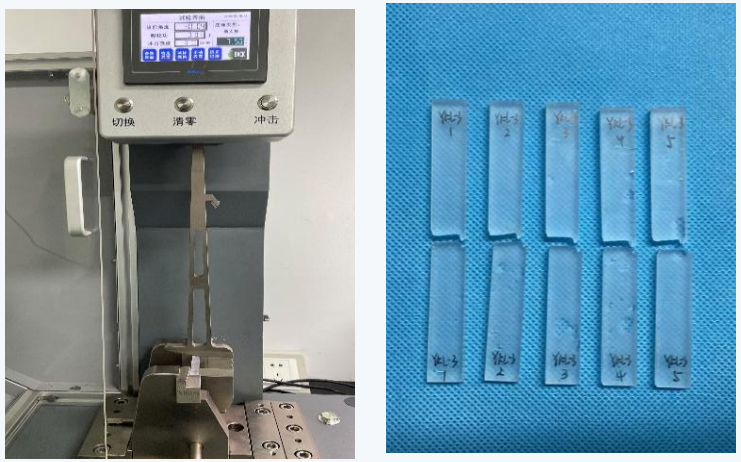
Acrylic is inherently brittle and has poor impact resistance. This test aims to quantitatively evaluate its impact toughness to provide a basis for structural impact resistance design.



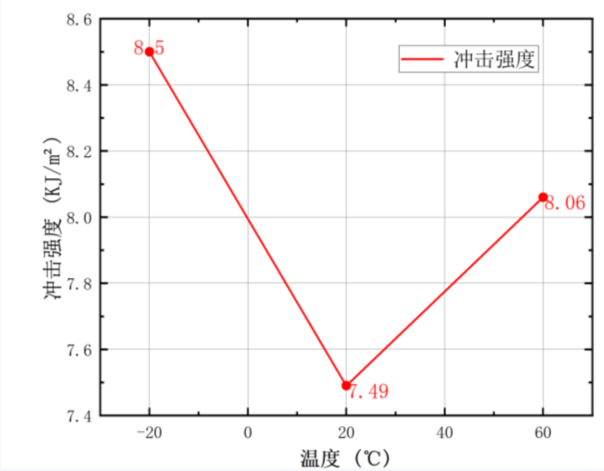
Temperature conditions
-20°C、20°C、60°C

Ten groups of tests are conducted for each condition

Standard GB/T 1043.1-2008



Impact Toughness Test



Temperature - Impact Strength

Temperature (°C)	-20	20	60
Impact Strength (kJ/m²)	8.50	7.49	8.06

- The impact strength of acrylic at room temperature is 7.49kJ/m^2, lower than those at -20 °C and 60 °C

2.2 Impact Toughness Test

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Temperature (℃)	-20℃	20℃	60℃
Impact Toughness（kJ/m2）	8.67	8.35	7.74
	8.53	---	7.74
	8.02	7.36	8.67
	8.57	8.31	8.03
	8.31	8.08	8.24
	8.60	8.21	7.69
	8.51	8.07	8.14
	8.19	---	8.18
	8.93	7.42	8.35
	8.66	8.75	7.80
Average value	8.50	7.49	8.06

Impact Toughness Test Result

2.3 Fracture Toughness Test

Research Objective

Acrylic is extremely sensitive to cracks and has poor crack resistance. This test aims to measure its fracture toughness and reveal the influence of temperature on its crack propagation resistance.

Temperature conditions
-20°C、20°C、60°C

Crack depth: 2.5~7.5mm

Three tests conducted at each temperature

US Standard ASTM D5045

Coupon type	Average Fracture Toughness （K_{IC}/ MPa*$m^{1/2}$）		
	-20 °C	20 °C	60 °C
Base material coupon	2.55	2.20	1.97
Connected coupon annealed at 85°C	2.16	1.94	1.80

Average Fracture Toughness

- At -20°C, 20°C, and 60°C, the fracture toughness of the connected seam (bulk polymerization) is 84.7%, 88.2%, and 91.4% of the base material
- As temperature increases, the fracture toughness decreases

2.3 Fracture Toughness Test

Temperature (°C)	Load Magnitude $P_Q\ (kN)$	Fracture Toughness Value $K_Q\ (Mpa \cdot m^{1/2})$	$2.5\left(\frac{K_Q}{\sigma_y}\right)^2\ (mm)$	Average Fracture Toughness $K_Q\ (Mpa \cdot m^{1/2})$
60	0.818	1.7230	2.9687	1.9716
	1.030	2.2351	5.6537	
	0.920	1.9567	3.9864	
20	1.027	2.1849	2.3676	2.2016
	1.072	2.1954	2.6059	
	1.055	2.2246	2.2593	
-20	1.129	2.3629	2.6925	2.5586
	1.258	2.6539	2.1738	
	1.244	2.6590	2.4465	

Base Material

2.3 Fracture Toughness Test

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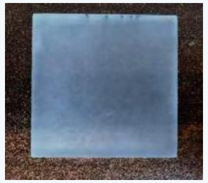
Temperature (°C)	Load Magnitude $P_Q\ (kN)$	Fracture Toughness Value $K_Q\ (Mpa \cdot m^{1/2})$	$2.5\left(\frac{K_Q}{\sigma_y}\right)^2\ (mm)$	Average Fracture Toughness $K_Q\ (Mpa \cdot m^{1/2})$
60	0.827	1.7754	3.6406	1.8019
	0.896	1.7999	3.9995	
	0.908	1.8503	3.8748	
20	1.062	2.0996	2.5301	1.9390
	0.914	1.8135	1.5860	
	0.987	1.9038	2.2830	
-20	1.131	2.2384	2.4162	2.1655
	0.997	1.9978	1.7739	
	1.135	2.2603	2.6067	

Connected coupon annealed at 85°C

2.4 Rockwell Hardness Test

Research Objective

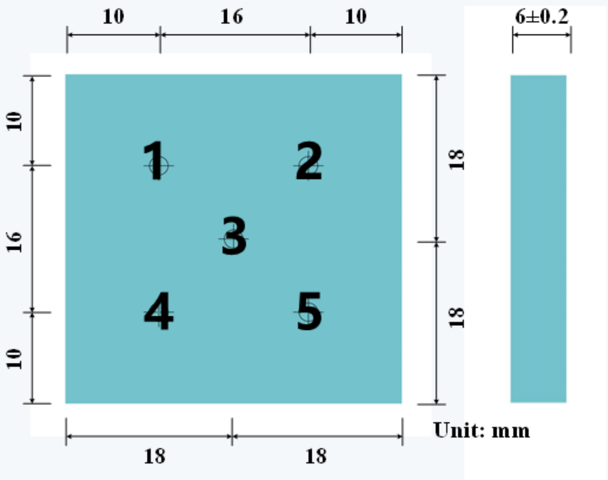
Acrylic exhibits low, temperature-sensitive surface hardness and poor wear resistance. This test measures its Rockwell hardness at various temperatures to evaluate surface damage resistance



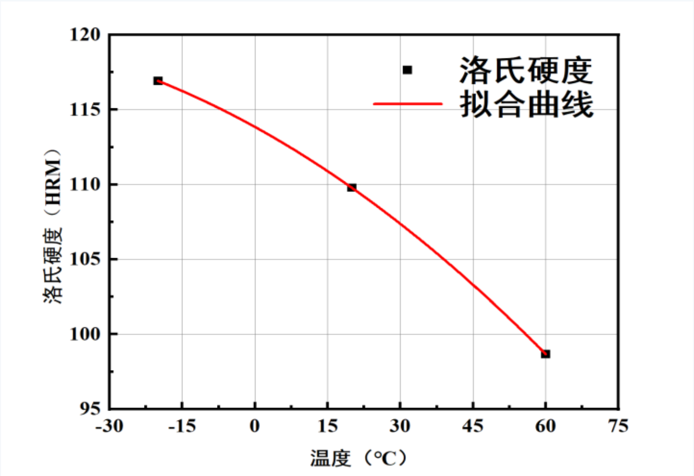
Temperature conditions
-20°C、20°C、60°C

Three sets of tests conducted at each temperature

Standard GB/T 3398.2-2008



Layout of Rockwell Hardness Measurement Points



Curve of Rockwell Hardness Variation with Temperature

- At room temperature, the Rockwell hardness of the acrylic is approximately HRM 109.78
- The hardness of acrylic decreases as the temperature increases

2.4 Rockwell Hardness Test

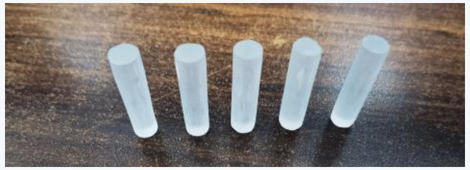
Rockwell Hardness Experimental Data

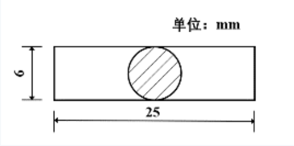
Sample No.		HRM 1	HRM 2	HRM 3	HRM 4	HRM 5	HRM Average	Rockwell Hardness Value
-20°C	1	117.7	117.6	116.2	116.3	115.7	116.7	R116.92
	2	118.6	117.1	116	117.4	116.7	117.16	
	3	118.3	117.2	116.9	116	116.1	116.9	
20°C	1	108.9	109.4	110.3	110	110.1	109.74	R109.78
	2	109.4	109.4	110.6	109.2	109.7	109.66	
	3	109	109.8	110.2	110.4	110.3	109.94	
60°C	1	96.5	98.4	103.4	98.1	98.9	99.06	R98.67
	2	93.4	98.4	98	98.9	98.1	97.36	
	3	95.4	98.8	100.2	102.5	101	99.58	

2.5 Linear Expansion Coefficient Test

Research Objective

Temperature has a significant impact on the linear expansion coefficient of Acrylic. This test aims to accurately determine its linear expansion coefficient to provide key parameters for structural design



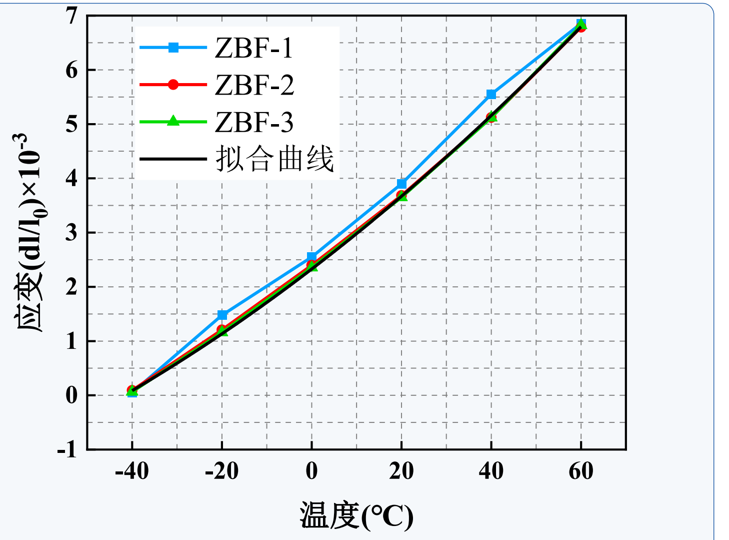


Temperature range
-40°C~60°C

Coupon height 25mm, diameter 6mm

Standard GB/T 1036-2008

Test Apparatus



Linear Expansion Coefficient and Fitted Curve

- The average linear expansion coefficient of acrylic is 7.0134×10^{-5} °C^{-1}
- As the temperature increases, the linear expansion coefficient of acrylic increases slightly
- Compared to concrete (1.0×10^{-5} °C^{-1}) and steel (1.2×10^{-5} °C^{-1}), the linear expansion coefficient of acrylic is significantly larger

2.5 Linear Expansion Coefficient Test

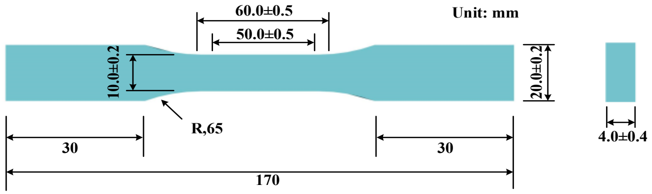
Linear expansion coefficient of acrylic at various temperatures

Temperature	Coupon No.	Linear Expansion Coefficient
-40°C	ZBF-1	6.958×10^{-5} °C^{-1}
	ZBF-2	5.492×10^{-5} °C^{-1}
	ZBF-3	5.194×10^{-5} °C^{-1}
	Average	5.881×10^{-5} °C^{-1}
-20°C	ZBF-1	7.217×10^{-5} °C^{-1}
	ZBF-2	5.745×10^{-5} °C^{-1}
	ZBF-3	5.784×10^{-5} °C^{-1}
	Average	6.249×10^{-5} °C^{-1}
0°C	ZBF-1	6.074×10^{-5} °C^{-1}
	ZBF-2	6.174×10^{-5} °C^{-1}
	ZBF-3	6.207×10^{-5} °C^{-1}
	Average	6.152×10^{-5} °C^{-1}

Temperature	Coupon No.	Linear Expansion Coefficient
20°C	ZBF-1	6.511×10^{-5} °C^{-1}
	ZBF-2	6.700×10^{-5} °C^{-1}
	ZBF-3	6.777×10^{-5} °C^{-1}
	Average	6.663×10^{-5} °C^{-1}
40°C	ZBF-1	7.125×10^{-5} °C^{-1}
	ZBF-2	7.784×10^{-5} °C^{-1}
	ZBF-3	7.991×10^{-5} °C^{-1}
	Average	7.633×10^{-5} °C^{-1}
60°C	ZBF-1	7.218×10^{-5} °C^{-1}
	ZBF-2	8.726×10^{-5} °C^{-1}
	ZBF-3	8.885×10^{-5} °C^{-1}
	Average	8.276×10^{-5} °C^{-1}

2.6 Creep test

When subjected to long-term loading, acrylic exhibits significant **creep behavior**, meaning strain increases over time. Failure caused by creep is one of the **primary failure modes** in engineering applications



GT-7049-DH Creep Testing Machine

Coupon type

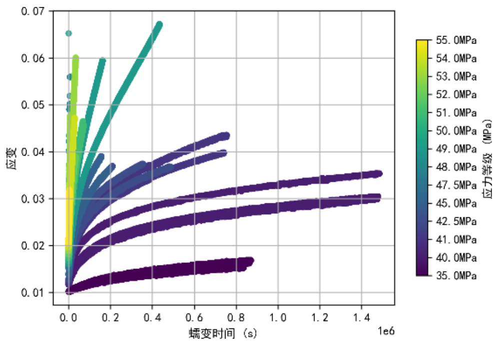
- Base material coupon
- Connected coupon annealed at **85°C and 65°C**

Creep temperature variables

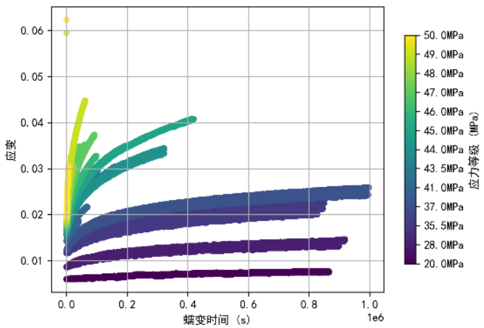
20°C and 40°C

The creep test lasted for four years

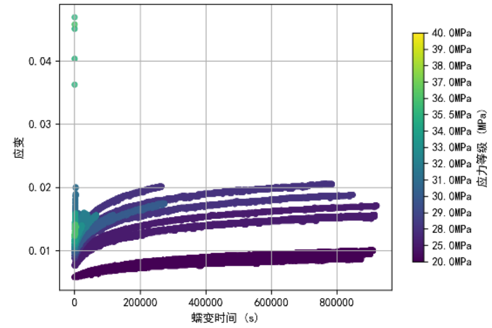
Long-term Creep Curves (5 Experimental Groups)



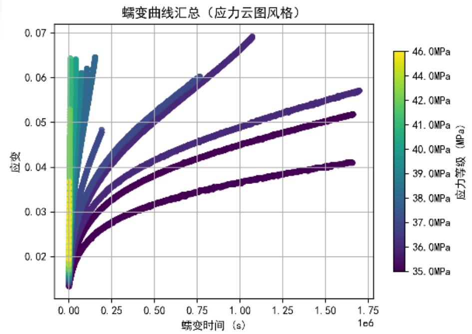
Base Material-20°C



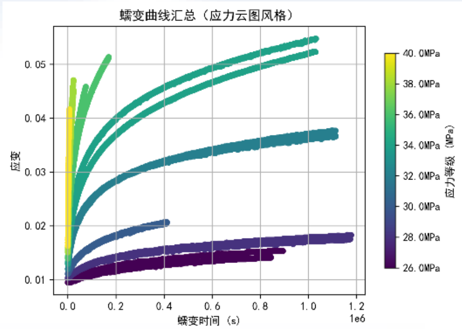
Connected coupon annealed at 85°C-20°C



Connected coupon annealed at 65°C-20°C

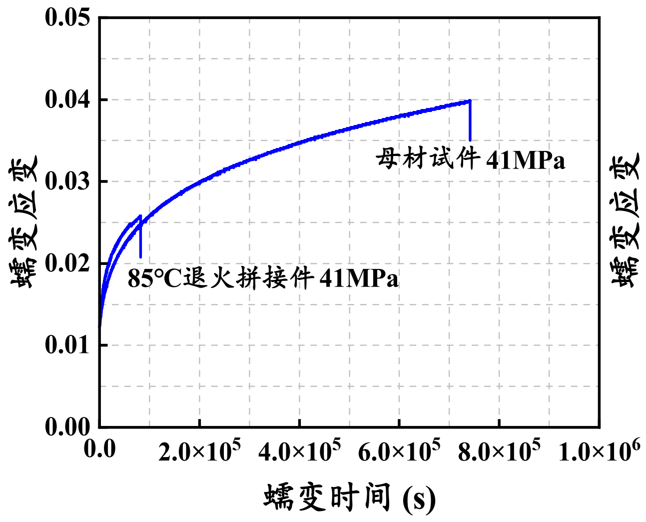


Base Material-40°C

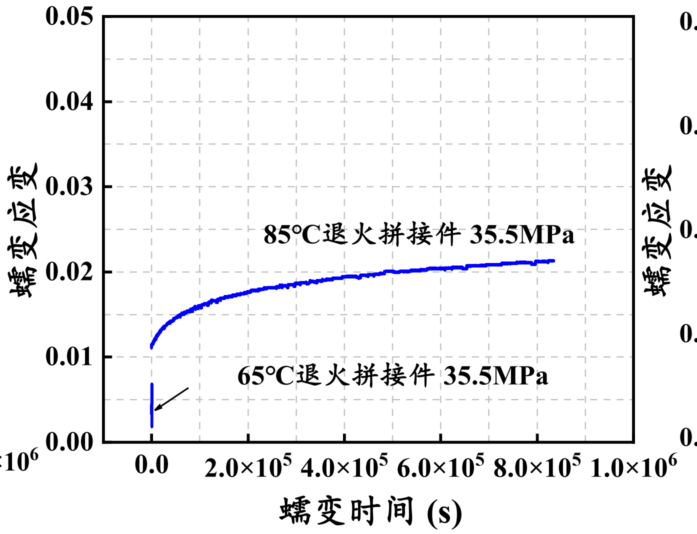


Connected coupon annealed at 85°C-40°C

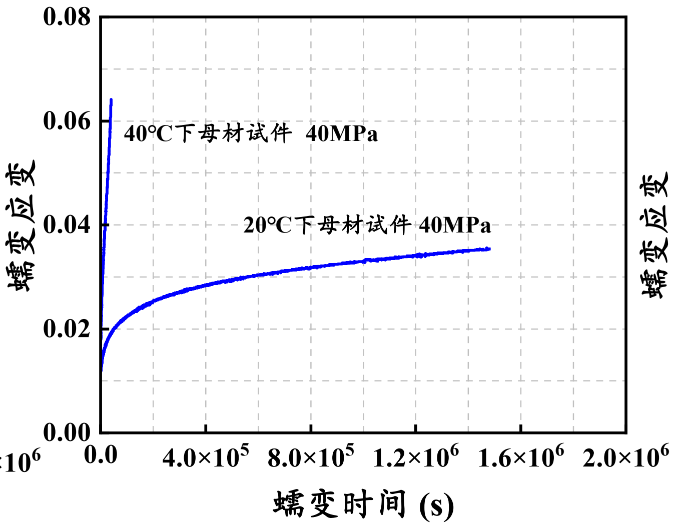
2.6 Creep test



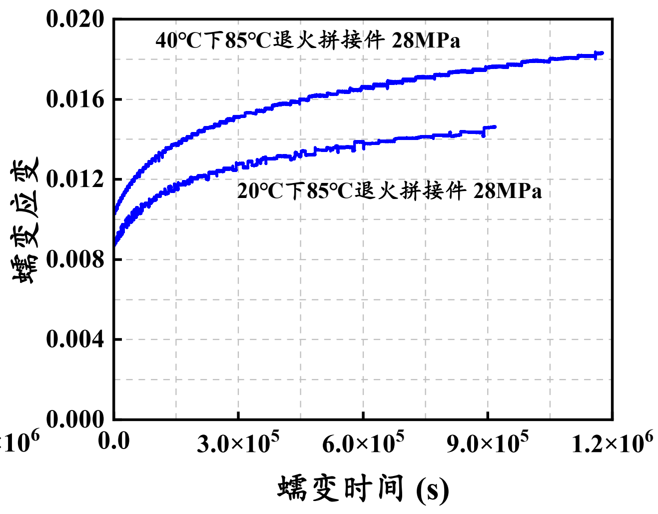
Base Material vs. 85°C Annealed at 20°C (41MPa)



85°C Annealed vs. 65°C Annealed at 20°C (35.5MPa))



Base Material at 20°C vs. Base Material at 40°C (40MPa)



85°C Annealed at 20°C vs. 85°C Annealed at 40°C

- **The creep performance of the connected seam is inferior to that of the base material;**
- **Lowering the annealing temperature weakens the creep performance of the connection;**
- **The higher the ambient temperature, the poorer the creep performance**

2.6 Creep test: creep life prediction

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Research Objective

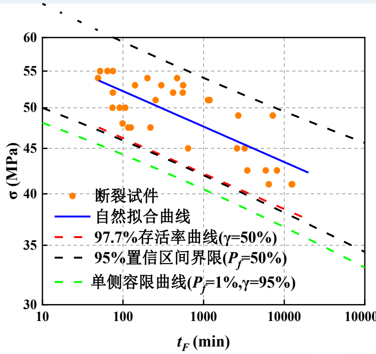
The creep life of acrylic is a **critical engineering concern**. Since creep life typically exhibits **variability**, establishing design curves based on different probability types provides a reliable basis for the service life design of acrylic

Design Curve Type

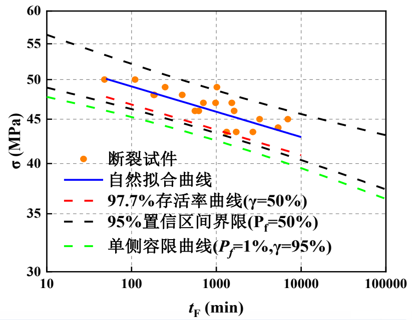
Basquin Equation: $\lg t_F = a + b \lg \sigma$

- **Creep Prediction Curve (Basquin Equation)**
- **Survival Rate Curve (Based on Failure Probability)**
- **Lower Confidence Limit Curve (Based on Confidence Level)**
- **One-sided Tolerance Limit Curve (Based on Confidence Level and Failure Probability)**

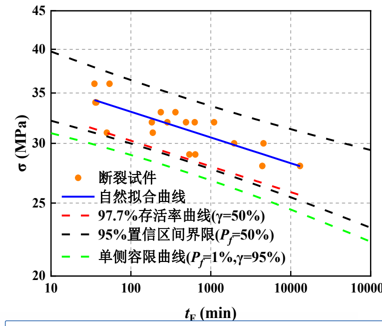
Creep Life Prediction and Design Curve Analysis



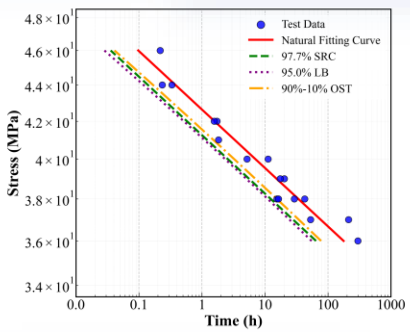
Base Material-20°C



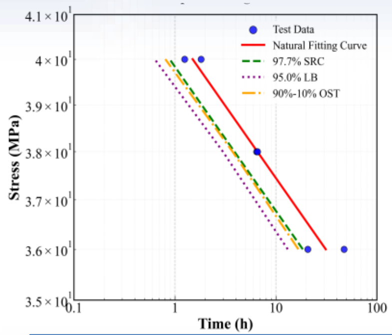
Connected coupon annealed at 85°C-20°C



Connected coupon annealed at 65°C-20°C



Base Material-40°C



Connected coupon annealed at 85°C-40°C

2.6 Creep test: creep life prediction (under 20°C)

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Creep Stress Corresponding to Failure Years Predicted by Three Types of Life Design Curves

Base Material

Design Life (year)	97.7% Survival Rate Curve (MPa)	ASTM: Lower Limit of 95% Confidence Interval (MPa)	One-sided Tolerance Limit Curve: 10% Failure Probability with 95% Confidence (MPa)
10	29.9	28.2	30.0
20	29.1	27.3	29.0
50	28.0	26.2	27.9
100	27.3	25.3	27.0

Connected coupon annealed at 85°C

Design Life (year)	97.7% Survival Rate Curve (MPa)	ASTM: Lower Limit of 95% Confidence Interval (MPa)	One-sided Tolerance Limit Curve: 10% Failure Probability with 95% Confidence (MPa)
10	34.1	31.5	32.7
20	33.4	30.7	31.9
50	32.5	29.6	30.9
100	31.9	28.8	30.1

Connected coupon annealed at 65°C

Design Life (year)	97.7% Survival Rate Curve (MPa)	ASTM: Lower Limit of 95% Confidence Interval (MPa)	One-sided Tolerance Limit Curve: 10% Failure Probability with 95% Confidence (MPa)
10	20.9	18.4	19.4
20	20.4	17.8	18.9
50	19.7	17.0	18.1
100	19.3	16.5	17.6

- The tests are conducted in the laboratory, which is better than the real condition;
- JNE: Stress smaller than 3.5 MPa, and local stress (stress concentration) lower than 5 MPa for a conservative design

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3.1 Design Parameter

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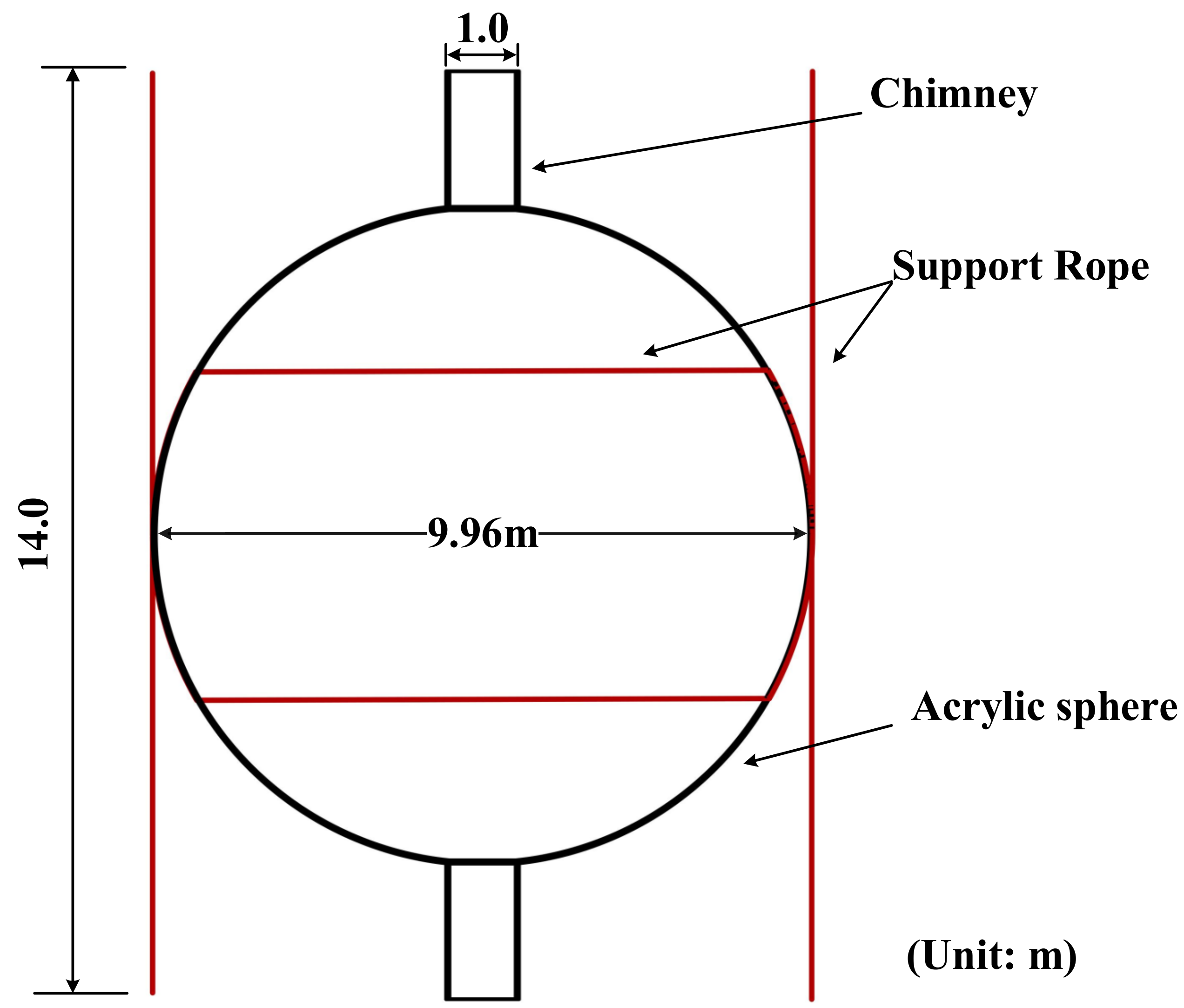
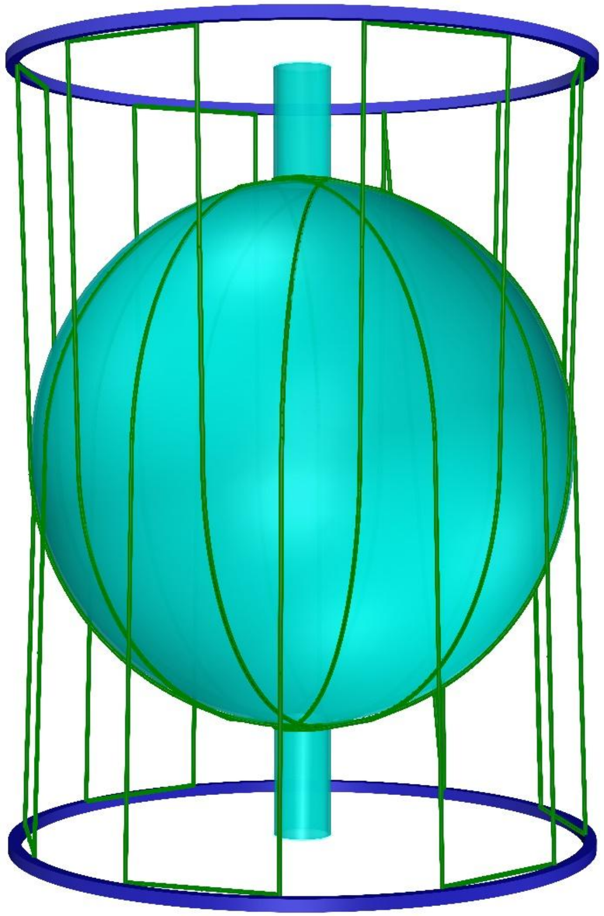


Structural Design

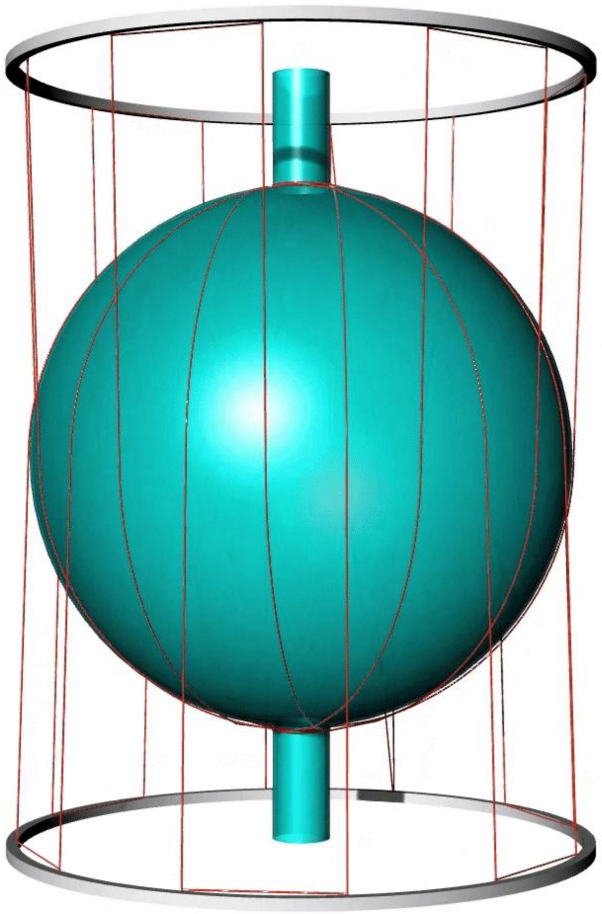
Diameter	9.96 m
Height	14 m
Shell Thickness	50 mm
Chimney Diameter	1.0 m
Capacity	501 m^3
Rope Diameter	35 mm
Number of Ropes	24
Chimney Features	Facilitates liquid replacement
Rope Material	Vectran（Low background）

3.2 Scheme 1

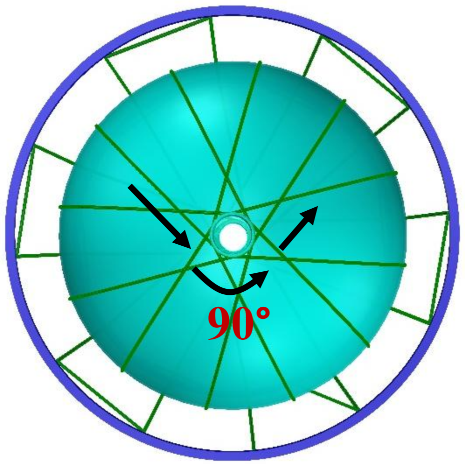
The entire support system is formed by winding a single continuous rope



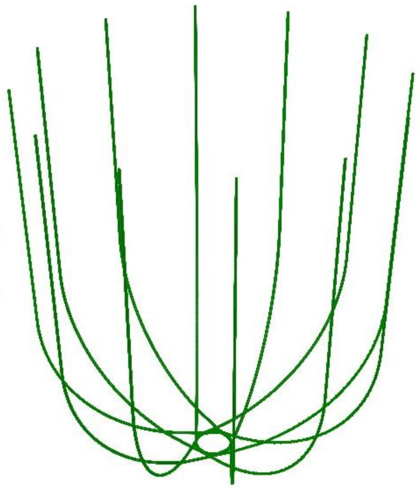
Schematic Diagram of Scheme 1



Assembly Diagram of Scheme 1



Top View

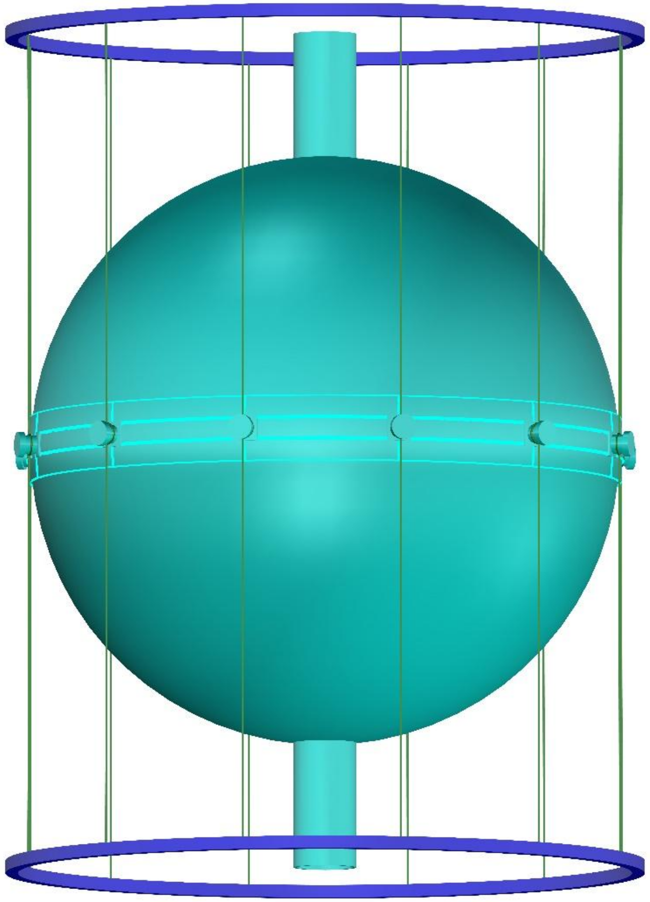


Ropes

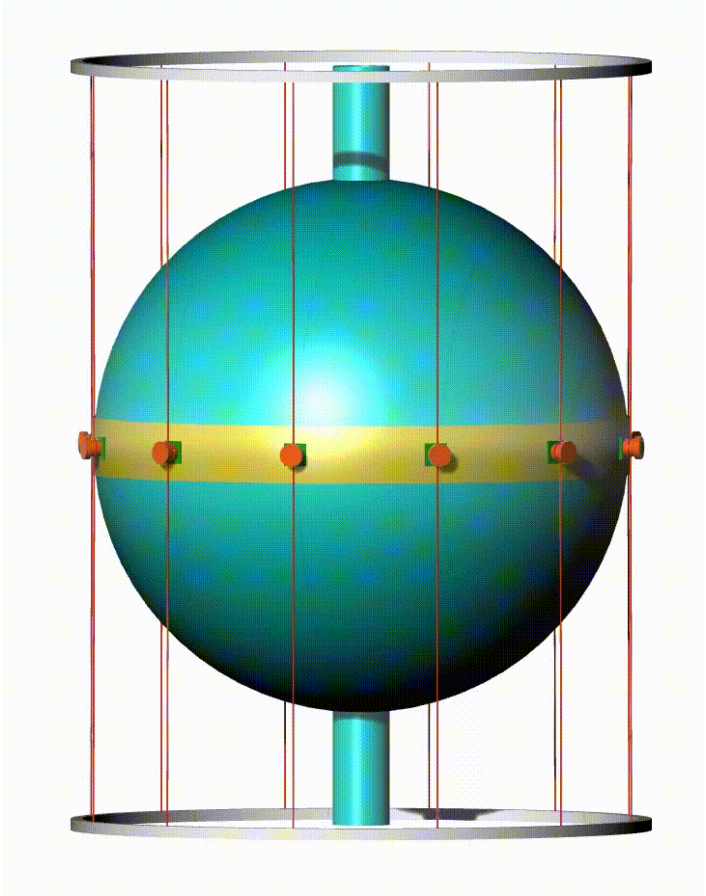
Advantage	**High resistance to buckling**

3.3 Scheme 2

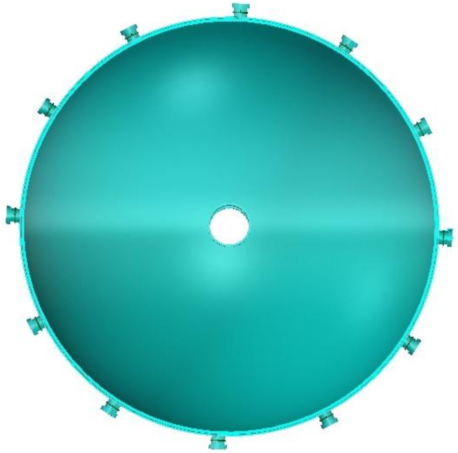
12 support handles are designed and arranged at the equator, along with a 50 mm equatorial reinforcement band



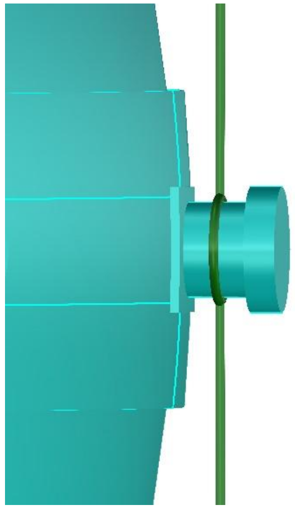
Schematic Diagram of Scheme 1



Assembly Diagram of Scheme 2



Top View

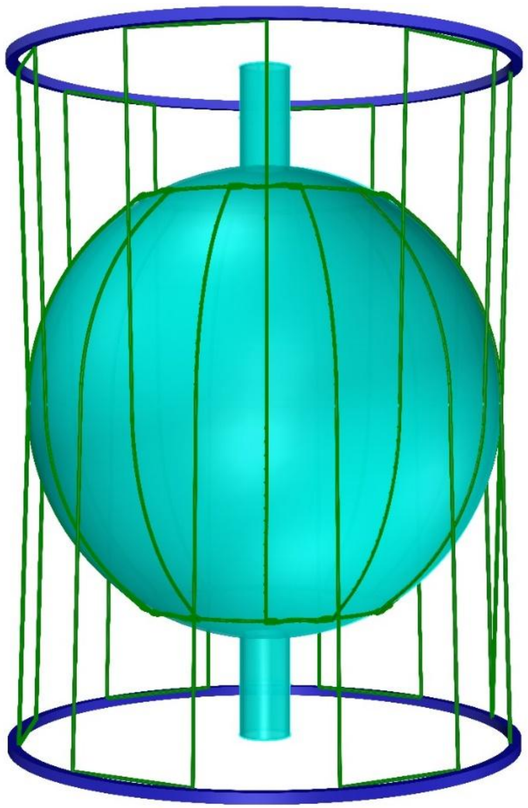


Detail View

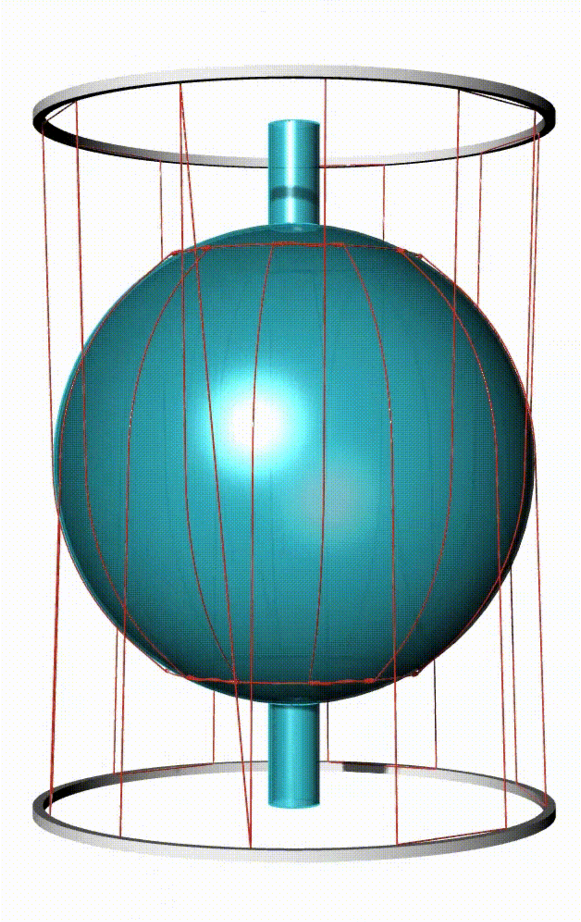
Advantage	High transparency

3.4 Scheme 3

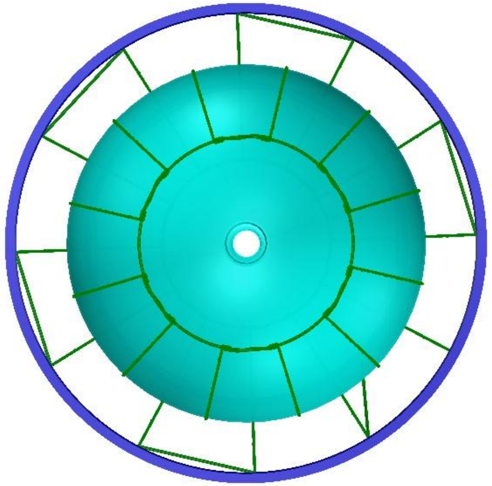
A rope circle is used to cradle the sphere, with the circle positioned 3.5 m away from the equator



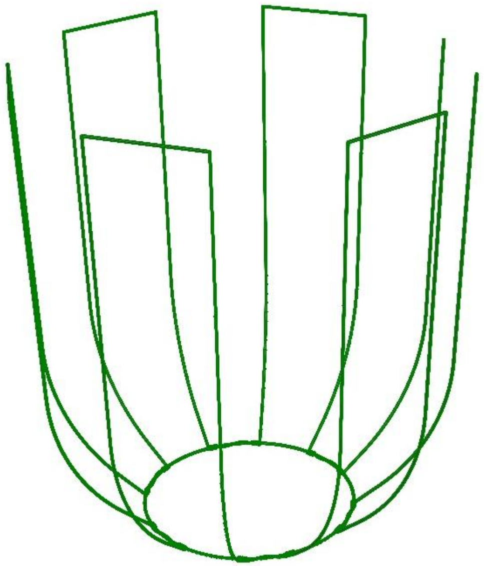
Schematic Diagram of Scheme 3



Assembly Diagram of Scheme 3



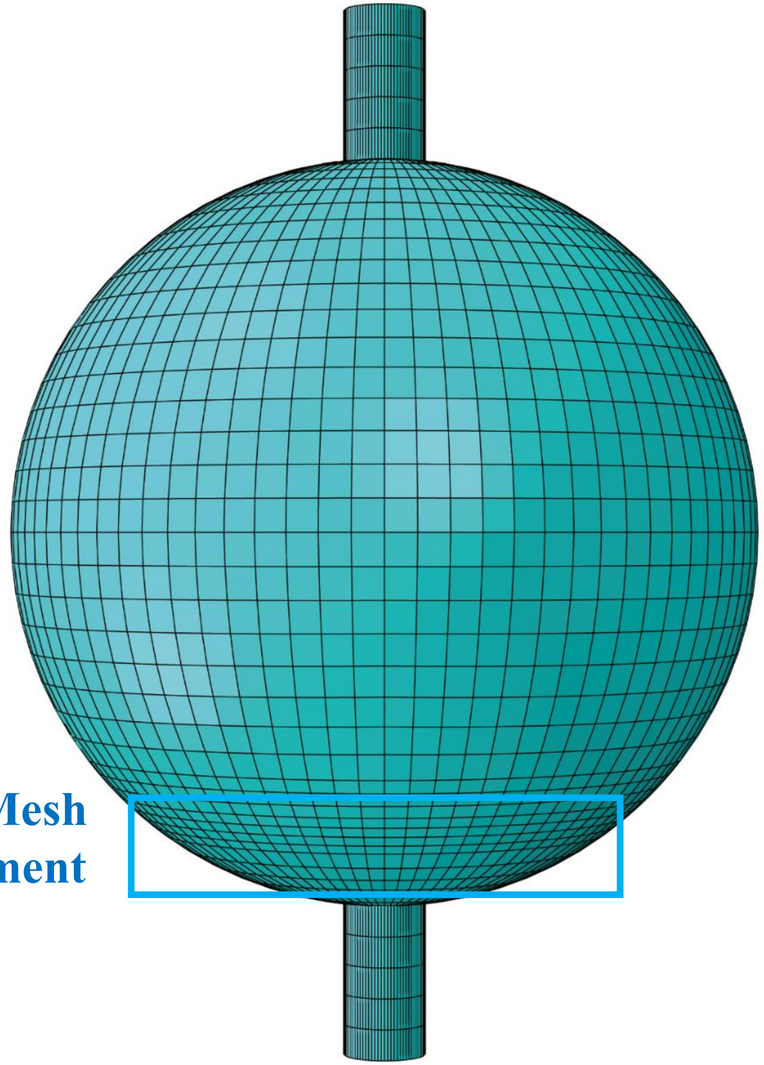
Top View



Rope Net

Advantage	Low sphere stress

3.5 FE study

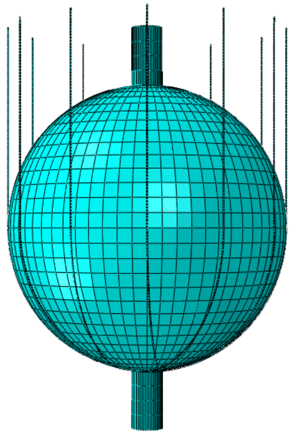


Choose the worst load condition

Property	Parameter
External Water	1.0 g/cm^3
Internal liquid	1.2 g/cm^3
Shell Thickness	50 mm
PMMA Elastic Modulus	3.0 GPa
PMMA Poisson's Ratio	0.376
PMMA Density	1.19 g/cm^3
Rope Elastic Modulus	15.0 GPa
Rope Poisson's Ratio	0.46
Rope Density	1.41 g/cm^3
Contact Relationship	Surface to Surface
Friction Coefficient	0.3
Element of ball	C3D8R Solid Element (to prevent penetration)
Element of rope	B31 Beam Element
	C3D8R Solid Element

3.5 FE Study: Results of Scheme 1

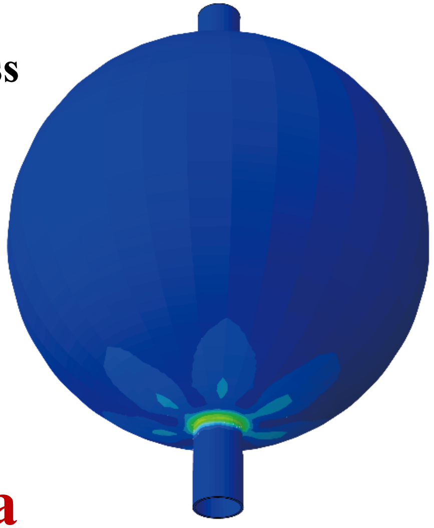
Ropes modeled with beam elements



Von Mises stress

+1.593e+07
+1.461e+07
+1.328e+07
+1.195e+07
+1.062e+07
+9.295e+06
+7.968e+06
+6.640e+06
+5.313e+06
+3.985e+06
+2.657e+06
+1.330e+06
+2.293e+03

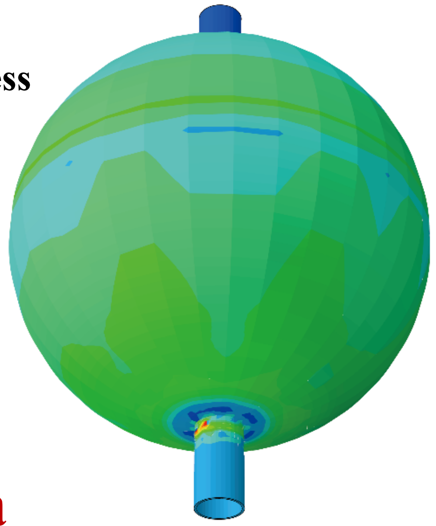
15.9 MPa



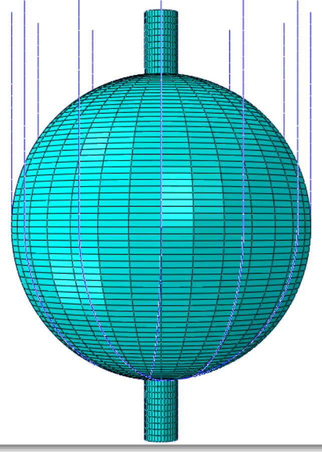
Maximum Principal Stress

+3.052e+06
+2.755e+06
+2.457e+06
+2.160e+06
+1.862e+06
+1.564e+06
+1.267e+06
+9.695e+05
+6.720e+05
+3.745e+05
+7.696e+04
−2.205e+05
−5.181e+05

3.1 MPa



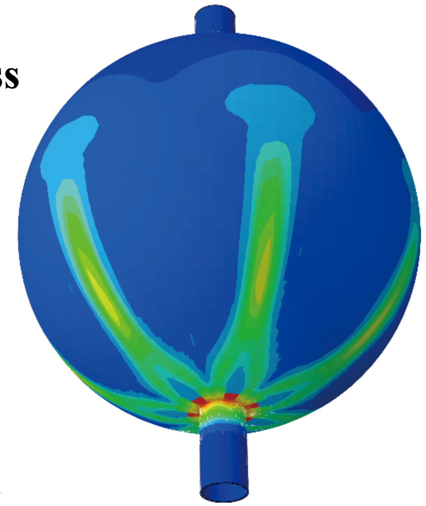
Ropes modeled with solid elements



Von Mises stress

+7.067e+06
+6.479e+06
+5.890e+06
+5.302e+06
+4.713e+06
+4.124e+06
+3.536e+06
+2.947e+06
+2.358e+06
+1.770e+06
+1.181e+06
+5.926e+05
+3.930e+03

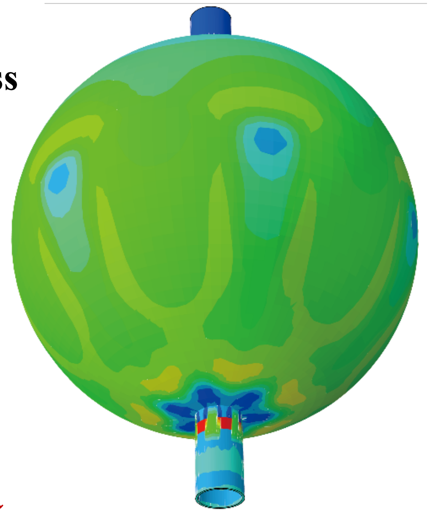
7.1 MPa



Maximum Principal Stress

+2.208e+06
+1.994e+06
+1.780e+06
+1.565e+06
+1.351e+06
+1.136e+06
+9.221e+05
+7.077e+05
+4.933e+05
+2.789e+05
+6.448e+04
−1.499e+05
−3.643e+05

2.2 MPa



3.5 FE Study: Results of Scheme 2

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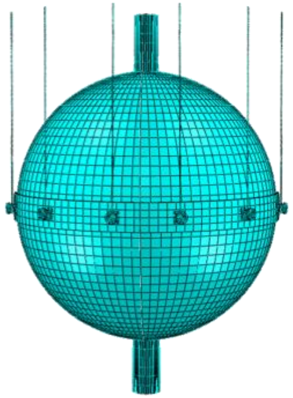
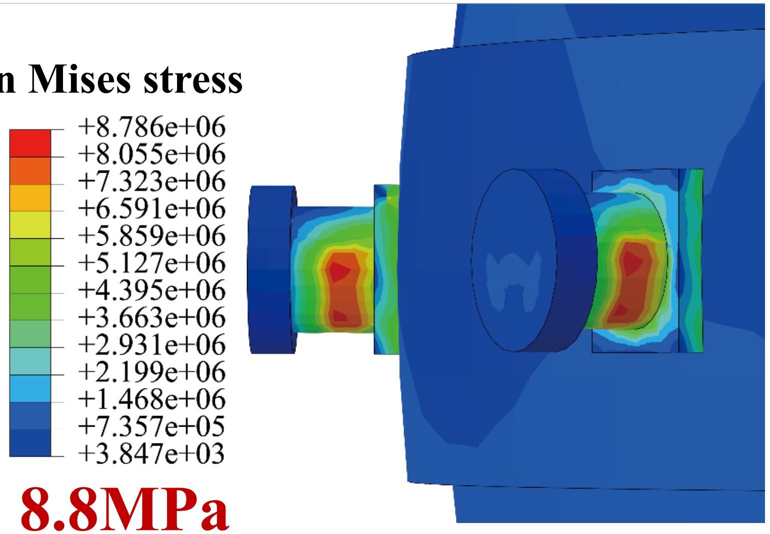
Ropes modeled with beam elements

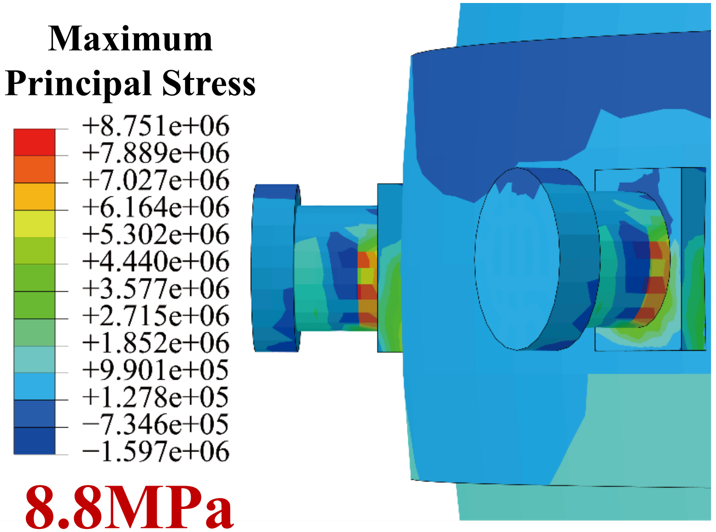


Von Mises stress



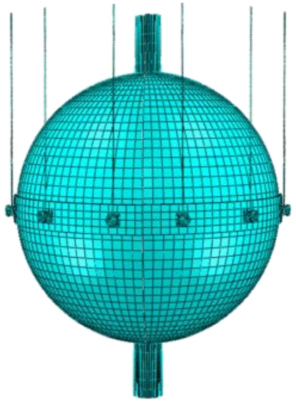
8.8MPa

Maximum Principal Stress

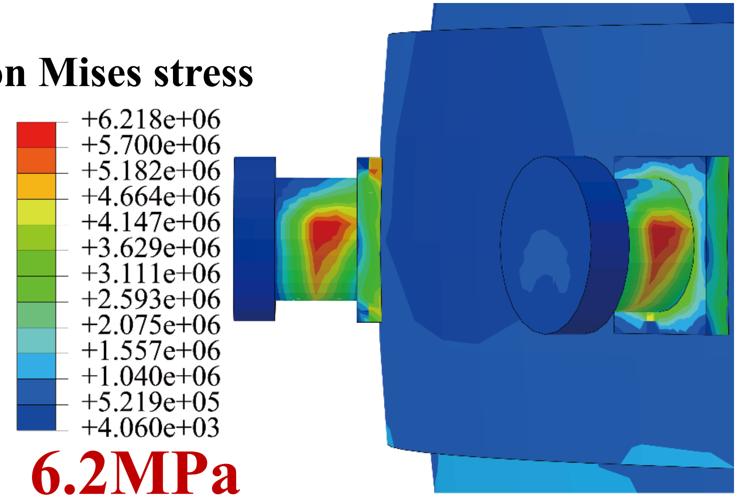


8.8MPa

Ropes modeled with solid Elements

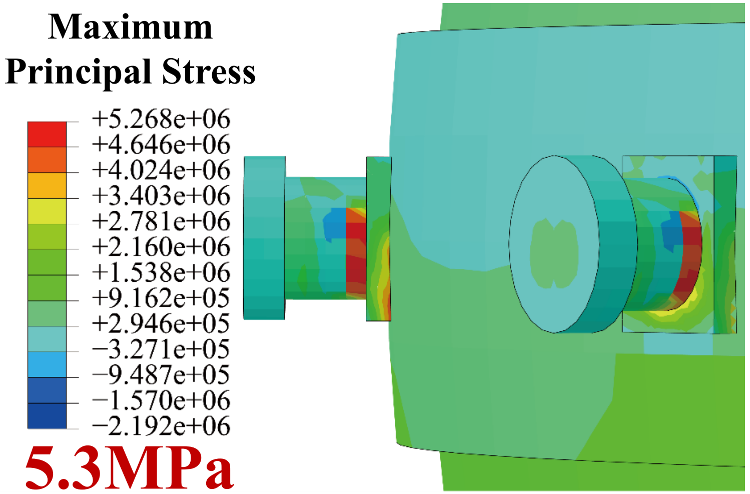


Von Mises stress



6.2MPa

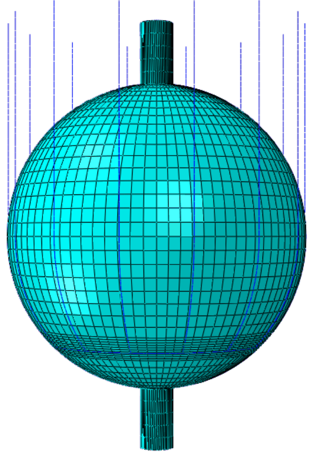
Maximum Principal Stress



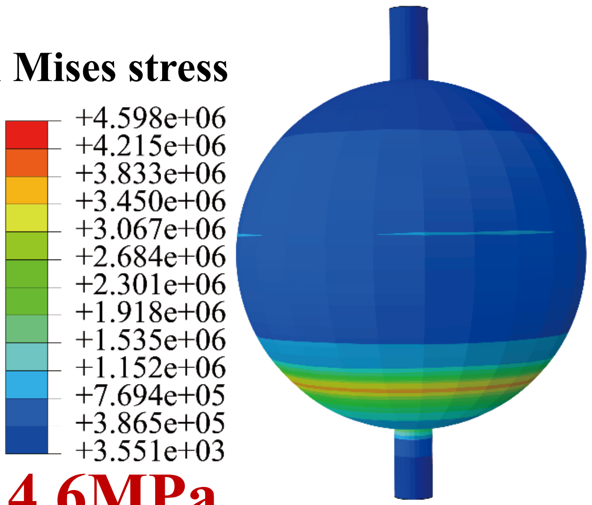
5.3MPa

3.5 FE Study: Results of Scheme 3

Ropes modeled with beam elements

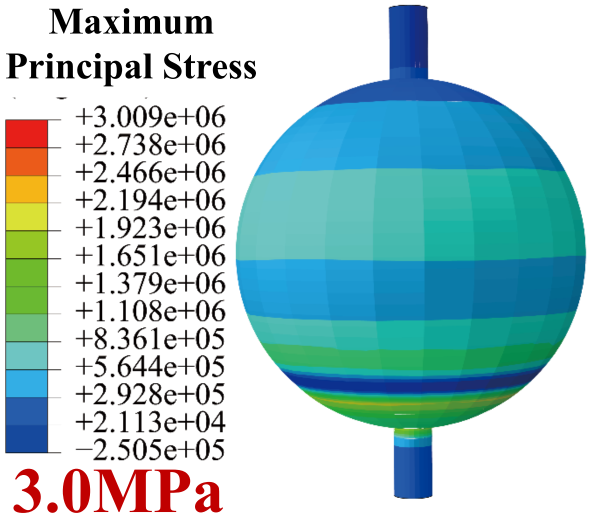


Von Mises stress



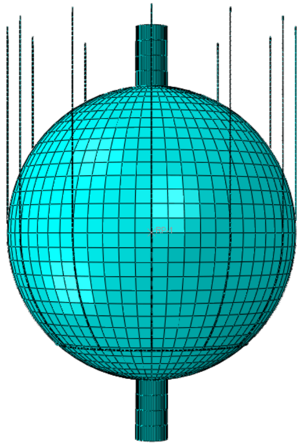
4.6MPa

Maximum Principal Stress

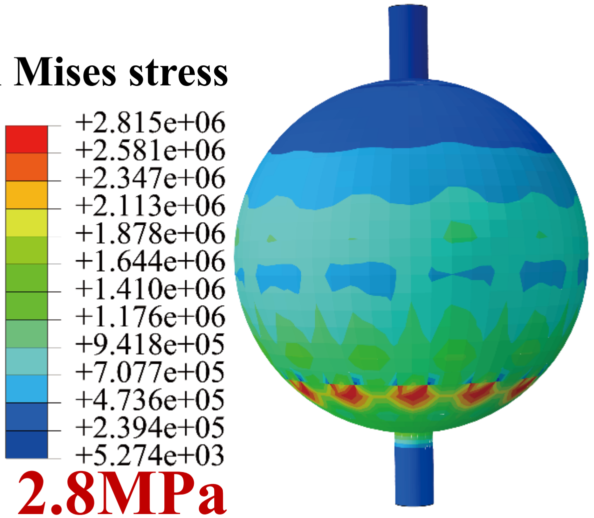


3.0MPa

Ropes modeled with solid elements

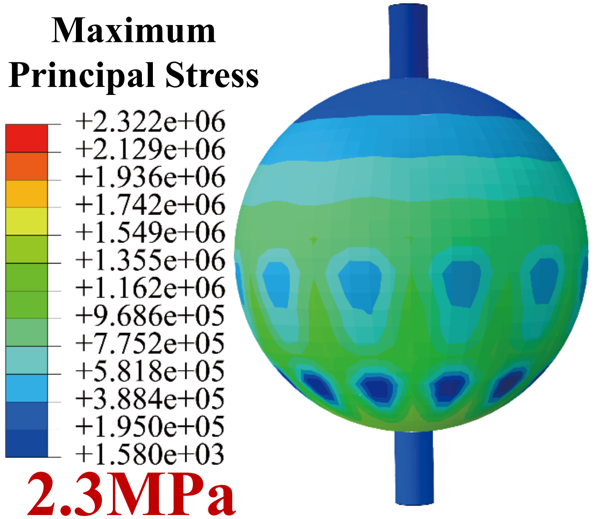


Von Mises stress



2.8MPa

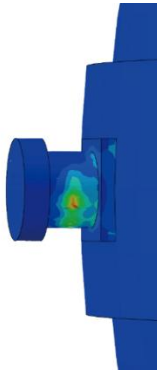
Maximum Principal Stress

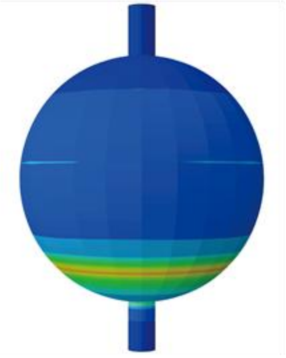


2.3MPa

3.6 Scheme Comparison

Principle of Scheme Selection: Under the condition that structural displacement and cable load do not exceed the limits, select the scheme with **the minimum stress**





Structural displacement < 600 mm

Rope load < 100 kN

Rope Element	Scheme No.	Max Mises Stress (MPa)	Max First Principal Stress (MPa)	Structural Displacement (mm)	Rope Load (kN)
Beam Element	Scheme 1	15.9	3.1	150	95.5
	Scheme 2	23.9	15.0	60	99.8
	Scheme 3	4.6	3.0	180	84.3
Solid Element	Scheme 1	7.1	2.2	150	107.7
	Scheme 2	14.2	9.2	70	98.6
	Scheme 3	2.8	3.0	180	99.6

- **Scheme 3** is better than Schemes 1 and 2

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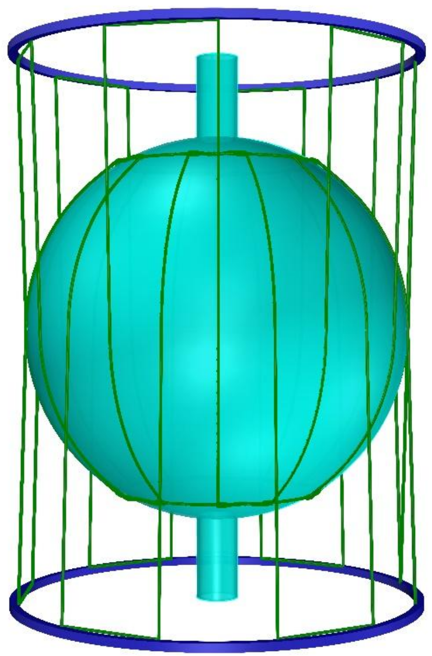
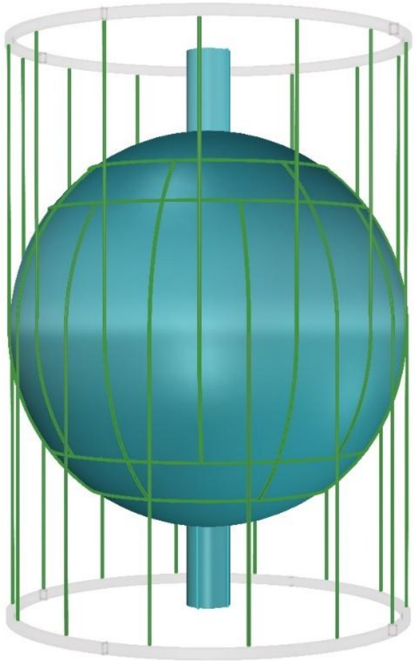
4.1 Scheme Optimization

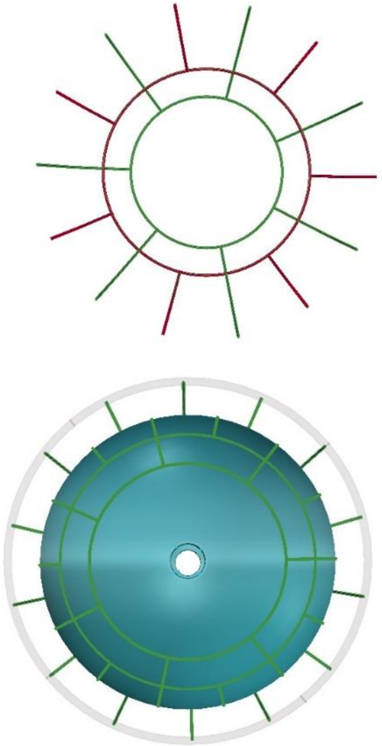
Optimization Objectives

- Reduce the stress magnitude on the acrylic ball
- To ensure the structure will not fail if the horizontal rope breaks

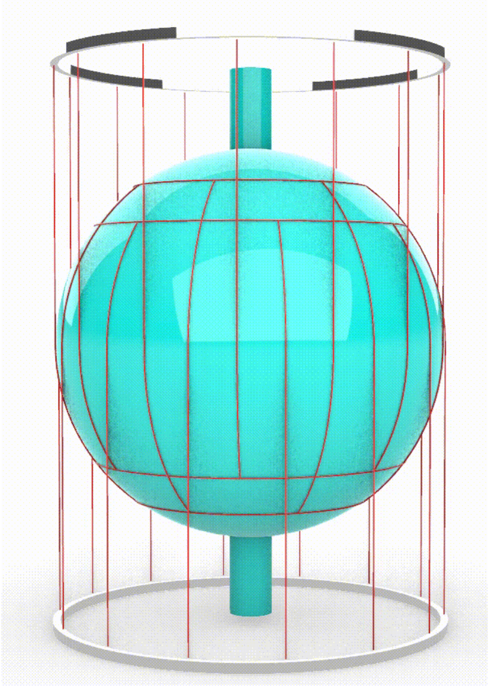


Single-layer rope Net





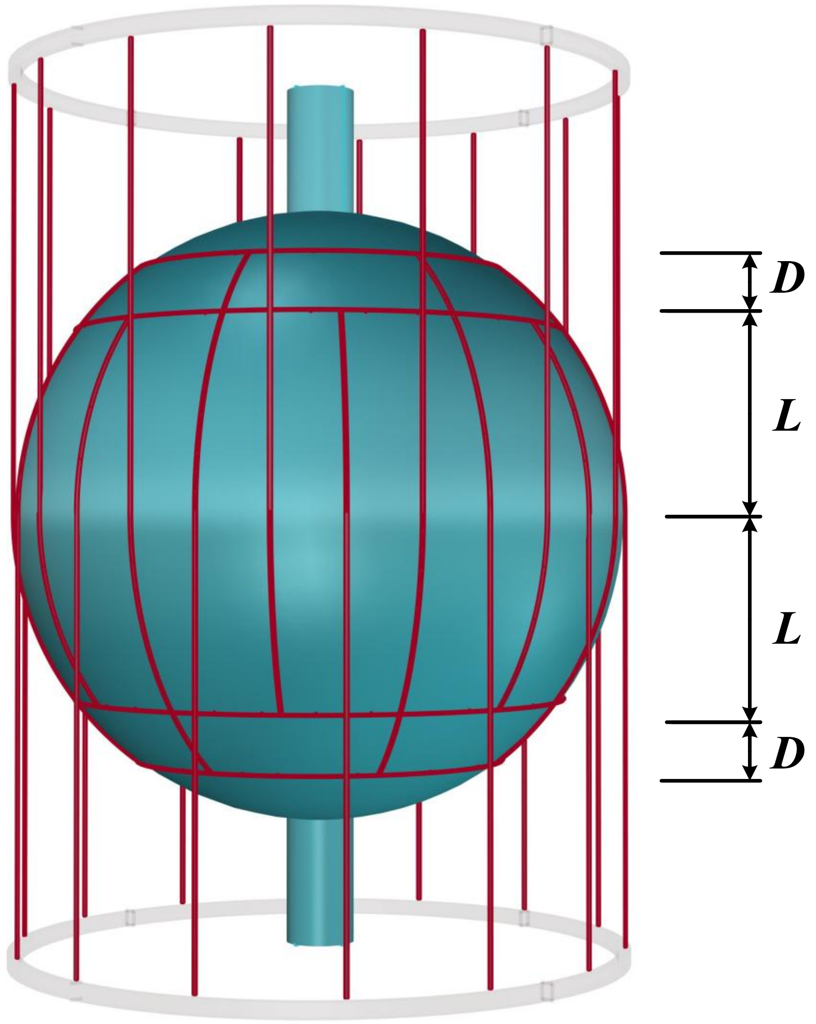
Double-layer rope Net



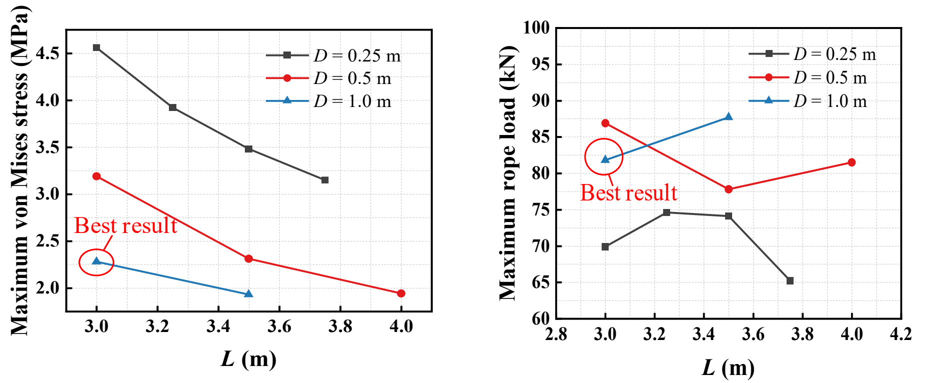
Optimization Measures

- The number of support ropes is increased from 12 to 14
- The two layers of ropes are distributed symmetrically

4.2 Analysis of Rope circle Position



Parameter study



D (m)	*L* (m)	Rope load (kN)	Maximum Stress on Sphere (MPa)
0.25	3	69.9	4.56
	3.25	74.6	3.92
	3.5	74.1	3.48
	3.75	65.2	3.15
0.5	2.5	Rope cirlce deformation too large, rope slips off	
	3	86.9	3.19
	3.5	77.8	2.31
	4	81.5	1.94
1	2.5	Rope cirlce deformation too large, rope slips off	
	3	81.8	2.28
	3.5	87.7	1.93
	4	Due to too small contact area, lack of hoop constraint	

***D* = 1.0 m and *L* = 3.0 m, best scheme**

4.3 Load-Bearing Performance Analysis

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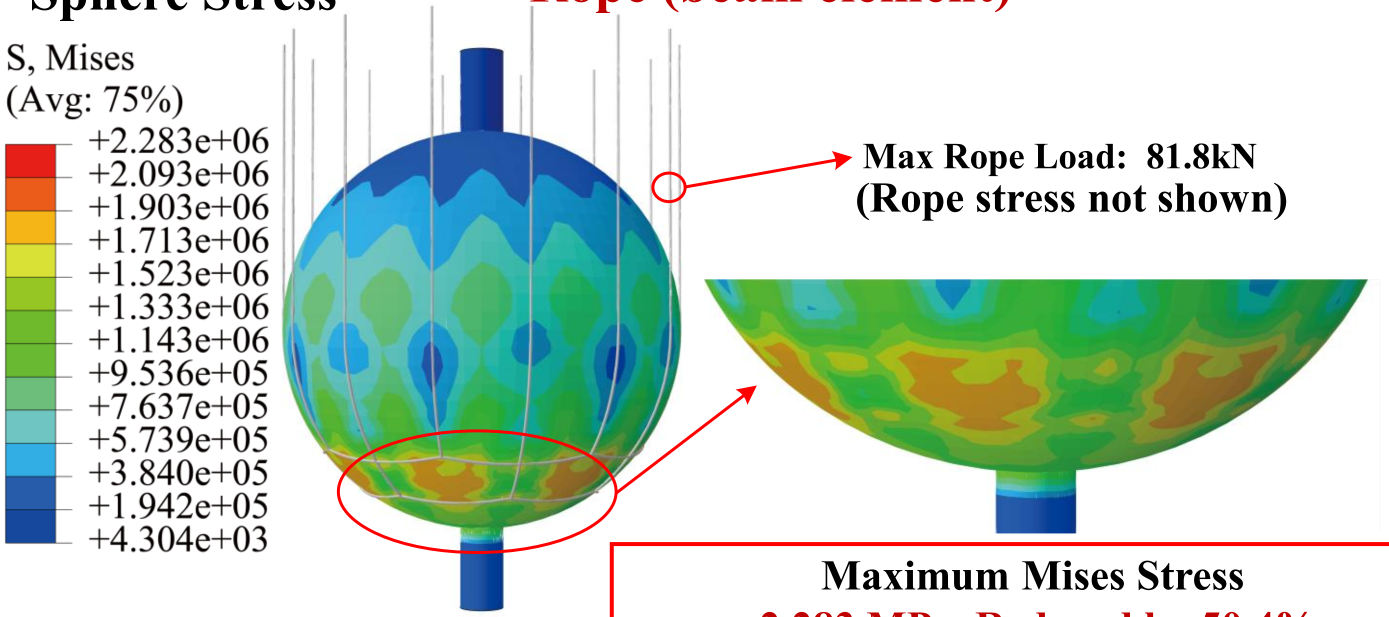
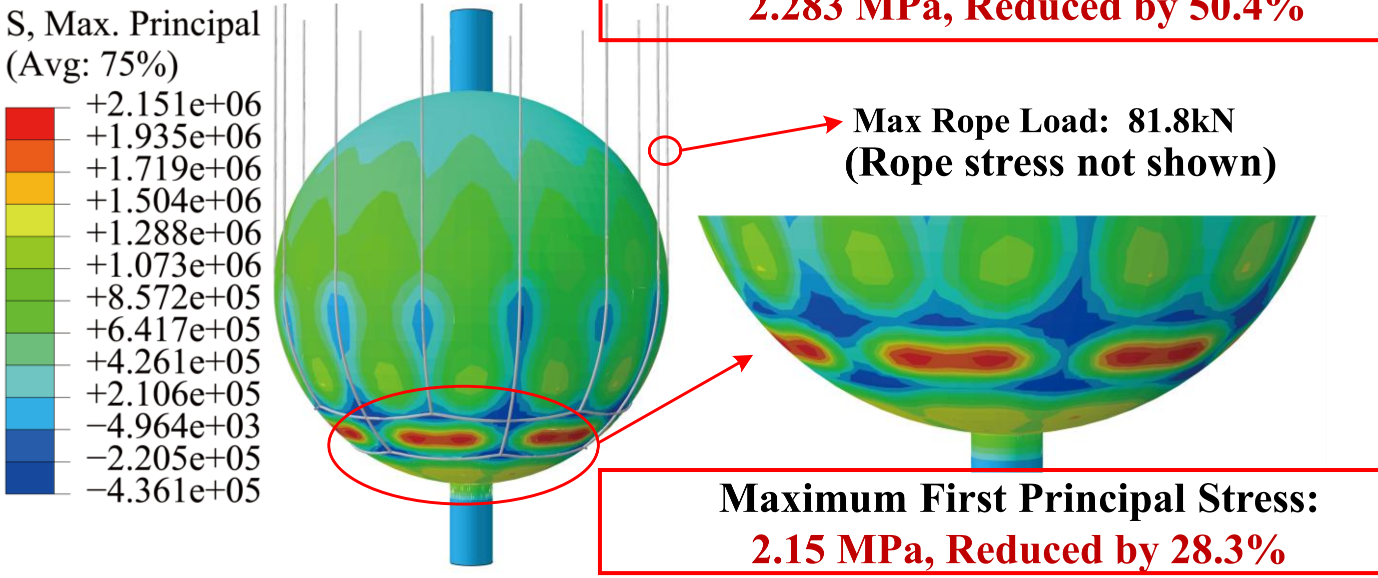
➤ Sphere Stress

Rope (beam element)

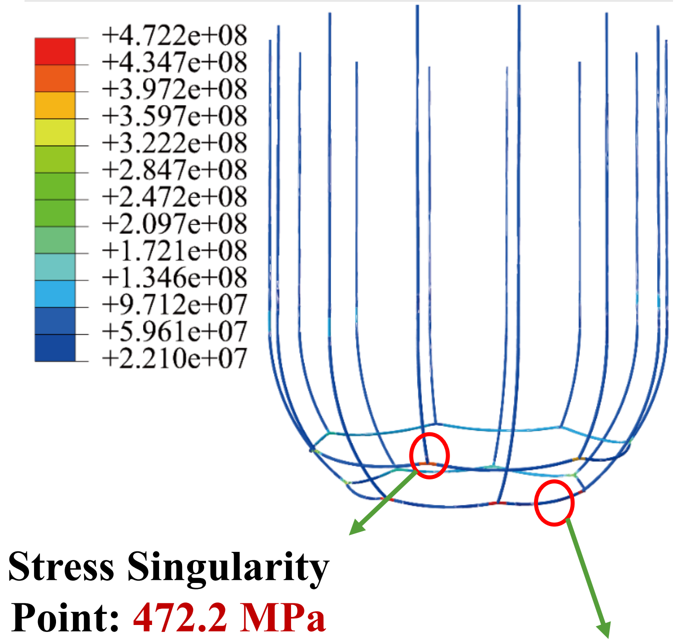


Maximum Mises Stress
2.283 MPa, Reduced by 50.4%



Maximum First Principal Stress:
2.15 MPa, Reduced by 28.3%

➤ Rope Stress



Maximum rope load
106.5 kN, 10.6% of breaking force

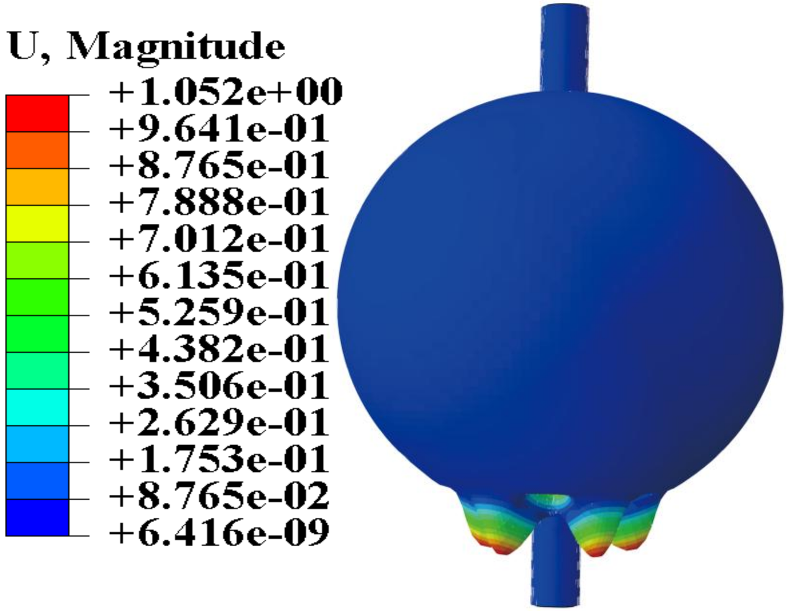
➤ Structural Displacement

Maximum structural displacement
243.8 mm, less than 600 mm

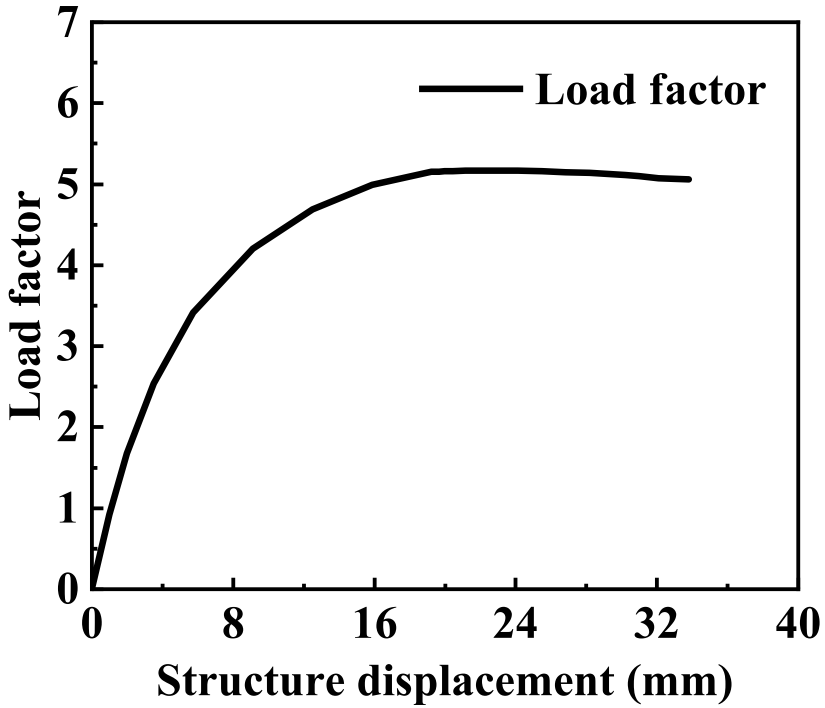
4.4 Buckling Analysis

When the density of the liquid outside greater than inside, buckling may occur

External liquid density 1.2 g/cm³, internal liquid density 1.0 g/cm³



Initial imperfection = 1/300 of the ball diameter



Eigenvalue of elastic buckling analysis: 14.72

Safety factor of geometric nonlinear buckling analysis: 5.3 greater than 3.0 (the requirement for pressure vessels)

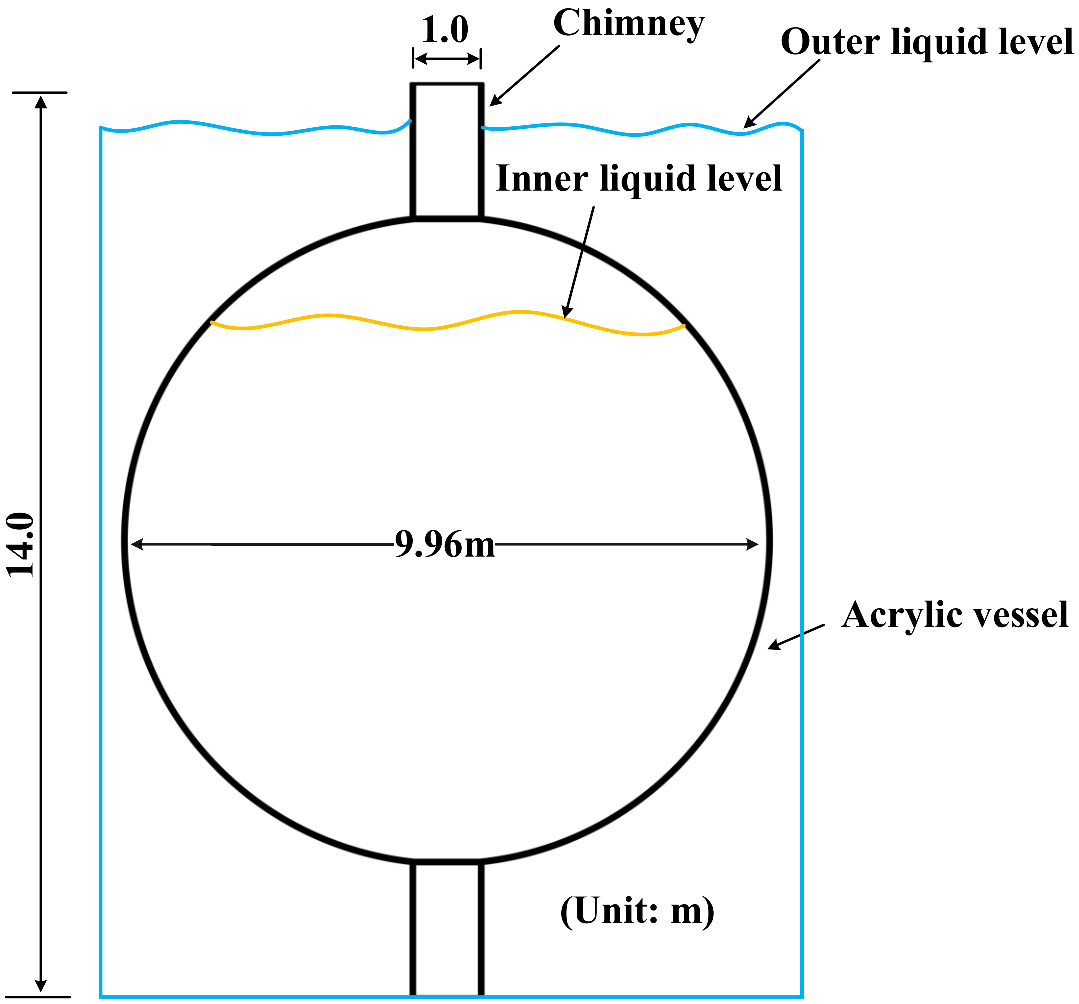
[1]ASME, Boiler and Pressure Vessel Code Section III American Society of Mechanical Engineers, New York, 2013
[2] ECCS, TC8 TGW 8.4 Shells, 'Buckling of Shells-European Design Recommendations', No.125398 p. 5th Edition (revised) ECCS, Multicomp Lda, Portugal, 2013(ISBN 978-92-9147-116-4).
[3] Chinese Standard: GB 150. Design of Pressure Vessels, 2011

4.5 Operating Condition

Load cases to be considered:

- **Various types of liquid adopted inside and outside the ball**
- **The maximum liquid level difference between the inside and outside of the ball is 2 m**

Target Substance	Chemical Formula	Density
Pure Water	H_2O	1.0g/cm^3
Liquid Scintillator	$C_{33}H_{62}O_{11}$ etc,	0.8g/cm^3
Slow Liquid Scintillator	--	1.2g/cm^3
------	------	------

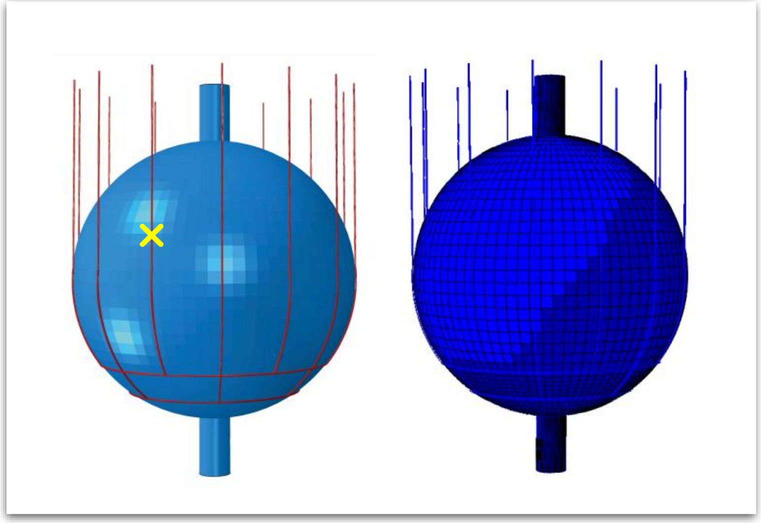


4.6 Analysis of Different Load Cases

Load Case	Max Mises Stress (MPa)	Max Principal Stress (MPa)	Max Structural Displacement (mm)	Max Rope Load (kN)
Construction	0.69	0.38	81	25.2
1	2.28	2.15	180	117.9
2	2.12	1.67	172	114.3
3	2.49	2.99	186	119.7
4	2.57	1.17	176	113.3
5	3.81	4.54	184	110.0
6	2.20	1.01	173	110.6
7	3.53	1.14	173	108.6
8	2.28	2.23	182	121.0

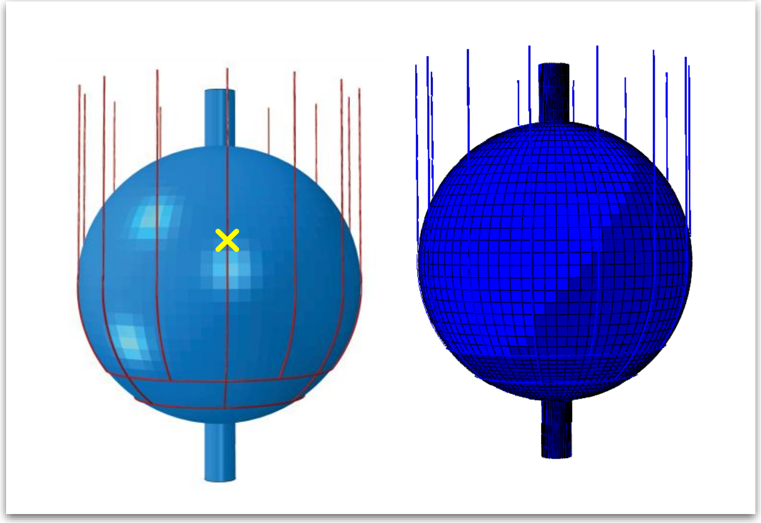
Under all extreme load cases, the structure meets requirement

4.7 Rope Failure Analysis



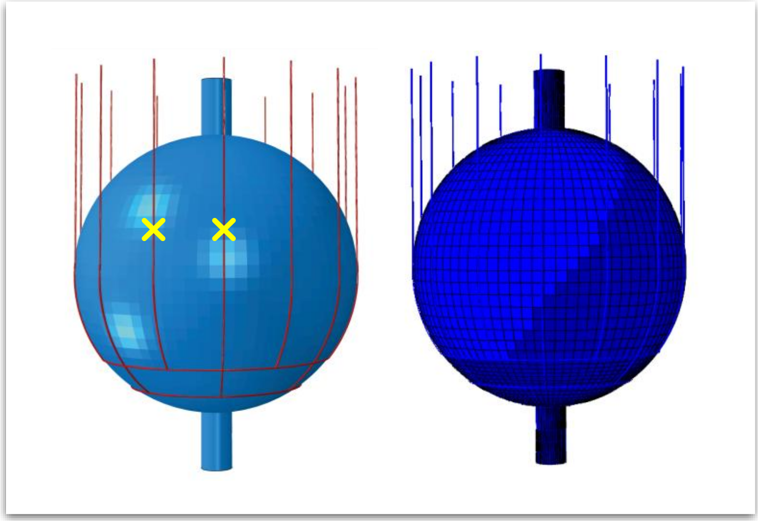
Structural Displacement	249mm
Max Mises Stress	3.7MPa
Max Rope Axial Force	140.3kN (14.3% of Breaking Force)

Failure Case A



Structural Displacement	273mm
Max Mises Stress	4.2MPa
Max Rope Axial Force	162.6kN (16.2% of Breaking Force)

Failure Case B

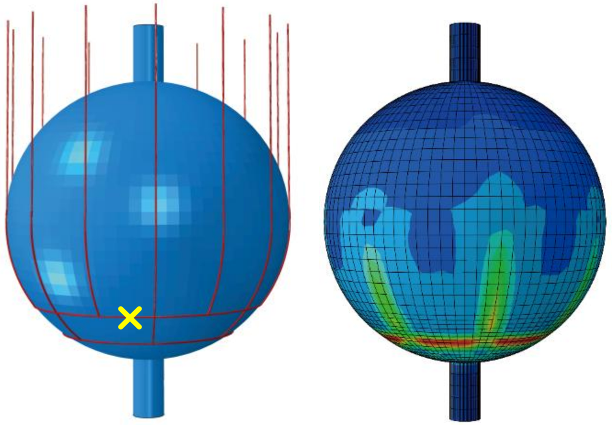


Structural Displacement	492mm
Max Mises Stress	3.4MPa
Max Rope Axial Force	134.5kN (13.4% of Breaking Force)

Failure Case C

4.7 Rope Failure Analysis

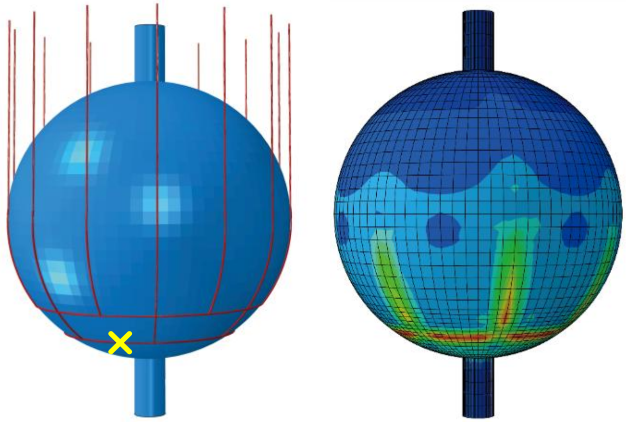
Upper Rope Net Horizontal Fracture



Structural Displacement	265mm
Max Mises Stress	5.1MPa
Max Rope Axial Force	203.7kN (20.3% of Breaking Force)

Failure Case D

Lower Rope Net Horizontal Fracture



Structural Displacement	263mm
Max Mises Stress	4.7MPa
Max Rope Axial Force	203.7kN (20.3% of Breaking Force)

Failure Case E

Failure Case	Increase in Sphere Displacement	Increase in Max Sphere Stress	Increase in Max Rope Axial Force
A	39.1%	62.3%	31.7%
B	52.5%	84.2%	52.7%
C	174.9%	49.1%	26.3%
D	48.0%	123.7%	91.3%
E	46.9%	106.1%	65.8%

Under various failure modes, the support system can still ensure the short-term safety performance of the structure

4.8 Analysis of Other Influencing Factors

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➢ Temperature Effect

	Temperature (°C)	Max Mises Stress (MPa)	Max First Principal Stress (MPa)	Structural Displacement (m)
	+20	2.70	2.47	0.17
	+10	2.70	2.47	0.18
Baseline►	0	2.28	2.15	0.18
	-10	2.70	2.57	0.19
	-20	2.55	2.42	0.17

Temperature has insignificant effect on the structure

➢ Effect of Rope Elastic Modulus

	Elastic Modulus (Gpa)	Max Mises Stress (MPa)	Max First Principal Stress (MPa)	Rope Displacement (m)
	5	2.43	2.29	362.9
	10	2.16	2.20	284.1
Baseline►	15	2.28	2.15	243.8
	20	2.32	2.25	203.6
	25	2.33	2.36	139.4

The elastic modulus of the rope has little effect on stress, but has a certain impact on structural displacement

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Thanks!

Xichang, China

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