

Structural design and mechanical properties analysis of the inter-supporting barrel yoke for the CEPC detector

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Abstract

Purpose: The barrel yoke of the Circular Electron-Positron Collider (CEPC) detector faces a condition in which the gravitational load of the internal sub-detectors exceeds its self-weight. Conventional polygonal staggered laminated barrel yoke structures struggle to meet the design requirements for stiffness, strength, and installation precision. This paper presents an inter-supporting barrel yoke structure and numerically assesses whether its mechanical performance and feasibility meet the design requirements.

Methods: An inter-supporting barrel yoke structure composed of 12 barrel yoke modules and 2 end flanges was designed. The end flanges serve the triple functions of structural reinforcement, assembly tooling, and precision datum. Based on the ANSYS finite element analysis software, static, modal, and seismic analyses were performed on both the conventional structure and the inter-supporting structures under the coupled action of self-weight, internal subdetectors' gravitational load, and electromagnetic force.

Results: Under the coupled action of the three loads, the optimized inter-supporting barrel yoke structure (with widened-bottom end flanges) achieves a maximum deformation of 1.8 mm (vs. 23.9 mm for the conventional structure), a maximum equivalent stress of 101.3 MPa (vs. 289.3 MPa for the conventional

structure), and a first-order natural frequency of 6.4 Hz (vs. 1.4 Hz for the conventional structure). Under seismic fortification intensity of Degree 8, the responses are also better than that of conventional structures. All mechanical performance indicators are significantly improved compared with the conventional structure.

Conclusion: The inter-supporting barrel yoke structure satisfies the design requirements of the CEPC detector in terms of stiffness, strength, dynamic stability, and seismic performance. Its installation scheme without an internal support frame is simple and efficient, and has a certain engineering feasibility basis.

Keywords: CEPC, Detector, Yoke, Inter-supporting, FEA

1 Introduction

The discovery of the Higgs boson [1, 2] has shifted the primary focus of particle physics towards the precise measurement of its properties, in pursuit of new physics beyond the Standard Model. Currently, the Large Hadron Collider (LHC) serves as the main facility for Higgs boson production. However, its proton-proton collision mechanism suffers from inherent drawbacks: the initial collision state is uncertain, and the background noise is extremely high. These factors render the vast majority of Higgs events unidentifiable, thus severely restricting the realization of precision measurement goals.

To address this challenge, researchers have proposed the Circular Electron-Positron Collider (CEPC) [3–5]. The CEPC adopts an electron-positron collision mode, which offers the advantages of a clear initial state and low background noise. Its design luminosity is three orders of magnitude higher than that of the Large Electron-Positron Collider (LEP) [5, 6], leading to a significantly enlarged detector system and imposing more stringent requirements on detector performance.

The overall layout of the CEPC detector is shown in Fig. 1, with the yoke being the outermost component. The main functions of the yoke are to provide a magnetic flux return path for the solenoid superconducting magnet, to support and fix the internal subdetectors and related components, to provide installation space for the muon detectors, and to absorb all particles except muons [7]. The yoke is divided into the barrel yoke and the endcap yokes, among which the barrel yoke provides the core supporting structure for the internal subdetectors and related components and is the most critical large-scale device in the detector [7, 8]. Existing detector barrel yokes (e.g., BESIII, Belle II, CMS) mostly adopt a steel plate stacking structure, with gaps reserved between laminations for installing muon detectors. However, the total weight of the internal subdetectors and related components of the CEPC detector reaches approximately 2145 t [9], exceeding the self-weight of the barrel yoke (approximately 1560 t). The self-weight of existing detector barrel yokes is invariably greater than their internal load; the two loading conditions are fundamentally different. Under such conditions, conventional barrel yoke structures face severe challenges in terms of stiffness and strength.

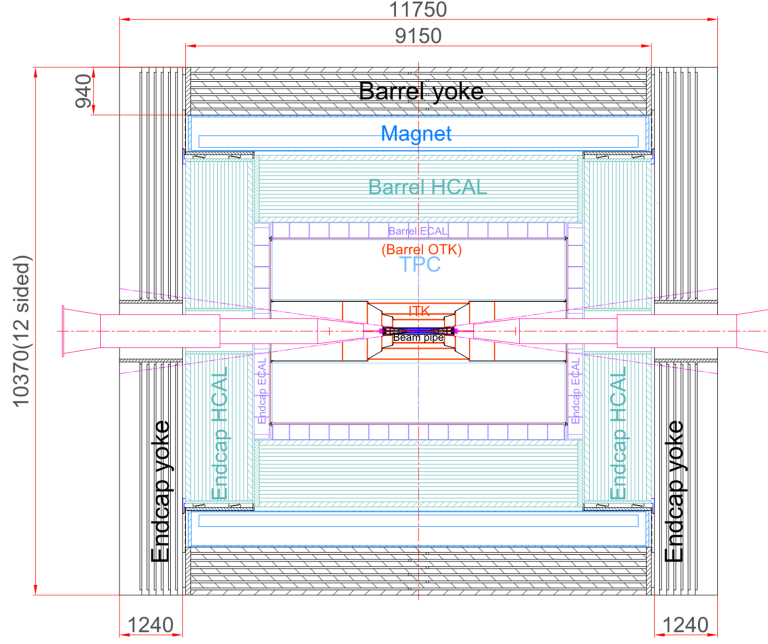


Fig. 1 Structural layout of the CEPC detector

To address the above issues, this paper proposes an inter-supporting barrel yoke structure from the perspective of mechanical structural design. The core design concept of this structure is as follows: end flanges are added at both ends of the barrel yoke modules, and through the synergistic mechanism of “the gravitational load of the modules is transferred to the end flanges, which provide support, thereby enabling the end flanges and modules to form a closed load-bearing frame,” inter-support among structural components is realized. The end flanges serve three functions: (1) as load-bearing structural components, they substantially enhance the overall stiffness and strength of the barrel yoke; (2) they replace the conventional internal support frame for installation, serving as tooling and precision datum for module assembly; (3) the flange structure can be further optimized to improve the stiffness and strength of the barrel yoke without affecting the module structure.

The organization of this paper is as follows: first, by investigating existing detector barrel yoke structures, the design requirements for the CEPC barrel yoke are distilled (Section 2); second, the structural design of the inter-supporting barrel yoke and the parametric study of the end flanges are presented (Section 3); then, the modeling methodology, parameter settings, and loading conditions of the finite element analysis (FEA) are systematically described (Section 4); finally, through static, modal, and seismic analyses, the mechanical performance of three barrel yoke configurations is compared (Section 5), and the research conclusions are summarized (Section 6).

2 Existing barrel yoke structures and design requirements for the CEPC barrel yoke

2.1 Overview of existing detector barrel yoke structures

Existing detectors that offer reference significance for the CEPC detector barrel yoke design mainly include BESIII [7, 8], Belle II [10], and CMS [11, 12]. The structural features, installation methods, and main issues of the three are summarized in Table 1. Fig. 2 shows the installation and structural details of the BESIII barrel yoke.

Table 1 Comparison of existing detector barrel yoke structures

	BESIII	Belle II	CMS
Number of modules	8 trapezoidal modules	8 trapezoidal modules	5 rings $\times$ 12-sided polygon
Barrel yoke weight (t)	~ 240	~ 608	~ 6000
Internal load weight (t)	~ 80	~ 268	~ 2000
Self-weight/internal load ratio	3.0	2.3	3.0
Installation method	Internal support frame	Internal support frame	Ferris-wheel-style internal support frame
Muon detector installation	Insertion from barrel yoke ends	Insertion from barrel yoke ends	Insertion from barrel yoke ends
Radial muon detection dead zone	Present at module connections	Present at module connections	Specially designed to avoid dead zones
Muon detector maintenance	Inconvenient (entrance blocked by cables)	Inconvenient (entrance blocked by cables)	Inconvenient (entrance blocked by cables)

From Table 1, three common characteristics and limitations of existing barrel yoke structures can be summarized:

1. Self-weight is consistently greater than the internal load. The self-weight-to-internal-load ratios of the BESIII, Belle II, and CMS barrel yokes are 3.0, 2.3, and 3.0, respectively. In contrast, the CEPC detector barrel yoke weighs approximately 1560 t, while the total weight of its internal subdetectors and related components is approximately 2145 t [9], yielding a self-weight-to-load ratio of approximately 0.73. It is the opposite of existing detectors. This means that the CEPC detector barrel yoke must support an internal load heavier than itself, imposing higher demands on its structural stiffness.
2. All adopt an internal support frame installation scheme. During installation, a temporary internal support frame is first erected, onto which the barrel yoke modules are assembled. After installation is completed, the frame is removed. This scheme has two drawbacks: first, the manufacturing cost of the internal support frame is high and the resource utilization rate is low; second, after the frame is removed, the upper part of the barrel yoke inevitably undergoes uncontrollable deformation due to gravity, compromising assembly precision.

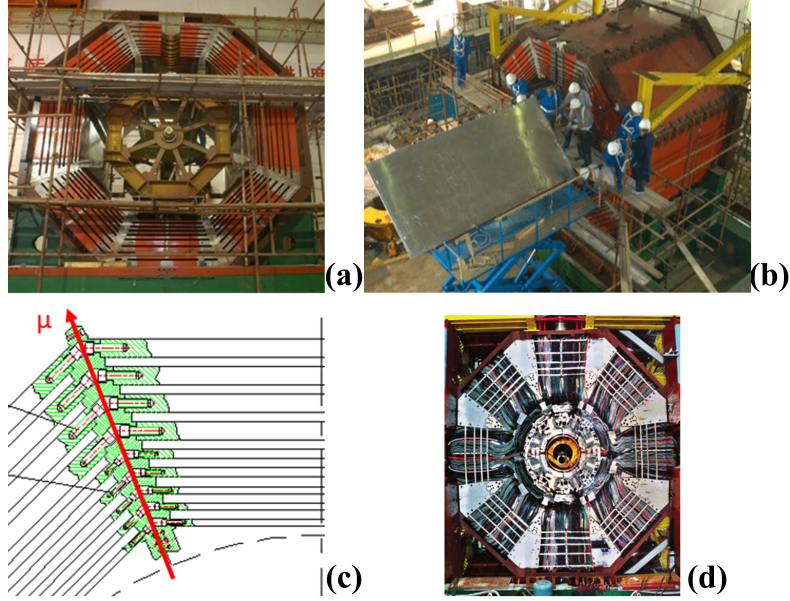


Fig. 2 Taking the BESIII barrel yoke as an example: (a) Installation of the BESIII barrel yoke; the yellow structure is the internal support frame, which must be removed after installation. (b) Barrel muon detectors of BESIII are inserted through the end entrances of the barrel yoke. (c) There are no muon detectors at the connections between BESIII barrel yoke modules; muons emitted through the connections cannot be detected, resulting in detection dead zones. (d) The installation entrances of the muon detectors are blocked by the cables of the internal subdetectors.

3. Maintenance of muon detectors is inconvenient. In existing schemes, all muon detectors are installed from the end entrances at both ends of the barrel yoke. After the full assembly of the detector, the cables of the internal subdetectors block the installation entrances of the muon detectors, making subsequent maintenance difficult.

2.2 Design requirements for the CEPC detector barrel yoke

Based on the above content and referring to the requirements for overall detector performance in the CEPC Conceptual Design Report [5] and the CEPC Reference Detector Technical Design Report [9], the barrel yoke should satisfy the following design requirements:

1. The dimensional tolerance of the barrel yoke inner boundary should satisfy $\pm 2\text{ mm}$ [9], thereby providing a reliable installation datum for the internal subdetectors. Under the coupled action of barrel yoke self-weight, internal load, and electromagnetic force, the maximum total deformation of the barrel yoke should be less than 2 mm to ensure the positional accuracy of the internal subdetectors.
2. The natural frequency of the barrel yoke should be far from the environmental excitation frequency band to avoid resonance risk. Seismic design shall be carried

out according to seismic fortification intensity Degree 8 in accordance with the Chinese Code for Seismic Design of Buildings (GB 50011-2010) [13].

3. The detection dead zone of the barrel muon detectors should be as small as possible. The connections between adjacent barrel yoke modules should be covered by muon detectors to ensure no detection dead zones at the connections. The installation entrances of the barrel muon detectors should be accessible during maintenance, enabling the maintenance of selected muon detectors without obstruction by other components.
4. The barrel yoke installation scheme should be simple, minimizing one-time-use assembly tooling to reduce tooling manufacturing costs and the impact of uncontrollable deformation caused by gravity after tooling removal.

3 Inter-supporting barrel yoke structure design

The CEPC detector barrel yoke is composed of 12 barrel yoke modules and 2 end flanges. This configuration is defined as the inter-supporting barrel yoke structure [9]. Its core concept is as follows: the modules and end flanges form a closed load-bearing frame. The majority of the gravitational load of the modules is transferred to the end flanges, which then transmit the load into the ground through their bottom supports. And the end flanges provide stable installation datum and constraint for the modules. The term “inter-supporting” originates from the mechanism of synergistic load-bearing between modules and end flanges.

3.1 Barrel yoke module

The barrel yoke adopts a modular design. The module structure and dimensional parameters are shown in Fig. 3 and Fig. 4. The material is carbon structural steel 10# (Chinese GB standard, equivalent to AISI 1010), which has already been used in the yoke structure of the BESIII [7]. This steel possesses both favorable mechanical properties and soft magnetic properties, satisfying the functional requirements of structural load bearing and magnetic flux return simultaneously.

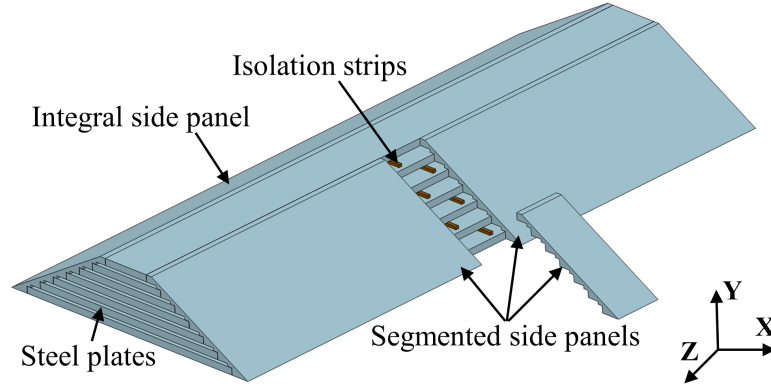


Fig. 3 Structure of the barrel yoke module

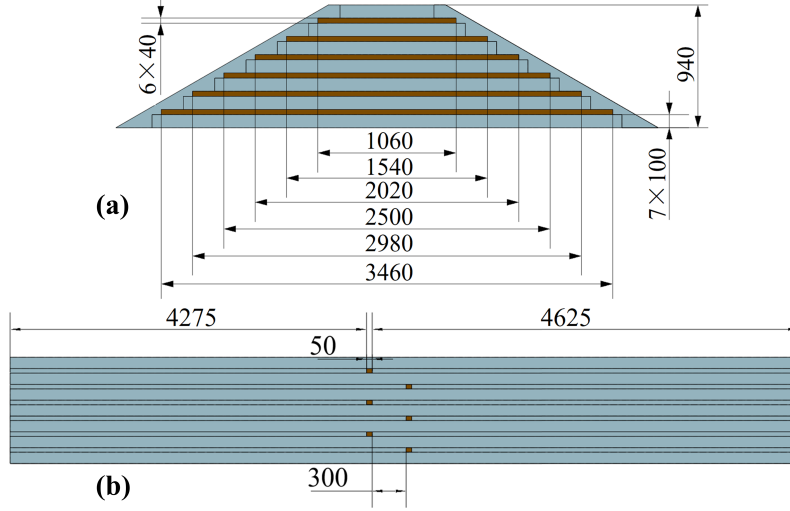


Fig. 4 Dimensional parameters of the barrel yoke module: (a) Z-direction view, (b) YZ-plane cross-sectional view

To meet the requirements of the solenoid superconducting magnet, the module is configured with 7 layers of steel plates from the inner to the outer side, each with a thickness of 100 mm. To satisfy the requirements of the barrel muon detectors, a 40 mm installation gap for muon detectors is reserved between steel plates, accommodating 6 layers of muon detectors. The installation space in each layer is divided into two sections by isolation strips, which avoids increasing the number of muon detector channels and reduces associated costs. The isolation strips also serve as structural stiffeners for the module, enhancing its strength. The width of the isolation strips is 50 mm. To avoid potential detection dead zones along the Z-axis, the isolation strips in each layer are arranged in a staggered manner, with an offset of 300 mm between adjacent layers, as shown in Fig. 4. In addition, the segmented side panels of the module adopt an openable design, enabling installation and maintenance of muon detectors from the side of the module; their cables can also be led out from the module side, alleviating the problem of blocked installation entrances encountered in existing schemes. The total thickness of the module is 940 mm, and the weight of a single module is approximately 130 t. The polygonal staggered laminated barrel yoke configuration (hereinafter referred to as Structure I) assembled from 12 modules has a total weight of approximately 1560 t, as shown in Fig. 5.

3.2 End flange

The end flange structure is shown in Fig. 6. The inner boundary is a regular dodecagon, and the outer boundary is an octagon, with the lower portion of the outer boundary extending to the flange bottom surface to form right-angle edges. Two end flanges are added, one at each end of Structure I, to form the inter-supporting barrel yoke structure shown in Fig. 6. (The structure composed of Structure I with end flanges having right-angle edges bottom is hereinafter referred to as Structure II.) To ensure

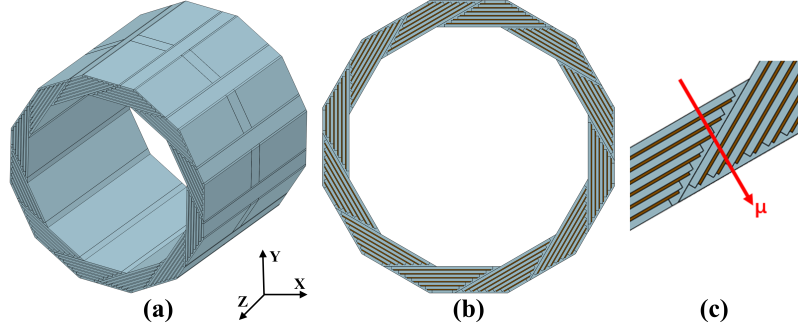


Fig. 5 Polygonal staggered laminated barrel yoke structure (Structure I): (a) and (b) are the isometric view and front view, respectively. (c) illustrates that the structure has muon detector coverage at the connections between adjacent modules, ensuring no detection dead zones at the connections.

the installation stability of the internal subdetectors and related components, the initial thickness of the end flanges is set to 100 mm [9]. The material is 10# steel, and the right-angle edges bottom design provides stable support for the structure.

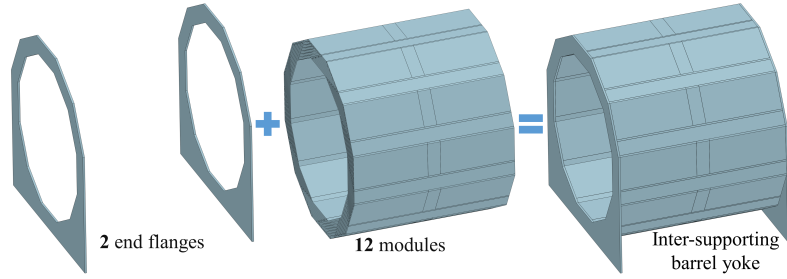


Fig. 6 Inter-supporting barrel yoke structure with end flanges having right-angle bottom edges (Structure II)

The end flanges bring three functions:

1. Acting as end constraints at both ends of the barrel yoke, the end flanges significantly enhance the overall stiffness and strength of the structure and effectively reduce the downward deformation of the barrel yoke top under gravity loading.
2. The end flanges can be directly used as assembly tooling. The two end flanges are first positioned and fixed to the ground, and then the 12 modules are installed one by one onto the flanges. This approach eliminates the internal support frame used in existing schemes, reduces tooling manufacturing costs, and the flanges remain permanently in the structure.
3. After installation of the end flanges, their positioning accuracy is ensured through collimation adjustment. The 12 modules are assembled using the positioning features on the flanges, ensuring the controllability of the overall assembly precision of the barrel yoke.

3.3 Parametric analysis of end flange

The barrel yoke modules have already satisfied the physical requirements of the muon detectors and the solenoid superconducting magnet, and their geometric configuration is constrained by the overall detector layout and is not suitable for substantial modification. Therefore, this section takes the end flanges as the object of study, investigating the influence of their thickness and bottom width on the overall mechanical performance of the barrel yoke structure.

First is the thickness analysis. Taking Structure II in Fig. 6 as the baseline, the external shape of the end flange is kept unchanged, and only the thickness t is used as the scanning parameter. t is incremented from the initial value of 100 mm in steps of 10 mm up to 200 mm. The upper limit of 200 mm is determined by the manufacturing cost constraint of rolled steel plates, and the lower limit of 100 mm is the baseline design of Structure II. At each thickness value, gravity load is applied to the barrel yoke, and the maximum deformation and maximum equivalent stress are recorded. The results are shown in Fig. 7.

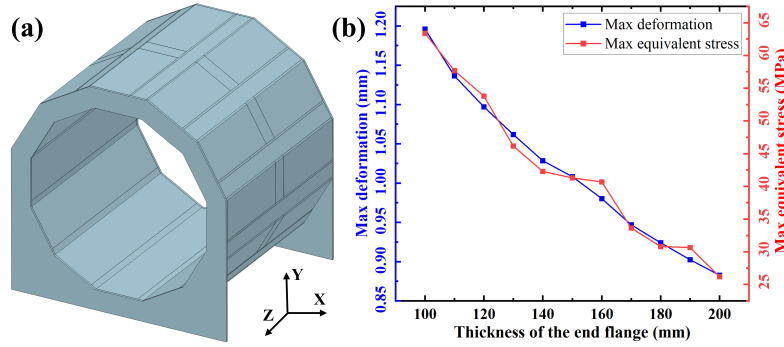


Fig. 7 (a) Structure II. (b) Under gravity loading, the maximum deformation and maximum equivalent stress of Structure II decrease gradually as the end flange thickness increases.

Next is the bottom width analysis. Keeping the end flange thickness constant at 100 mm, the bottom support width x is taken as the scanning parameter (as shown in Fig. 8). x is increased progressively from the corresponding width of Structure II (10.37 m). The upper limit is 15 m, determined by calculation based on the design installation width of the underground experimental hall for the CEPC reference detector [9]. An excessively wide bottom may cause interference between the structure and the equipment in the underground experimental hall. Gravity load analysis is performed at each width value, and the results are shown in Fig. 8.

From Fig. 7, it can be seen that when the end flange thickness increases from 100 mm to 200 mm, the maximum deformation of the barrel yoke decreases from approximately 1.2 mm to 0.9 mm, but the rate of reduction diminishes with increasing thickness. For every 0.1 mm reduction in deformation, the end flange mass increases by approximately 10.2 t. Doubling the thickness means a near doubling of material usage and manufacturing cost, while the deformation improves by only about 0.3 mm, yielding poor economic efficiency. Therefore, in the subsequent analyses, the

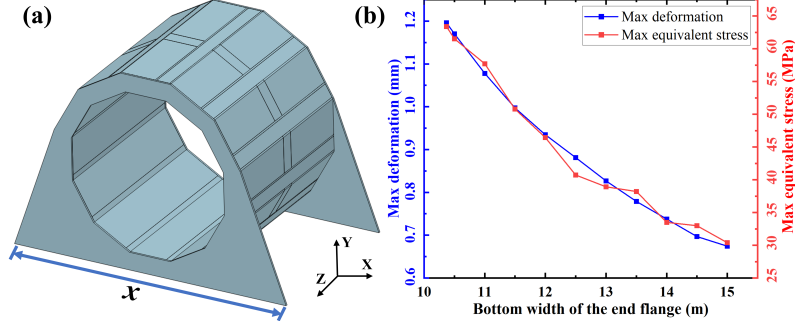


Fig. 8 (a) Inter-supporting barrel yoke structure with widened-bottom end flanges; the width x is 15 m in this figure (Structure III). (b) Under gravity loading, the maximum deformation and maximum equivalent stress of Structure III decrease gradually as the bottom width increases.

flange thickness is fixed at 100 mm. And this thickness also does not affect the overall Z-dimension of the CEPC detector.

Further observation of the influence of bottom width (Fig. 8) reveals that both the maximum deformation and the maximum equivalent stress decrease monotonically with increasing width, and for every 1 m increase in width, the maximum deformation can be reduced by approximately 0.1 mm. At this point, for every 0.1 mm reduction in deformation, the end flange mass increases by only approximately 2.6 t, far superior to the increment when merely increasing the flange thickness. This quantitative relationship provides a basis for the trade-off between space and performance in engineering design. The barrel yoke structure with widened-bottom end flanges shown in Fig. 8(a) is defined as Structure III, and will serve as the representative configuration of this structural type in subsequent sections for mechanical performance comparison with Structure I and Structure II.

4 Finite element analysis settings and loading conditions

This section focuses on describing the parameter settings and loading conditions of the finite element analysis. All analyses are performed using the ANSYS finite element analysis software. Simulation parameters and boundary conditions are kept consistent across all analysis cases to ensure the comparability of results.

4.1 Simulation parameters and boundary conditions

4.1.1 Material parameters and mesh

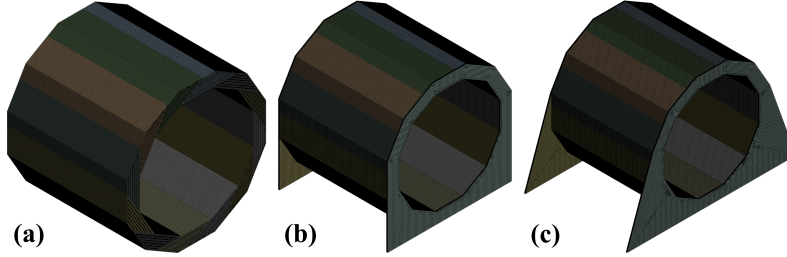
Both the barrel yoke modules and the end flanges are made of 10# steel. The detailed mechanical property parameters are listed in Table 2.

To balance computational accuracy and efficiency, the minimum mesh size of the finite element model is set to 50 mm. The mesh type is predominantly hexahedral,

Table 2 Material property parameters of 10# steel

Property	Value
Density	7850 kg m^{-3}
Elasticity modulus	206 GPa
Poisson's ratio	0.3
Tensile strength	335 MPa
Yield strength	205 MPa
Allowable stress	136.7 MPa

with tetrahedral elements used in some geometrically complex regions. The average mesh skewness is < 0.2 , and the average element quality is > 0.8 , satisfying the computational requirements. The generated meshes are shown in Fig. 9.

**Fig. 9** (a), (b), and (c) are the meshes of Structures I, II, and III, respectively

4.1.2 Contact and boundary conditions

In the actual working condition, all components of the barrel yoke structure are connected by bolts. If all bolted connection interfaces were modeled using a full nonlinear contact model, thousands of contact pairs would be involved, with the computational scale far exceeding the available hardware capacity and extremely difficult convergence. In the finite element analysis of such large-scale steel structures, adopting bonded contact simplification is an industry-standard practice. Similar simplification strategies have been employed in the literature on analogous large-scale scientific facilities, such as the CMS yoke [12] and the BESIII yoke [7]. Therefore, all contact pairs in this study are uniformly set as bonded contact.

Bonded contact also has certain limitations. The bonded contact assumption may overestimate the overall structural stiffness to some extent. Actual bolted connections under loading may result in slightly larger actual deformations and local stress peaks than the values calculated in this paper. However, since the three structures (I, II, and III) in this study adopt exactly the same contact simplification strategy, the systematic bias introduced by the contact assumption is effectively canceled out in the inter-structure comparison, and the relative ranking of structural performance and the optimization trends are not affected by the contact settings.

In the actual installation, the barrel yoke structure is mounted on a fixed base. The bottom surfaces of the end flanges and modules are fixed and restrained against horizontal displacement and rotation. Therefore, the bottom surfaces are set as fixed support constraints.

4.2 Loading conditions

The barrel yoke structure is subjected to three types of main loads under operating conditions. And to ensure operational safety, seismic effects should be considered in the design of the barrel yoke structure, seismic loads should be included in the analysis.

1. Self-weight load of the barrel yoke. The self-weight gravity load of the barrel yoke is applied by imposing gravitational acceleration on all structural components. The total weight of the barrel yoke ranges from approximately 1560 t (Structure I) to approximately 1635 t (Structure III).
2. Internal subdetectors and related component loads. The heavier internal subdetectors and related components [9] include: the solenoid superconducting magnet, barrel hadron calorimeter, endcap hadron calorimeter, barrel electromagnetic calorimeter, endcap electromagnetic calorimeter, and barrel muon detectors, with a total weight of approximately 2145 t. Lighter components such as the tracking detector are temporarily not included. To simplify the simulation, the 2145 t equivalent mass is distributed as follows: the 60 t barrel muon detector load is applied inside the 12 barrel yoke modules, while the 2085 t load of the internal subdetectors and related components is applied on the dodecagonal inner boundary of the end flanges.
3. Electromagnetic force load. The barrel yoke, serving as the magnetic flux return path for the solenoid superconducting magnet, experiences significant electromagnetic force loading after the magnet is energized. The design central field strength of the CEPC solenoid superconducting magnet is 3 T [14]. A one-twelfth magnet-yoke coupled electromagnetic model is established to calculate the electromagnetic body force density distribution throughout the yoke. The yoke material is assigned the nonlinear BH curve of 10# steel [15] to accurately simulate the magnetic field distribution. Details of the magnet-related parameters and the specific magnetic field distribution can be found in reference [9]. The computed electromagnetic body force density distribution is imported as a load into the static analysis, and solved in a coupled manner with the other two loads.
4. Seismic load. The seismic load is analyzed using the single-point response spectrum method. The seismic response spectrum is generated based on the seismic influence coefficient curve specified in the Chinese Code for Seismic Design of Buildings (GB 50011-2010) (seismic fortification intensity Degree 8, Site Class II, Design Earthquake Group 2) [13], with a damping ratio of 0.04. The response spectrum is loaded along the X, Y, and Z directions, respectively.

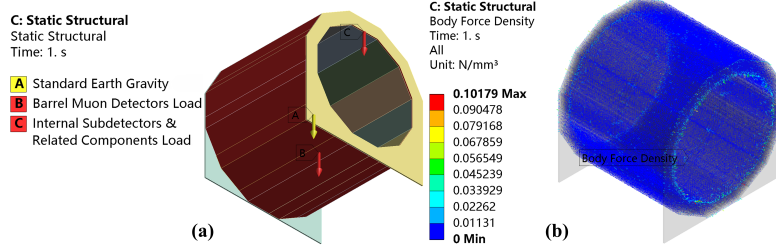


Fig. 10 (a) shows the gravity load and the load application positions of the internal subdetectors and related components. (b) Distribution of the electromagnetic body force density in the barrel yoke.

5 Mechanical properties analysis and discussion

In this section, static, modal, and seismic analyses are performed on three barrel yoke structures (Structure I, Structure II, and Structure III) and the effectiveness of the inter-supporting structure design is verified through comparison of results. The analysis workflow is as follows: in the static analysis, the three types of loads are applied, and the results are imported into the modal analysis as prestress conditions. After the modal analysis extracts the first six natural frequencies and mode shapes, the results are imported into the response spectrum module for seismic response calculation along the X, Y, and Z directions, respectively; the seismic responses are finally superposed with the static analysis results to obtain the total response under the seismic condition.

5.1 Static analysis

The static analysis examines the structural response under the coupled action of three loads which represents the maximum loading condition for the barrel yoke. The static analysis module is used, with the design targets of maximum deformation less than 2 mm and maximum equivalent stress less than the material allowable stress of 136.7 MPa. The static analysis results of the three structures are listed in Table 3. The total deformation and equivalent stress contour plots of Structure III are shown in Fig. 11.

Table 3 Static analysis results of the three barrel yoke structures

Structure	Max deformation (mm)	Max equivalent stress (MPa)
Structure I	23.9	289.3
Structure II	3.3	135.7
Structure III	1.8	101.3

The following conclusions can be drawn from Table 3:

1. Under the coupled action of the three loads, the maximum deformation of 23.9 mm and maximum equivalent stress of 289.3 MPa for Structure I both far exceed the design allowable values, indicating that the polygonal staggered laminated configuration cannot meet the stiffness and strength requirements of the CEPC detector.

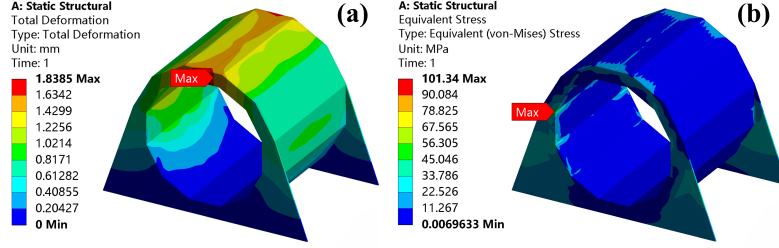


Fig. 11 Static analysis results of Structure III

The root cause of its failure lies in the following: lacking the constraint and support, the modules on the left and right sides at the bottom of the barrel yoke undergo significant bending deformation under the upper gravity loading, which in turn leads to large overall structural deformation and high stress.

2. Structure II, formed by merely adding end flanges with right-angle bottom edges (thickness 100 mm) to Structure I, reduces the maximum deformation sharply from 23.9 mm to 3.3 mm (a reduction of 86.2%) and the maximum equivalent stress from 289.3 MPa to 135.7 MPa (a reduction of 53.1%). This shows the pronounced enhancing effect of the end flanges on the stiffness and strength of the barrel yoke structure. The end flanges provide effective constraint and support, suppressing the bending deformation of the bottom modules. However, the maximum deformation of 3.3 mm still does not meet the design requirements.
3. Structure III, which further optimizes the end flange bottom width to 15 m on the basis of Structure II, reduces the maximum deformation to 1.8 mm and the maximum equivalent stress to 101.3 MPa. Both indicators satisfy the design requirements, and the equivalent stress retains a safety margin of 25.9%. This shows that by optimizing the end flange structure, the overall mechanical performance can be further enhanced without altering the barrel yoke module structure.

5.2 Modal analysis

Modal analysis is used to obtain the inherent dynamic characteristics of a structure. Modal properties, as intrinsic attributes of the structure, depend on its mass distribution and stiffness distribution. Considering that the barrel yoke undergoes significant stress stiffening effects under the three types of loads, its geometric stiffness cannot be neglected. Therefore, the modal analysis takes the static analysis results under the coupled three loads as the prestress condition to account for the effect of loading on structural stiffness.

The CEPC is planned to be constructed approximately 100 m underground [4, 5, 9]. The environmental excitation is dominated by extremely low frequencies, mainly underground micro-vibrations. The frequency range of conventional surface micro-vibrations is approximately between 0.1 and 5 Hz, while the micro-vibration frequencies at 100 m underground are even lower, with the overwhelming majority below 1 Hz. For a large-scale structure such as the barrel yoke, the first-order mode possesses the highest effective participating mass and the lowest natural frequency, making it the most prone to couple with external low-order excitation and trigger structural failure;

it is therefore the core indicator for evaluating dynamic stability. To avoid resonance, the first-order natural frequency of the barrel yoke structure must be far from this frequency band. The natural frequencies and mode shapes of the first six modes of the three structures are summarized in Table 4. The first-order mode shape contour plots are shown in Fig. 12.

Table 4 Summary of natural frequencies and mode shapes of the first six modes for the three structures

Mode	Structure I Freq. /Hz (Mode shape)	Structure II Freq. /Hz (Mode shape)	Structure III Freq. /Hz (Mode shape)
1	1.4 (X-axis sway)	4.3 (X-axis sway)	6.4 (X-axis sway)
2	3.2 (Z-axis sway)	9.5 (Y-axis pumping)	12.4 (Y-axis pumping)
3	3.8 (Y-axis pumping)	10.0 (Z-axis sway)	12.9 (Z-axis sway)
4	6.4 (Torsional, Y)	14.6 (Torsional, Y)	14.8 (Torsional, Y)
5	7.2 (Ovalizing shell, Z)	16.9 (Ovalizing shell, Z)	20.2 (Triangular shell, Z)
6	9.8 (Triangular shell, Z)	20.0 (Triangular shell, Z)	20.8 (Ovalizing shell, Z)

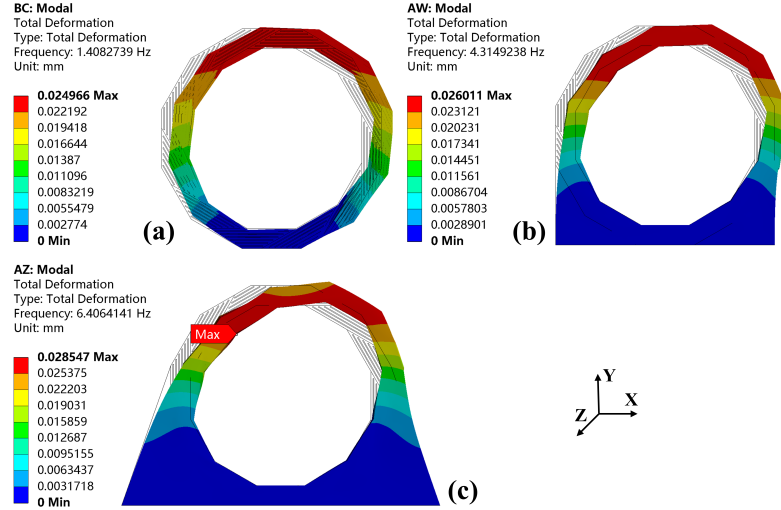


Fig. 12 First-order mode shape contour plots of the three barrel yoke structures. (a) Structure I, (b) Structure II, (c) Structure III. The first-order modal shapes for all three structures are X-axis sway modes.

The following conclusions can be drawn from Table 4 and Fig. 12:

1. From Structure I to Structure III, the first-order natural frequency gradually increases. The fundamental frequency of 1.4 Hz for Structure I is close to the environmental low-frequency excitation band, posing resonance risk. Structure II, by

adding end flanges, increases the fundamental frequency by 207%, successfully moving it away from the environmental excitation band. After Structure III further optimizes the flange bottom width, the fundamental frequency increases to 6.4 Hz. The overall elevation of frequencies across all modes indicates that the overall structural stiffness has been substantially strengthened, with a markedly improved safety margin.

2. The first mode shape of all three structures is X-axis translation, and torsional modes do not appear until the fourth order. This indicates that the lateral stiffness of the barrel yoke structure in the X direction is the weakest link in the overall dynamic performance and is also the critical controlling factor determining its fundamental frequency. In subsequent structural optimization design, the X-direction stiffness should be taken as the primary strengthening target.
3. Comparing the three structures reveals that after the end flanges are added in Structure II, not only is the overall frequency elevated, but the stiffness distribution relationship between the Y and Z directions is also altered. In Structure I, the Z-direction translational frequency is lower than the Y-direction pumping frequency, whereas in Structures II and III, the Y-direction pumping frequency surpasses the Z-direction translational frequency, indicating that the addition of flanges yields a more pronounced improvement in Y-direction vertical stiffness than in the Z-direction.
4. Observing the fifth and sixth higher-order modes, the ovalizing and triangular shell mode frequencies of Structure II are 16.9 Hz and 20.0 Hz, whereas Structure III elevates them to 20.2 Hz and 20.8 Hz, and the order of the two modes is swapped. This indicates that the optimization of the bottom width not only enhances the overall stiffness but also significantly improves the local shell deformation resistance, thereby enhancing the local stability of the structure.

5.3 Seismic analysis

Seismic analysis evaluates the structural response of the barrel yoke under the combined action of seismic load and static loads. The seismic load is analyzed using the single-point response spectrum method. The seismic response spectrum is generated based on the GB 50011-2010 code (seismic fortification intensity Degree 8, Site Class II, Design Earthquake Group 2, damping ratio 0.04), and the response spectrum curve is shown in Fig. 13. The response spectrum is loaded along the X, Y, and Z directions, respectively. The Square Root of the Sum of Squares (SRSS) method is used for modal combination, and the results are finally superposed with the static analysis results to obtain the total response under the seismic condition. The analysis results of the three structures under seismic response spectrum loading in each direction are listed in Table 5.

The following conclusions can be drawn from Table 5:

1. From Structure I to Structure III, the seismic performance achieves substantial improvement. Specifically, Structure II, by adding end flanges, reduces the maximum deformation in the X-direction sharply from 38.0 mm to 6.0 mm (a reduction

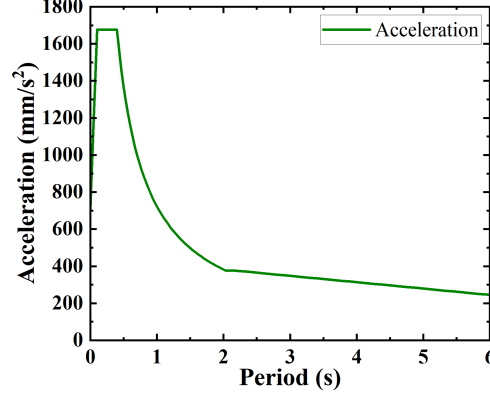


Fig. 13 Seismic response spectrum curve

Table 5 Maximum deformation ($D_{\max}$) and maximum equivalent stress ($\sigma_{\max}$) from seismic analysis of the three structures

Structure	X-axis		Y-axis		Z-axis	
	$D_{\max}$ (mm)	$\sigma_{\max}$ (MPa)	$D_{\max}$ (mm)	$\sigma_{\max}$ (MPa)	$D_{\max}$ (mm)	$\sigma_{\max}$ (MPa)
Structure I	38.0	376.6	27.6	321.7	27.8	292.9
Structure II	6.0	168.1	3.8	150.4	3.6	146.7
Structure III	3.1	128.8	2.1	114.2	2.1	110.3

of 84.2%) and the maximum equivalent stress from 376.6 MPa to 168.1 MPa. Structure III, after further optimizing the flange bottom width, reduces the X-direction deformation to 3.1 mm (a further reduction of 48.3% relative to Structure II) and the equivalent stress to 128.8 MPa. Overall, compared with the original Structure I, Structure III achieves deformation reductions of over 90% in all directions and a stress reduction of approximately 65%, with significant improvements in stiffness and strength.

2. For all three structures, the maximum response values under the X-direction seismic condition are consistently greater than those under the Y- and Z-directions. This is consistent with the conclusions from the aforementioned modal analysis, indicating that the X-direction is the weakest direction of the structure in terms of stiffness and is also the key optimization target for subsequent seismic design.

6 Conclusions

To satisfy the design requirements of the CEPC detector for the barrel yoke structure in terms of stiffness, strength, dynamic stability, seismic performance, and other aspects, this paper proposes an inter-supporting barrel yoke structure and verifies its mechanical performance and engineering feasibility through finite element analysis. The main conclusions are as follows:

1. The inter-supporting barrel yoke structure outperforms the conventional polygonal staggered laminated barrel yoke structure in mechanical performance. Under identical loading conditions and boundary constraints, Structure III (inter-supporting barrel yoke with end flange bottom widened to 15 m) achieves improvements over Structure I (polygonal staggered laminated barrel yoke) across all indicators in static, modal, and seismic analyses: the maximum deformation reduces from 23.9 mm to 1.8 mm (92.5% reduction), the maximum equivalent stress reduces from 289.3 MPa to 101.3 MPa (65.0% reduction), and the first-order natural frequency increases from 1.4 Hz to 6.4 Hz (357% increase), effectively avoiding potential resonance. All mechanical indicators of Structure III satisfy the design requirements of the CEPC detector.
2. The end flange is the core component of the inter-supporting structural system, serving the triple functions of load-bearing structural component, assembly tooling, and precision datum. This eliminates the need for a conventional internal support frame in the installation process, avoiding the uncontrollable gravity deformation problem that arises after the frame removal in conventional schemes.

In summary, the inter-supporting barrel yoke structure proposed in this paper satisfies the design requirements of the CEPC detector, showing the effectiveness and engineering feasibility basis of this structure. Future work will focus on further optimization of the barrel yoke structure, particularly topology optimization of the end flange and structural reinforcement along the X-axis.

Statements and Declarations

- Competing interests: The authors declare no competing interests.
- Data availability: The data that supports the findings of this study are available from the corresponding author upon reasonable request.

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