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COMPARATIVE FINITE ELEMENT ANALYSIS OF DOUBLE-BEVELED AND CONICAL BOROSILICATE WINDOWS

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Abstract

In this study, the structural behavior under pressure of double-beveled and conical hyperbaric window geometries modeled from borosilicate glass was examined comparatively. The window geometries were dimensioned according to the design principles defined in the ASME PVHO-1 standard, and the resulting models were analyzed using the finite element method under a test pressure of 1.65 MPaThe evaluation of structural behavior was based on the maximum total displacement (URES) and maximum principal stress (P1) results. The analyses revealed that the conical window geometry exhibited significantly lower displacement compared to the double-beveled geometry; however, the maximum principal stress values were found to be quite close for both geometries. Furthermore, it was observed that high principal stresses are locally concentrated in limited areas near the window–flange interface and geometric transition zones. The results obtained indicate that, under the conditions studied, the window geometry plays a decisive role, particularly in terms of deformation behavior, and that the conical geometry exhibits more favorable behavior than the double-beveled geometry in terms of limiting deformation.

Keywords: ASME PVHO-1, Borosilicate glass, Finite element method, Hyperbaric chamber, Window

INTRODUCTION

Hyperbaric chambers are manned pressurized systems that provide a controlled working and treatment environment at pressure levels above atmospheric pressure. Structural strength and safety are fundamental design requirements for these systems, which are used primarily for hyperbaric oxygen therapy, as well as for diving, decompression, and various underwater applications [1,2]. Transparent windows (portholes), which allow the interior of the cabin to be viewed from the outside, are critical structural components not only because they provide visibility but also because they form part of the pressure boundary [3].

The design principles for transparent windows used in pressurized vessels containing personnel are defined in the ASME PVHO-1 standard. Within the scope of the standard, window geometry, design pressure, temperature, dimensional ratios, and service conditions are evaluated collectively [4]. It is noted that, in the structural behavior of transparent pressure elements, window geometry and the thickness-to-opening ratio have a significant effect on stress distribution, deformation, and damage mechanisms [5,6]. For this reason, determining the effect of window geometry on mechanical behavior under pressure is important from a design perspective.

In addition to polymer-based materials commonly used in hyperbaric window applications, borosilicate glass is considered an alternative transparent material due to its high chemical resistance and thermal stability [7]. However, when borosilicate glass windows are chosen due to their brittle mechanical behavior, tensile stresses—and

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particularly the maximum principal stress—are of great importance. Geometric design also plays a decisive role in this behavior. A study examined the structural behavior of conical transparent windows under high pressure and demonstrated that conical geometry can be effective in controlling deformation behavior [8]. This situation makes it important to conduct a comparative evaluation of different window geometries under the same material and loading conditions.

In this study, the structural behavior of double-beveled and conical hyperbaric window geometries modeled from borosilicate glass was compared. To enable a direct evaluation of the geometric effect, the visible window diameter, window thickness, material properties, and loading conditions were kept the same in both models. The models, sized according to ASME PVHO-1 standards, were analyzed using the finite element method under a test pressure of 1.65 MPa, and the effects of geometric differences on the maximum total displacement (URES) and maximum principal stress (P1) were evaluated.

EXPOSITION

Borosilicate glass is used as an alternative to polymer-based materials in hyperbaric window applications. The most notable properties of this material are its higher surface hardness and dimensional stability compared to polymers. From a mechanical standpoint, borosilicate glass exhibits brittle behavior. When the elastic limit is exceeded, sudden fracture occurs without any yielding.

***Table 1**. Mechanical and thermal properties of borosilicate glass*

Property	Value
Elastic Modulus	64000 MPa
Poisson's Ratio	0.20
Shear Modulus	26700 MPa
Mass Density	2230 kg/m^3
Tensile Strength	40 MPa
Compressive Strength	800 MPa
Yield Strength	40 MPa
Thermal Conductivity	0.2256 W/(m.K)
Specific Heat	1386 J/(kg.K)

An examination of the data presented in Table 1 reveals that the compressive strength of borosilicate glass is significantly higher than its tensile strength. This difference indicates that the material exhibits more favorable behavior under compressive loads. However, the fact that the yield and tensile strength values are the same reveals the material's brittle nature, which can result in sudden fracture and damage once the elastic limit is exceeded without entering a ductile region.

MATERIAL AND METHOD

The window geometries examined in this study were dimensioned not only for visual modeling purposes but also by taking into account the design principles and safety limits defined in the ASME PVHO-1 standard. The design of transparent windows in hyperbaric systems is carried out by jointly evaluating material behavior, loading conditions, and the empirical calculation methods provided in the standard. In this context, the geometric modeling process has been developed in accordance with the safety criteria of the relevant standard.

In the sizing process according to the PVHO-1 standard, the Conversion Factor (CF)—which represents the material's temperature-dependent behavior—and the Short-Term Critical Pressure (STCP)—which determines the material's strength limit—were used as the basis. The window thickness (t) and other geometric parameters were determined based on data obtained from the design charts provided in the standard. As a result of these calculations, the required strength values for each window type (double-beveled and conical) were obtained, and three-dimensional (3D) solid models were created based on these values. To compare the performance of different window geometries, key parameters of the models—such as the visible opening diameter (Di = 300 mm)—were kept constant. In contrast, the window thickness and chamfer angles were customized according to the design characteristics required by the geometric type. Thanks to

this approach, the stress distribution and displacement behavior of different geometries under pressure were examined comparatively.

Design Calculations According to the PVHO-I Standard

The window sizing process is based on the empirical methods specified in the ASME PVHO-1 standard. In this context, the design pressure is considered the primary parameter in determining safe operating limits. The design pressure represents the maximum safe pressure to which the system may be subjected under continuous operating conditions. It serves as the basis for sizing procedures in accordance with the PVHO-1 standard [4]. Accordingly, the operating pressure has been set at 10 bar (1.0 MPa), and the design pressures have been set at 11 bar (1.1 MPa), taking the safety factor into account.

Short-Term Critical Pressure (STCP) and Calculation Methodology

In the PVHO-1 standard, one of the key parameters used in the design of transparent windows is defined as Short-Term Critical Pressure (STCP). The STCP value represents the maximum pressure that the window can withstand under short-term loading conditions. In cases where experimental data is not available, the STCP value is determined using the following equation.

$$STCP = CF * P \quad (1)$$

Conversion Factor

In the PVHO-1 standard, one of the fundamental parameters used in the design of transparent windows is defined as the conversion factor (CF). The CF value is a coefficient that expresses the relationship between the design pressure (P) and the short-term critical pressure (STCP), and it varies depending on the window's geometric shape and material type. Values for this parameter are presented in tables in the standard, based on empirical data for different window geometries. The CF values for the double-beveled and conical porthole geometries examined in this study were taken from Table 2.

Table 2. *Conversion factors for conical and double-beveled windows*

Operational Pressure Ranges	Temperature, °F (°C)				
	50 (10)	75 (24)	100 (38)	125 (52)	150 (66)
N= 1 2,500 psi (17.2 MPa)	CF = 5	CF = 6	CF = 8	CF= 10	C= 16
N= 2 5,000 psi (34.5 MPa)	Conversion factors for these pressures shall be interpolated between the upper and lower values shown.				4,500 psi (31 MPa)
	CF = 4	CF = 5	CF = 7	CF= 9	
N= 3 7,500 psi (51.7 MPa)	CF = 4	CF = 5			
N= 4 10,000 psi (69 MPa)	CF = 4	CF = 5 ….	8,000 psi (55.2 MPa)		

In the PVHO-1 standard, Conversion Factor (CF) values depend not only on the window geometry but also on the operating temperature of the material. Considering the applications of hyperbaric systems in Europe, it is a common practice to use upper limit temperature values in the design. For this reason, the value of 38 °C (100 °F) has been chosen both because it represents the operating conditions accepted in the literature and to err on the side of safetyThis value is considered a typical upper limit representing in-chamber operating conditions in hyperbaric oxygen therapy (HBOT) applications [2].

The PVHO-1 standard recommends that environmental effects and time-dependent deformation of the material be taken into account in the design of transparent windows [4]. Accordingly, to ensure operational safety and account for potential changes in material behavior, a CF value of 8 was selected for all window geometries in accordance with Table 3. This selection demonstrates that a safety-focused approach was adopted in the design.

Short-Term Critical Pressure (STCP)

One of the key parameters used to determine the pressure resistance of transparent windows in the PVHO-1 standard is defined as the short-term critical pressure (STCP). The STCP value represents the maximum pressure a window can withstand under short-term loading. This parameter is used as an important criterion, particularly in evaluating the behavior of acrylic and similar polymer-based transparent materials under pressure [4]. In cases where experimental data are not available, the STCP value is calculated using the equation provided in the section titled "Short-Term Critical Pressure (STCP) and Calculation Methodology." For a pressure of 11 bar (1.1 MPa) and both porthole geometries:

STCP=8x11=88 bar

is calculated. These calculated values are independent of the material. As long as the temperature remains constant, STCP values vary only as a function of the design pressure. The test pressures, however, were used as loading conditions in finite element analyses rather than in sizing calculations.

Thickness-to-Inner Diameter (t/Di) Ratio and Sizing

After determining the STCP value, the charts provided in the standard are used to calculate the required window thickness. These charts are used to obtain the thickness-to-diameter ratio (t/Di) corresponding to the short-term critical pressure. This ratio is then correlated with the window's apparent diameter (Di) to calculate the required minimum thickness.

Double-Beveled Window Sizing

To evaluate the effect of the two-step transition in the edge regions of double-glazed windows on stress distribution, the sizing calculations were performed using the graph shown in Fig. 1.

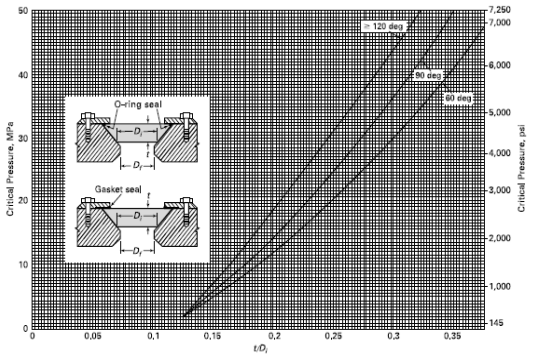


***Fig. 1**. Short-term critical pressure of double-glazed and conical windows*

The double-bevel design helps the window fit more securely into the frame. In this study, a 90° chamfer angle was adopted in the design of the double-chamfered model for the sake of consistency and safety. This angle was selected to limit the window's axial movement within the frame under pressure loads, reduce stress concentrations in the edge regions, and ensure greater stability of the sealing surface. For a design pressure of 11 bar, the t/Di ratio read from the graph corresponding to the target STCP value of 88 bar was determined to be 0.1825, and the window thickness was modeled as 54.75 mm.

Conical Window Sizing

Conical windows are one of the preferred geometries in high-pressure hyperbaric systems, as they are able to transfer the pressure load to the socket over a wider surface area. The design curves shown in Fig. 1, which are also used for double-beveled windows, have been taken as the basis for the dimensioning of this geometry.

In the calculations based on the graphs, a 90° bevel angle was selected as the design parameter. This angle helps to transfer the pressure load to the frame more evenly and ensures that the window sits more securely in the frame. It also helps to limit any deformation that may occur under high pressure. As a result of the calculations, the t/Di ratios read from the 90° curve and the corresponding window thicknesses were determined for a design pressure of 1.1 MPa.

For a design pressure of 1.1 MPa, the t/Di ratio was determined from the graph to be 0.1825, corresponding to the target STCP value of 88 bar, and the window thickness was modelled as 54.75 mm.

Finite Element Model and Mesh Structure

This section describes a mesh convergence study conducted to evaluate the effect of the mesh structure used in numerical analyses on the results. Mesh convergence analyses were performed separately for each window geometry and loading condition. In this process, a coarser mesh structure was initially created, and the analyses were then repeated while gradually reducing the maximum element size. Convergence was assessed when the difference between the results obtained from successive mesh configurations fell below a certain threshold.

For each mesh configuration, the maximum displacement and principal stress values were evaluated. The solution was considered to have converged when the difference between the results obtained from successive mesh configurations decreased and the results stabilized at a certain level. [9, 10]. Mesh convergence studies were conducted separately for double-beveled and conical window geometries at pressure levels of 1.65 MPa.

To evaluate the sensitivity of the finite element model to mesh density and to verify that the solution had become sufficiently independent of element size, separate mesh convergence studies were performed for the conical and double-beveled window geometries. For each geometry, the element size was gradually reduced in the critical contact and chamfer regions where high stress gradients occur, and the maximum stress values obtained at different mesh densities were compared. The element size at which the variation in maximum stress between successive mesh densities fell below the specified acceptance limit was determined as the optimal mesh structure by jointly evaluating solution stability and computational cost. The specified mesh structure, geometric model, boundary conditions, and load and contact definitions were retained for use in the final analyses.

The optimal mesh structure was determined by considering both the stability of the results obtained through mesh refinement and the computational cost. As a result of this evaluation, a mesh structure with element sizes ranging from a maximum of 6 mm to a minimum of 3 mm was used in the final analyses.

Boundary Conditions and Loading Conditions

In this study, a pressure level of 1.65 MPa was adopted to enable a comparison of the structural behavior of window geometries under more critical loading conditions. In this context, three different pressure values were considered: operating pressure, design pressure, and test pressure. The operating pressure refers to the system's normal operating pressure. In this study, the operating pressure was set at 10 bar (1.0 MPa). The design pressure has been set at 11 bar (1.1 MPa), taking into account a 10% margin above the operating pressure. Window thicknesses were calculated using these values in accordance with the PVHO-1 standard. The test pressure is the highest pressure value used to verify the system's strength. This value was set at 16.5 bar (1.65 MPa), which is 1.5 times the design pressure. Finite element analyses were also performed using these test pressure values.

Evaluation of Analysis Results for the Double-Beveled Window Geometry

The analysis results for borosilicate glass with a double-beveled window geometry under a pressure of 1.65 MPa are detailed below. The analyses were evaluated based on the maximum displacement (URES) and maximum principal stress (P1) parameters.

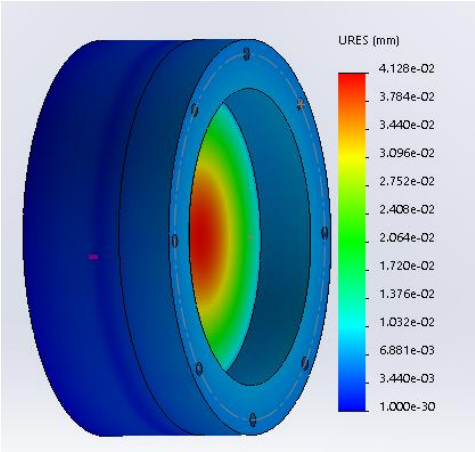


***Fig. 2**. Displacement results for a borosilicate glass double-beveled window geometry under a pressure of 1.65 MPa*

The total displacement distribution of the borosilicate glass window with a double-beveled design under a pressure of 1.65 MPa is shown in Fig. 2. As a result of the analysis, the maximum displacement was determined to be 0.04128 mm. It can be seen that the deformation is concentrated in the central region of the window and decreases significantly toward the edges and contact areas.

The gradual decrease in the displacement distribution from the center toward the periphery indicates that the load is transferred symmetrically for this window geometry and window material configuration. The fact that displacement values remain low in the edge regions demonstrates that the boundary conditions result in stiffer behavior in these regions, as expected.

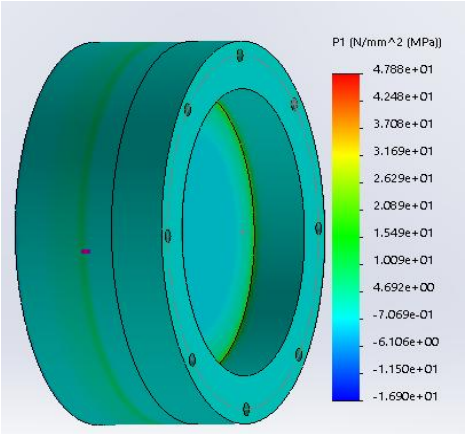


***Fig. 3.** Result of the principal stress for a borosilicate glass double-beveled window geometry under a pressure of 1.65 MPa*

An examination of Fig. 3 reveals that the maximum principal stress (P1) value for borosilicate glass under a pressure of 1.65 MPa reaches approximately 47.9 MPa. It is evident that the stress does not spread across the entire surface but occurs locally at the window–flange interface and in the geometric transition zone. In the visible load-bearing portion of the window, stress levels are largely distributed within the range of 20–25 MPa. This indicates that the maximum P1 value represents a local peak stress resulting from contact conditions, and that the structure's overall stress behavior must be evaluated in conjunction with the stress contours.

Evaluation of Analysis Results for the Conical Window Geometry

This section presents the analysis results for borosilicate glass under a pressure of 1.65 MPa, focusing on the geometry of a conical window. The analysis examines total deformation (URES) and maximum principal stress (P1) in detail.

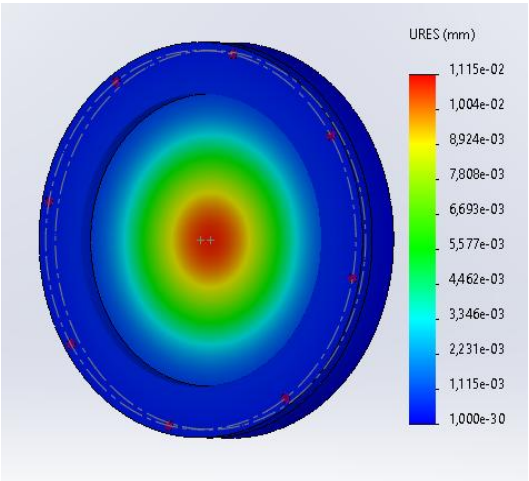


***Fig. 4**. Displacement results for a borosilicate glass conical window geometry under a pressure of 1.65 MPa*

As shown in Fig. 4, the total displacement in the borosilicate glass window under an internal pressure load of 1.65 MPa was determined to be approximately 0.011 mm. Upon examining the color scale representing the displacement results, it can be seen that, as expected, the maximum displacement occurred in the exact center of the window

and that this value rapidly decreased toward the edges, approaching zero. Given the high elastic modulus of borosilicate glass, the low deformation values obtained indicate that the material exhibits rigid behavior.

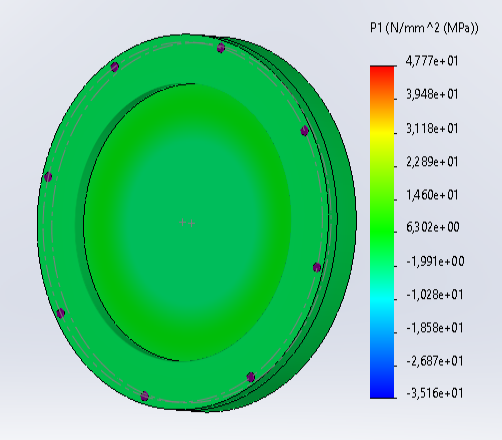


Fig. 5. *Result of the principal stress for the geometry of a borosilicate glass conical window under a pressure of 1.65 MPa*

Upon examining the distribution of the maximum principal stress (P1) shown in Fig. 5, it can be observed that the tensile stress values generally remain at low levels and exhibit a homogeneous distribution across a large portion of the window. Although the analysis indicates that the maximum tensile stress is approximately 48 MPa, an evaluation of the stress distribution and color scale together reveals that the principal stress values vary between 5 and 15 MPa across the entire window surface. While lower and relatively homogeneous stress levels develop in the central region of the window, it is observed that stress gradients increase as one approaches the edges and contact areas. This behavior is attributed to the transfer of the load caused by internal pressure from the center of the window to its periphery and, from there, to the supporting structure via the contact surfaces. Restrictions on movement and the presence of geometric transitions in the contact zones lead to the formation of local stress concentrations in these areas. Consequently, while the maximum P1 value of 47.77 MPa represents a local peak value, the window's overall stress behavior is characterized by lower principal stress levels.

Geometrical Comparison

In this section, the structural behavior of double-beveled and conical window geometries analyzed under the same window material and loading conditions is compared. To determine the geometric effect, the results for maximum total displacement (URES) and maximum principal stress (P1) were evaluated together. Since borosilicate glass was used as the material and an internal pressure of 1.65 MPa was applied in both models, the differences in the results primarily highlight the effect of window geometry on structural behavior.

Table 3*. A Comparison of the Structural Performance of Double-Chamfered and Conical Window Geometries Under 1.65 MPa Pressure*

Parameters	Doubled Bevel	Conical	Percentage Change (%)
Maximum Displacement (URES)	0,04128 mm	0,01110 mm	-73,11
Maximum Principal Stress (1st Principal)	47,88 MPa	47,77 MPa	-0,23
Overall Principal Stress Distribution	20-25 MPa	5-15 MPa	Lower in the conical geometry

An examination of Table 3 reveals that the most pronounced effect of the geometric difference is evident in the total displacement values. The maximum total displacement, determined to be 0.04128 mm for the double-beveled window geometry, decreased to 0.01110 mm for the conical geometry. When using the double-bevel geometry as a reference, this change corresponds to a reduction of approximately 73.1% in maximum displacement. Since the material properties, window thickness, apparent diameter, and applied pressure are the same for both models, it is clear that this significant difference in displacement is primarily due to the geometric structure.

The sloped surface structure of the

conical geometry alters the manner in which the pressure load is transferred between the window and the supporting region and increases the window's geometric stiffness against deformation. In contrast, the more pronounced bending behavior in the central region of the double-beveled geometry's transition structure results in higher displacement values. These results show that the conical geometry offers a distinct advantage over the double-beveled geometry in terms of limiting deformation under the loading conditions examined.

However, when comparing the maximum principal stress results, it is evident that the difference between the geometries is quite limited. The maximum principal stress, determined to be 47.88 MPa for the double-beveled geometry, was obtained as 47.77 MPa for the conical geometry. The approximate 0.23% difference between these values indicates that the effect of geometric variation on the maximum principal stress value is quite limited compared to that of displacement.

However, upon examining the stress contours of both models, it is observed that these maximum values do not represent the overall stress level of the window; rather, high principal stresses are locally concentrated in limited areas near the window–flange interface and geometric transition zones. In a large portion of the window, however, the principal stress levels are lower than the maximum peak values. Therefore, when evaluating the structural behavior of these geometries, it is necessary to consider not only the maximum principal stress values but also the stress distribution and the overall displacement behavior.

Although the maximum principal stress values are quite close to one another, a closer examination of the stress contours reveals a distinct difference in the overall stress distribution among the geometries. While the principal stresses in the visible load-bearing region of the double-beveled geometry were largely distributed in the range of 20–25 MPa, it was determined that these values remained in the range of approximately 5–15 MPa across a large portion of the conical geometry. This indicates that, despite a limited difference of approximately 0.23% in the maximum principal stress values, the conical geometry results in lower principal stress levels across the entire window.

CONCLUSION

In this study, the structural behavior of double-beveled and conical hyperbaric window geometries modeled from borosilicate glass under an internal pressure of 1.65 MPa was compared using maximum principal stress and total displacement criteria. The results obtained revealed that geometric variations are particularly decisive in determining deformation behavior. While the conical geometry reduces the maximum total displacement by approximately 73.1% compared to the double-bevel geometry, it was determined that the maximum principal stress values for the two geometries are quite close to one another. The fact that high principal stresses are concentrated in the local contact and geometric transition zones in both models highlights the importance of considering not only peak stress values but also stress distribution in the evaluation. As a result, it was determined that, within the scope of the loading, material, and boundary conditions examined, the conical window geometry exhibited more favorable behavior than the double-beveled geometry in terms of deformation control and geometric stiffness.

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