Design Analysis of the Stainless Steel Structure of the Jinping Neutrino Detector

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1.1 Research Background

➢ Neutrinos are fundamental to particle physics, astrophysics, and cosmology, but their weak interaction with matter makes them extremely difficult to detect. **Therefore, detector construction is essential for neutrino experiments.**

1 Scientific Objective

Key studies on solar neutrinos and supernova neutrinos.

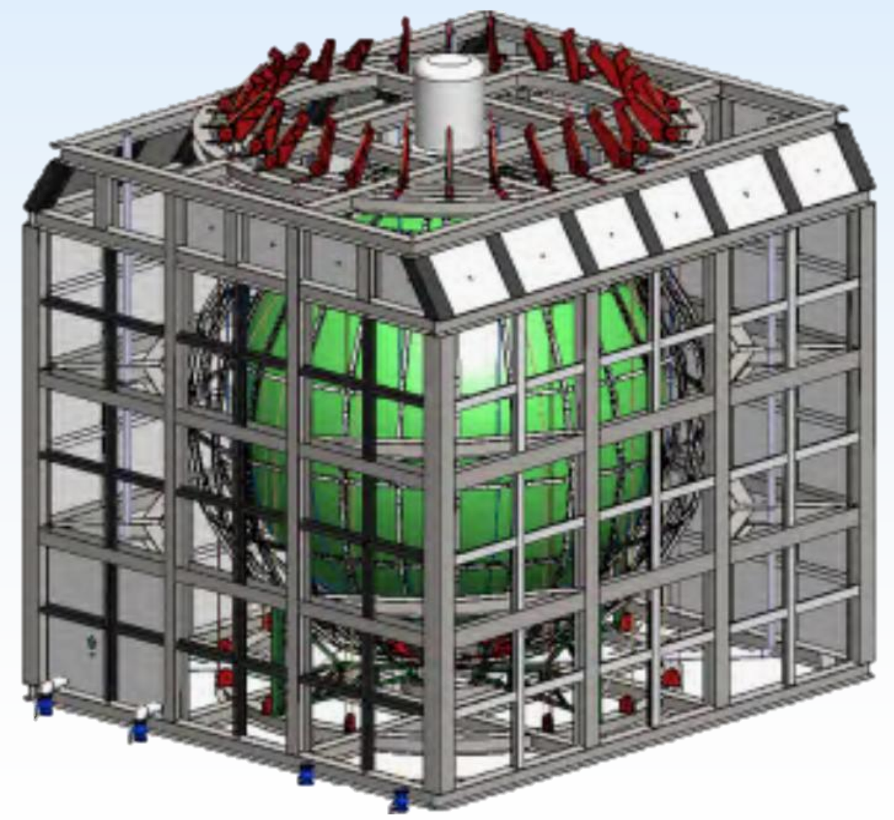
2 Site Location

China Jinping Underground Laboratory is located about 2400 m underground in Sichuan, providing excellent shielding from external radiation.

3 Structural System

- ☐ Acrylic sphere: liquid scintillator + high-strength rope
- ☐ Spherical reticulated shell: PMT mounting + bracing
- ☐ Steel vessel: structural support + buffer liquid storage

Structural Schematic of the Jinping Neutrino Detector



1.2 Design Challenges

Design Challenges

1 Material Selection

- Deep underground/humid/corrosive;
- Low-background and non-magnetic;
- High strength with reasonable cost.

S35657 stainless steel

2 Multi-functional Loading

- Hydrostatic pressure from buffer liquid far exceeds that of conventional vessels;
- Suspension load from the acrylic sphere;
- Dense PMT arrangement introduce buoyancy effects.

3 Construction Space Limits

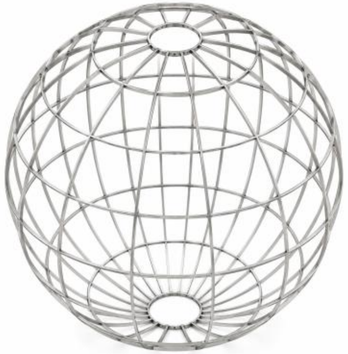
- 500t solution and 900 mm detector space;
- Shell diameter 12.06 m, frame width 12.90 m;
- A safe gap and installation tolerance must be ensured.

Research Objects

Stainless Steel Frame

Stainless Steel Plate

Stainless Steel Spherical Shell



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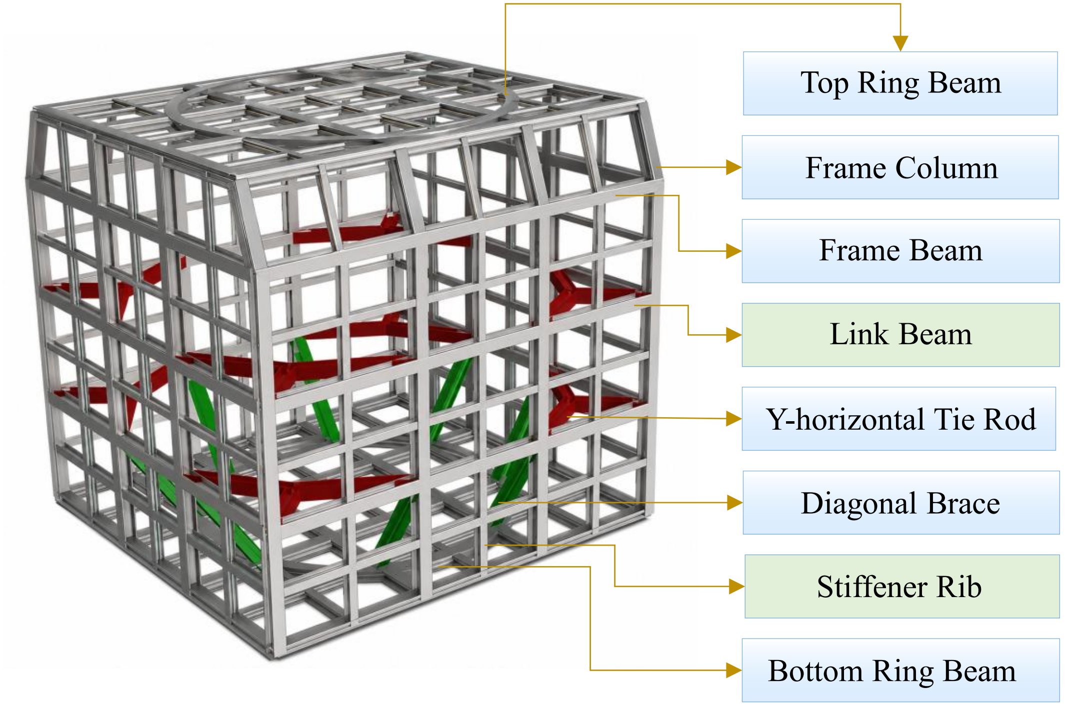
2.1 Steel Frame Structure and Loading Cases

Steel Frame Structural



Design Considerations

- Buoyancy effects: I-shaped steel members;
- Lateral water pressure : Diagonal braces and horizontal tie rods;
- Construction space： Member depth < 400 mm; Y-horizontal tie rod.

Loading Cases and Design Requirements

Hydrostatic Pressure: Buffer liquid induces lateral pressure; maximum at the bottom: 129.50 kPa

Equipment Load: Electronic equipment on the top : 2 kN/m^2

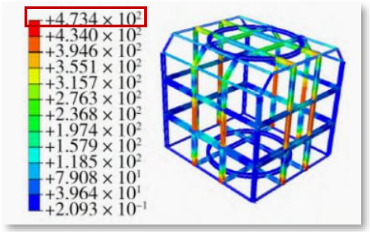
Acrylic Sphere: 14 ropes connect to the upper and lower ring beams; about 84 kN per rope

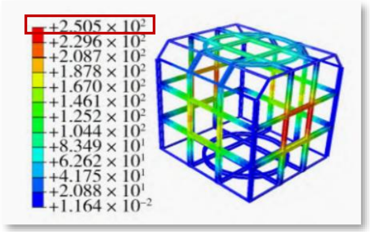
Design Requirement	Strength	Stiffness
Primary Members	415MPa	L/400
Secondary Members		L/250

2.2 Frame Optimization Analysis

Original Scheme

- ☐ No auxiliary load-carrying members
- ☐ 400×400×12×21





Critical Members

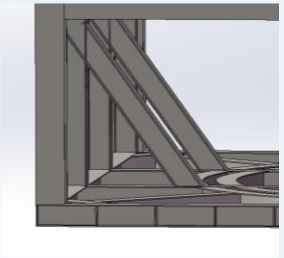
- ☐ Top central beam
- ☐ Link beam
- ☐ Middle column
- ☐ Bottom central beam

Maximum Stress
473.40 MPa

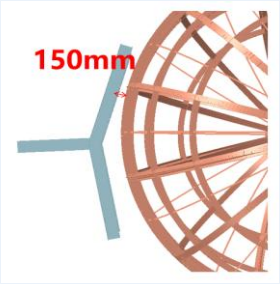
Maximum Deformation
250.50 mm

Optimization Measures

- ✓ **Diagonal braces**



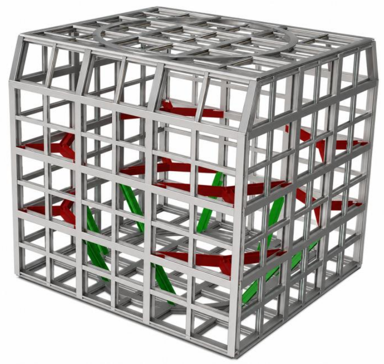
- ✓ **Y-horizontal tie rods**

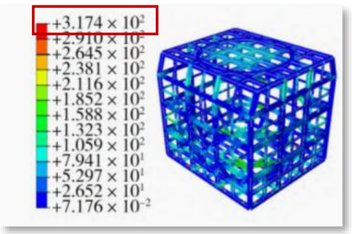


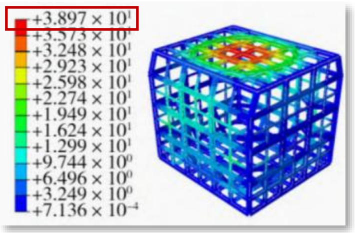
- ✓ **Adjust the sections of critical members**

- 400×450×13×21

Optimized Scheme







Strength Results of Critical Members

Frame	Member	Bending Moment M (kN · m)	Axial Force N (kN)	Section Strength (MPa)
Main frame	Top beam	458.23	—	108.53
	Link beam 1	380.61	663.29	115.90
	Link beam 2	450.35	563.42	128.60
	Edge column	27.51	150.54	14.87
	Middle column	280.41	401.84	100.37
	Bottom beam	533.60	—	155.47
	Ring beam	169.39	—	49.30
	Diagonal brace	146.65	794.81	79.60
	Horizontal tie rod	240.08	2800.23	200.52

Deflection Results of Critical Members

Frame	Member	Deflection (mm)	Code Limit (mm)
Main frame	Top beam	33.20	35.50
	Link beam	9.30	35.50
	Column	9.01	28.70
	Bottom beam	3.30	32.50

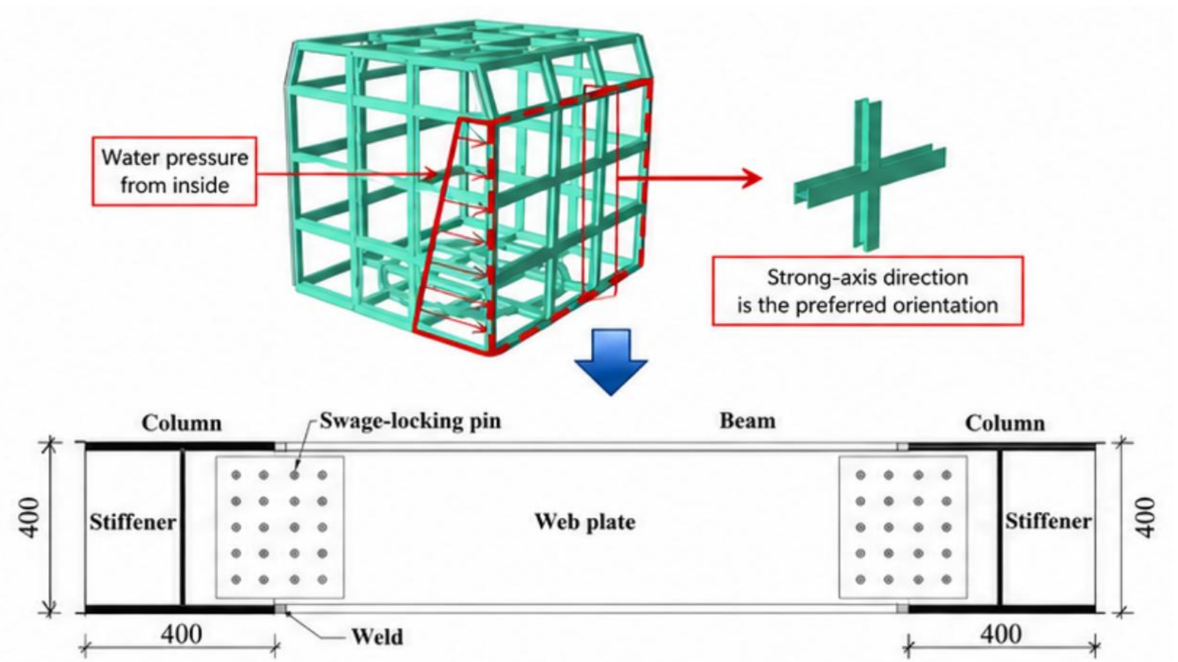
Maximum Stress
317.40 MPa

Maximum Deformation
33.20 mm

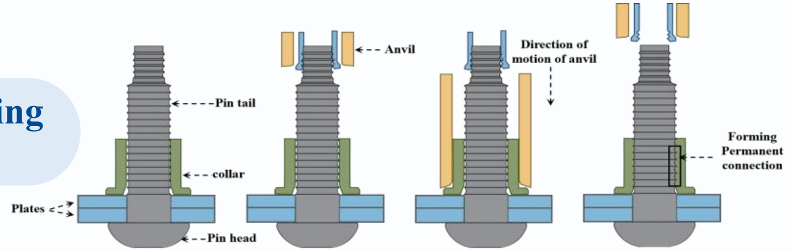
Both maximum stress and displacement are significantly reduced, satisfying the code requirements.

2.3 Joint connected with Swage-Locking Pin

Joint Detail



Swage-Locking Pin



Design Highlights

M20 stainless steel swage-locking pins

No galling/fast installation/ non-magnetic / corrosion resistant.

Water-tightness of the steel vessel

Beam-to-column outer flanges are welded to prevent leakage

Design Check

Design slip resistance of one M20 pin

$N_v^b{}_{,Rd} = 139.50$ kN

Maximum silp resistance on the key pin

$N_v^b{}_{,max} = 106.54$ kN

106.54 kN < 139.50 kN - Satisfactory

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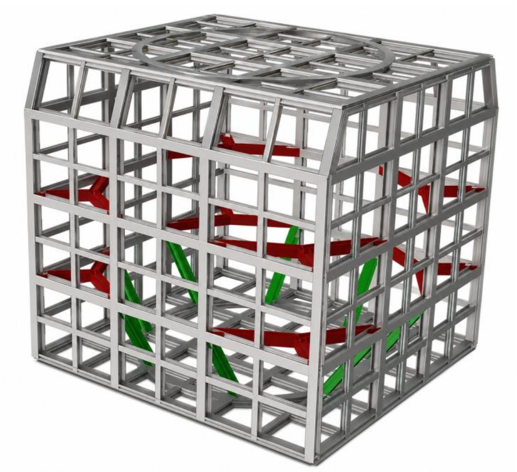
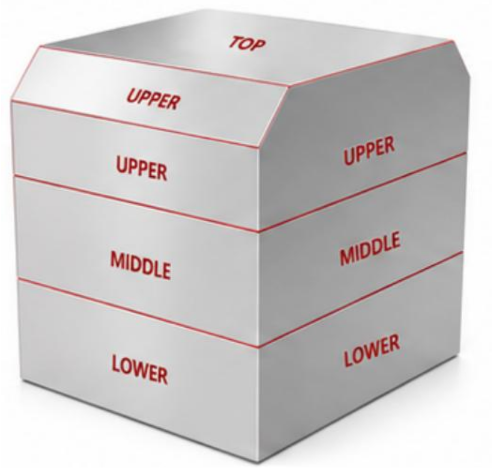
3.1 Stainless Steel Plate Design Requirements

Plate Configuration





Design Requirements

Welded Water-Tightness

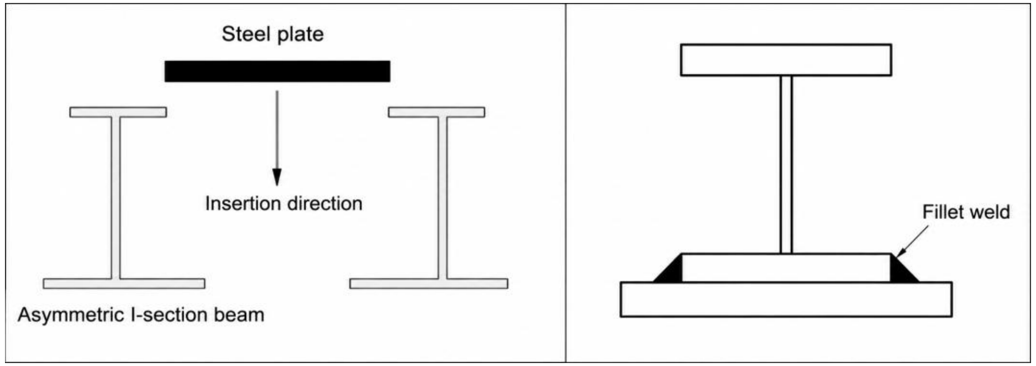
Plates are welded to the frame to form a steel vessel and prevent leakage

Steel Consumption

Stiffeners work together with the steel plates to resist lateral water pressure, enabling reduced plate thickness and lower steel consumption.

Residual Deformation

Stiffening density should be controlled to prevent welding-induced residual deformation.

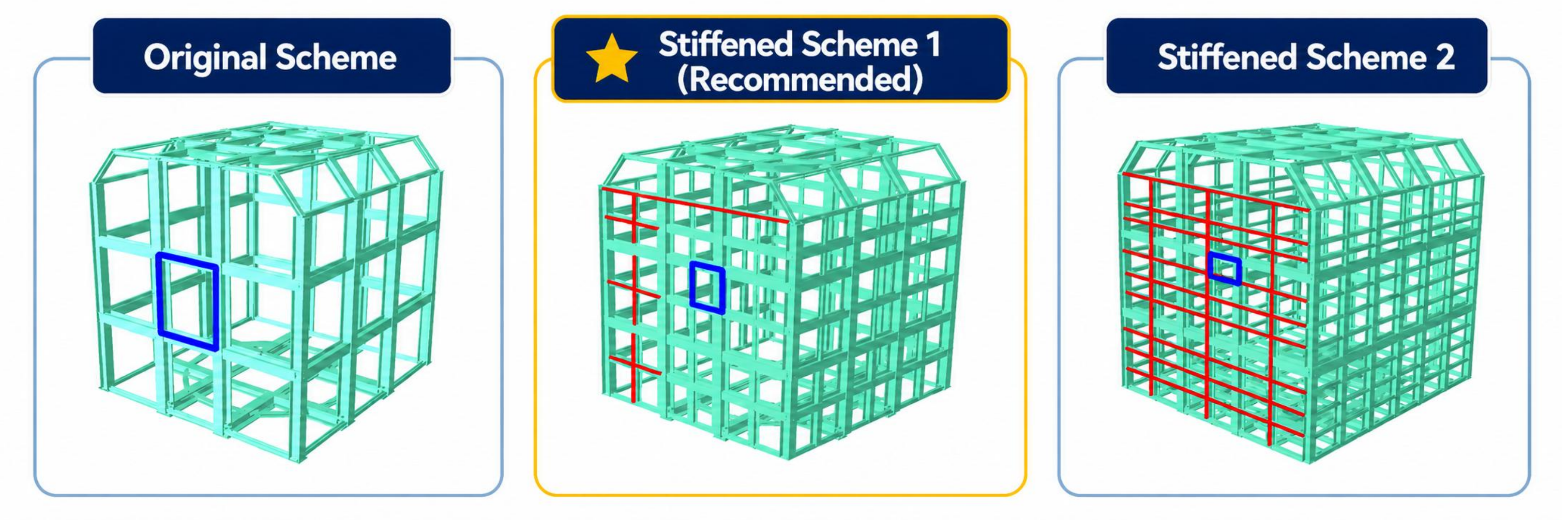


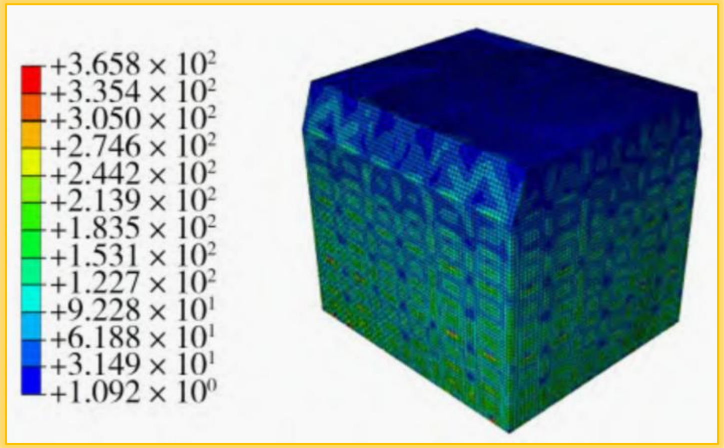
Design Control Targets

Strength Control	Member stress < 415 MPa
Stiffness Control	Stiffener limit < L/250
Design Goal	Satisfy structural requirements while reducing steel consumption

→ Balance

3.2 Comparison of Steel Plate Optimization Schemes





Comparison	Original Scheme	Stiffened Scheme 1 (Recommended)	Stiffened Scheme 2
Stiffening Layout	None	Cross stiffeners + frame beams	Further increased stiffeners
Plate Thickness (mm)	10-45	10-20	4
Steel Consumption (t)	277	186	158
Weld Length (m)	None	Moderate	Excessive

Maximum plate stress

365.80 MPa

<415 MPa

Meets the design requirement

Considering both stee consumption and the infuence of welding on plate, Stiffened Scheme1 is selected as the final plate scheme.

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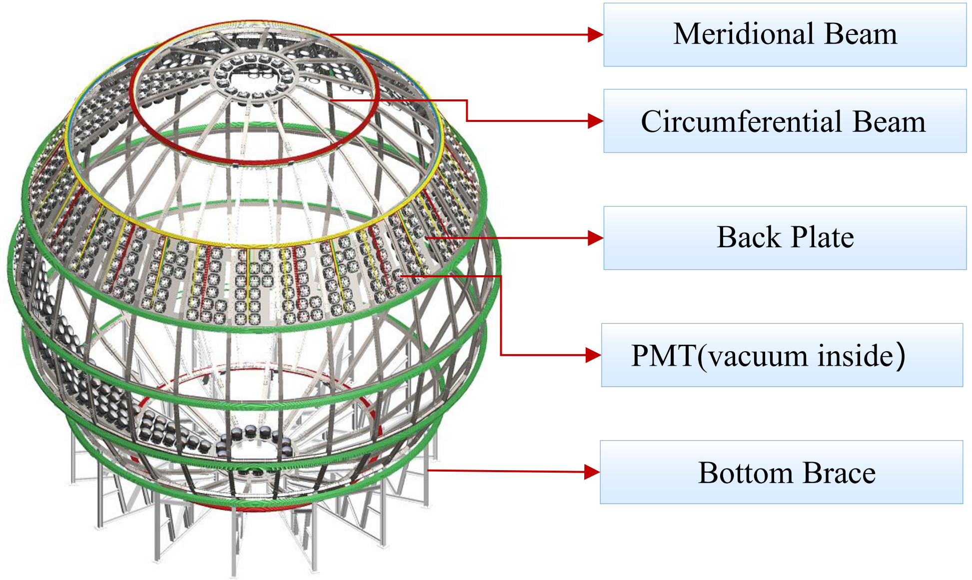
4.1 Spherical Shell Structure and Load Cases

Shell Structure

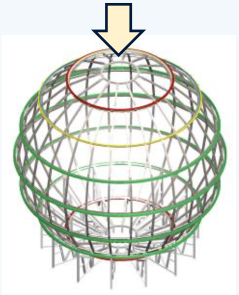


- Outer diameter: 12.06 m;
- 9 circumferential rings divide the shell into 8 layers;
- 14 meridional beams;
- 1.5m openings reserved at the top and bottom for liquid-replacement chimneys;
- PMTs are mounted on the back plates;
- The shell is supported by bottom diagonal braces.

Load Cases and Design Targets

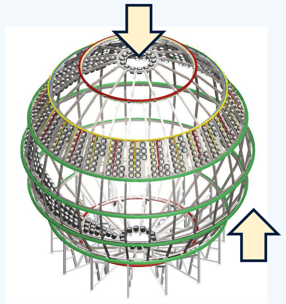
Without Buoyancy

- Before filling, the shell carries only self-weight



With Buoyancy

- After filling, many PMTs are in vacuum, so the shell is subject to buoyancy

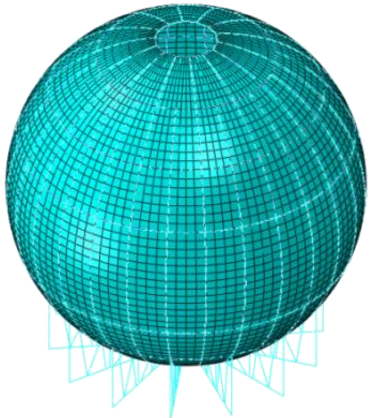


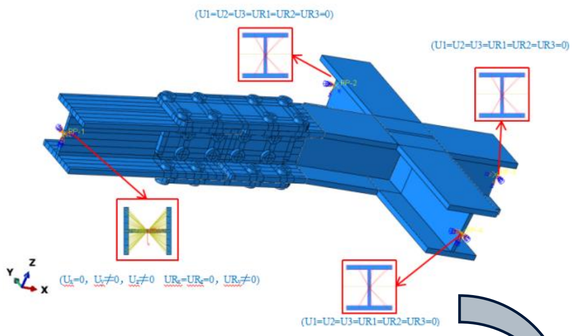
Design Targets

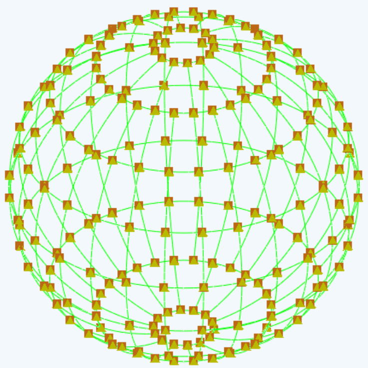
	Strength	Stiffness
Member Optimization	415 MPa	L/400
Nonlinear Stability	Mode factor>4.2; Load factor>2.0	

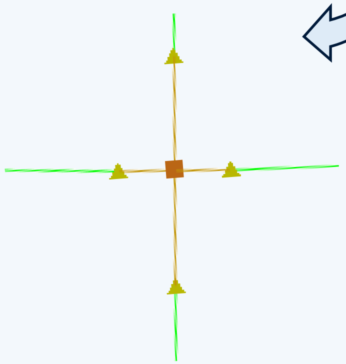
4.2 Numerical Model of Spherical Shell

FE Model


Global finite element model

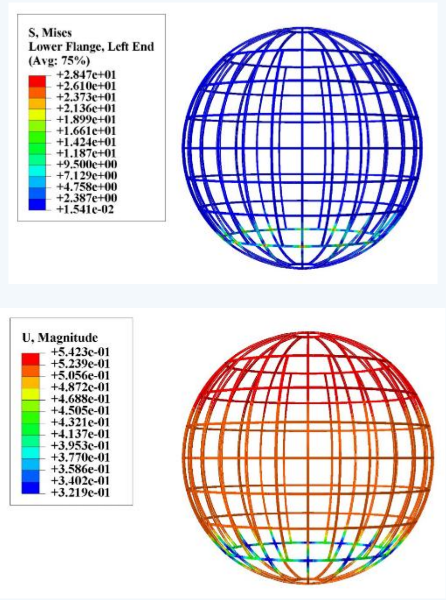

Joint configuration

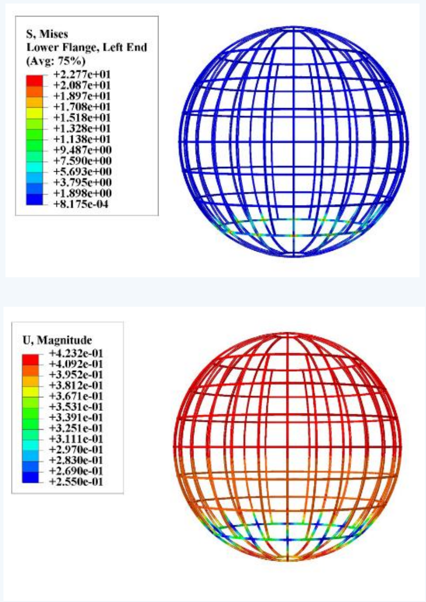

Simplified FE model


Semi-rigid connection modelling

Member Optimization Results

Without Buoyancy | With Buoyancy





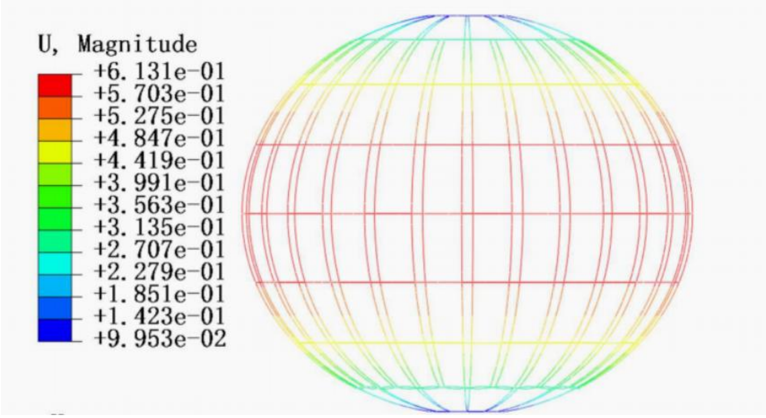
- A safe clearance is maintained between the reticulated shell and the acrylic spherical vessel, ensuring no physical contact.
- I-section members with a depth of 100 mm/Steel consumption: 22 t

Maximum Stress
28.47 MPa

Maximum Deformation
1.00 mm

4.3 Stability Analysis of the Spherical Shell

Linear Eigenvalue Buckling



The first buckling mode is dominated by overall flattening of the spherical shell.

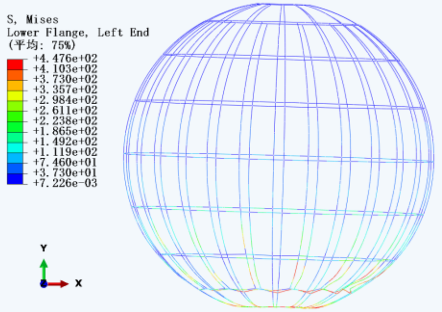
Case	Model factor	Peak LPF	Amplified Load/kN
Without Buoyancy	39.474	19.2759	198.16
With Buoyancy	47.647	19.415	199.59

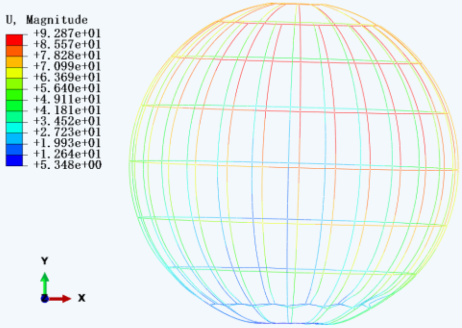
- ☐ The first-order buckling mode from eigenvalue analysis has a mode factor greater than 4.2.
- ☐ Buoyancy increases the critical buckling load.

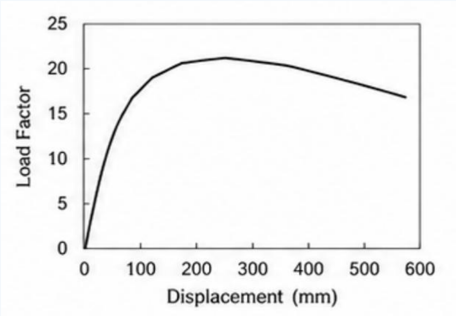
Initial Defect

Nonlinear Stability

Without buoyancy (unfavorable condition)







- **The maximum load factor reaches 21.05, greater than 2.0.**

➢ **The results satisfy JGJ 7-2010: Technical Specification for Space Grid Structures.**

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