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부텐 구형저장조의 설계해석
Design Analysis of Butene Storage Spherical Tank

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ABSTRACT

Spherical storage tank for chemical plant is analyzed for the loads and their combinations in accordance with Section VIII, Division 2 of the ASME Boiler and Pressure Vessel Code. Design Analysis of Butene storage tank is carried out by utilizing 3-dimensional plate and beam elements of a general purpose finite element program. Two separate 3-D finite element models are used; one for the global analysis of the entire spherical storage tank, the other for the local analysis of junction part and its vicinity of shell-to-supporting structures. The analysis is focused on the equator plate in the shell and the junction part of shell-to-supporting structures.

1. Introduction

Spherical tank is regarded as one of the most practical pressure vessel as a structural and economical point of view. However, the difficulties in construction hindered the design of this type of the pressure vessel. The recent development of techniques to build the pressure vessel has made it easier to manufacture the spherical tank.

In this study, the structural integrity of spherical tank is investigated in accordance with the ASME Sec. Ⅷ, Div. 2, 1989 Edition including 1991 Addenda along with the Owner's Specifications. The focus is laid on the equator plate in the shell and the junction part of shell-to-supporting structures rather than the shell structure itself. For the detailed stress analysis of the junction part, the local structural analysis is separately performed for the portion of the junction with the local refinement. The designated loads are applied at the junction part cut free of the entire spherical tank structure for local analysis, and the displacements computed in the global analysis are also applied along the boundary of the junction part. The schematic tank configuration is shown in Fig. 1.1.

2. Design Criteria

2.1 Design Conditions

The applied codes for investigating structural integrity in this analysis are the ASME

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Sec. Ⅷ, Div. 2 and the AISC codes. The design load conditions are basically taken from the Owner's specifications. Specifically, the wind load is based on the BS code and the seismic load is based on the UBC code as designated in the Owner's specifications. The design conditions are tabulated in Table 1.

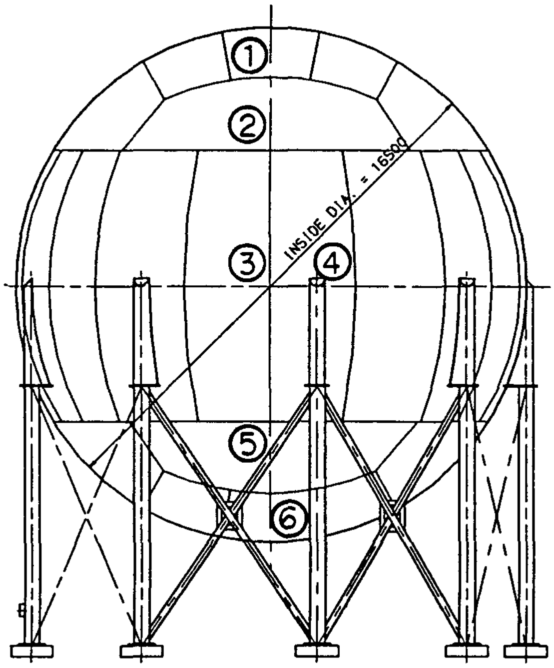

Fig. 1.1 Schematic Tank Configuration

Table 1 Design Conditions

Content Liquid		Butene
Density of Content (kg/cm^3)		0.57×10^{-3}
Internal Pressure (kg/cm^2)	Design	9.0
	Hydrotest	11.25
Design Temperature (℃)		75.0
Density of Water (kg/cm^3)		1.0×10^{-3}
Corrosion Allowance (mm)	Shell	2.0
	Support	3.0
Design Wind Speed (m/sec)		50.0
Seismic Zone		Zone 3

2.2 Allowable Stresses

The material of spherical shell is the pressure vessel plate A516 GR 70 and the material of supporting structures is the carbon steel pipe A53 GR B. The reference temperature is 75℃. In accordance with the ASME Sec. Ⅷ, Div. 2, AD-151.1 and Appendix 4-130, the allowable stress intensity applied to investigate the structural integrity varies with each loading condition. The allowable stress intensity under the design condition and the design condition with seismic load can be obtained by multiplying the design stress intensity by K factor. The design stress intensity and K factor are given in the ASME Sec. Ⅷ, Div. 2, AD-150.

In case of the hydrotest condition, the allowable stress intensity is also determined in accordance with the ASME Sec. Ⅷ, Div. 2, AD-151.1. The design stress intensity, K factor and the allowable stress intensity for each loading condition are given in Table 2.

The unity check according to the AISC code is performed for the supporting structures which is considered the same as the beam since the ASME code does not provide any appropriate regulation on buckling.

Table 2 *Design Stress Intensity, K factor and Allowable Stress Intensity*

Loading Condition	K factor	Design Stress Intensity (S_m)	Max. Stress Intensity Limits ($S_m'=K \cdot S_m$)	Stress Catagory	Allowable Stress Intensity (kg/cm^2)
Design Condition	1.0	1628.7 kg/cm^2	1628.7 kg/cm^2	P_m	$1.0 \cdot S_m'$ = 1628.7
				P_L, P_L+P_b	$1.5 \cdot S_m'$ = 2443.0
Design Condition with Seismic Load	1.2	1628.7 kg/cm^2	1954.4 kg/cm^2	P_m	$1.0 \cdot S_m'$ = 1954.4
				P_L, P_L+P_b	$1.5 \cdot S_m'$ = 2931.7
Hydrotest condition with Wind Load	σ_y = 2671.7 kg/cm^2			P_m, P_L	$0.9 \cdot \sigma_y$ = 2404.5
				$P_m + P_b^*$	$1.07 \cdot \sigma_y$ = 2858.7

P_m : Primary General Membrane Stress
P_L : Primary Local Membrane Stress
P_b : Primary Bending Stress
* : The value of $P_m + P_b$ in Hydrotest Condition with Wind Load under the assumption that P_m is equal to $0.9 \times \sigma_y$.

3. Global Analysis for Entire Structure

3.1 Finite Element Modelling

3.1.1 Material Data

The pressure vessel plate A516 GR70 is used for the shell and the carbon steel pipe A53 GR B for the supporting structures. Since the design temperature ranges from -6.3℃ to 75℃, the reference temperature is taken as 75℃ for the conservatism in the selection of the design stress intensity and other material properities. The data of the material properties obtained from the ASME Sec. Ⅷ, Div. 2 are listed in Table 3.

Table 3 Material Properties

Material Specification	A516 GR 70	A53 GR B
Minimum Ultimate Tensile Strength (kg/cm^2)	4921.6	4218.5
Minimum Yield Strength (kg/cm^2)	2671.7	2460.8
Modulus of Elasticity (kg/cm^2)	2037367.7	2040000.0
Poisson's Ratio	0.3	0.3
Design Stress Intensity (S_m, kg/cm^2)	1628.7	N/A

3.1.2 Geometrical Modelling

For the global analysis, only the half of entire structure is modelled considering the symmerties of geometry and loading. The spherical shell of tank is modelled using 3-D plate elements, and the supporting structures using 3-D beam elements. The rigid links are used to connect the plate elements of the shell to the beam elements of supporting structures.

The equator plates for global analysis are identically defined by the boundary nodes of the equator plate for local analysis because the displacements resulted from the global analysis are imposed on the equivalent nodes of local model as forced displacements.

Fig. 3.1 shows the finite element model of spherical tank for global analysis. The physical properties of shell and supporting structures are tabulated in Table 4. The shell thicknesses are the minimum thicknesses after reducing corrosion allowances.

3.1.3 Boundary Conditions

The nodes connected to the ground foundation are restrained in all the directions of translations and rotations. Taking advantage of symmetrical geometry and loading, the nodes at the boundary of the half model are restrained to have the symmetric reactions and displacements. The boundary conditions for global analysis are shown in Fig. 3.2.

Table 4 Physical Properties of Shell and Support Structures (mm)

Shell Thickness	A Part ①,②	24.0	Column	Outer Diameter	609.6
	B Part ③	24.3		Thickness	14.45
	C Part (Equator Plate) ④	25.8	Bracing	Outer Diameter	323.85
	D Part ⑤,⑥	24.6/24.8		Thickness	11.28

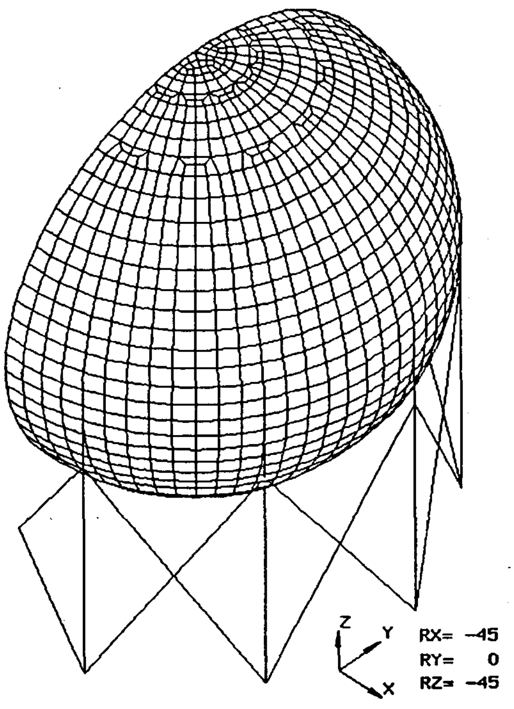

Fig. 3.1 Finite Element Model for Global Analysis

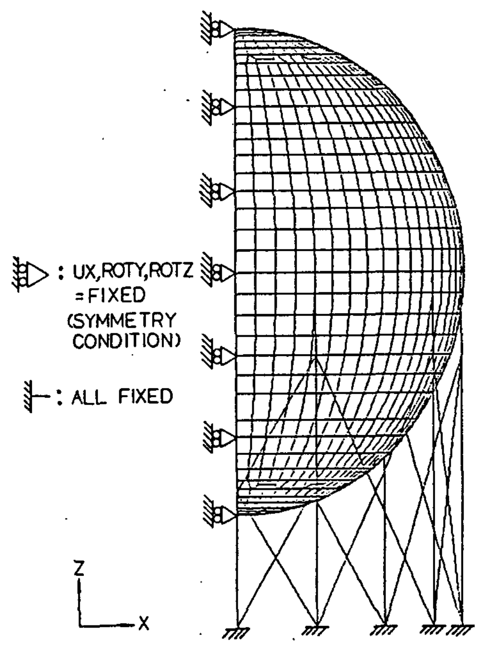

Fig. 3.2 Boundary Conditions for Global Analysis

3.1.4 Loading Conditions

In the analysis, six(6) kinds of loads are considered. They are as follows:

1) Design Internal Pressure
2) Dead Load and Live Load

3) Hydrostatic Liquid Pressure due to Content Liquid
4) Hydrotest Water Pressure
5) Wind Load
6) Seismic Load

The loads are evaluated in accordance with the Owner's Specifications. The internal design pressure is 9.0 kg/cm^2. The dead and live load of steel structures and accessories are distributed evenly on all the elements by adjusting steel density to yield the same total sum of dead and live load. The hydrostatic liquid pressures due to content liquid and the hydrotest water pressures are distributed on the submerged elements. The wind load is evaluated in accordance with the BS CP3, Chap. Ⅴ, 1972 Edition. The maximum design wind speed is 50.0 m/sec. Though the design wind pressure varies in proportion to the height from the ground, it is assumed that the maximum design wind pressure is distributed uniformly on all elements of spherical shell structure regardless of the height. The seismic load is evaluated in accordance with the UBC, Sec. 2312, 1988 Edition. The Seismic Zone is Zone 3 and the equivalent horizontal acceleration for quasi-static analysis is 0.259 of the gravitational acceleration, g. The seismic load is due to the inertia force of the entire structure and the dynamic liquid pressure of content liquid acting on the internal surface of spherical shell. The dynamic liquid pressures are evaluated in accordance with the paper, "Sloshing Effects in Spherical Tanks", JHPI Vol. 16, No. 3, 1978.

The directions of the wind load and the seismic load are selected to yield the symmetric reactions and displacements. Three(3) load combinations are examined in this analysis, that is, the design conditions, the design condition with seismic load and the hydrotest condition with wind load. The loads are properly added together to obtain load combinations in accordance with the Owner's Specifications. The wind and seismic loads are assumed not to act simultaneously. The summary of the loads and three(3) load combinations are tabulated in Table 5.

Table 5 Loads and Load Combinations for Global Analysis

Load Catagory	Load Case No.	Description			Total Force for Half Model (kg)		
					Fx	Fy	Fz
Loads	1	Internal Pressure	A	Design	1.925×10^7	0.0	573.8
			B	Hydrotest	2.406×10^7	0.0	717.2
	2	Dead Load and Live Load (Z-dir.)			0.0	0.0	1.415×10^5
	3	Hydrostatic Liquid Pressure due to Content Liquid (90% Volume)			6.386×10^5	0.0	6.058×10^5
	4	Hydrotest Water Pressure			1.768×10^6	0.0	1.178×10^6
	5	Wind Load (Y-dir.)			1.595×10^4	1.595×10^4	0.0
	6	Seismic Load (Y-dir.)	A	Inertia Force of Entire Structure	0.0	3.665×10^4	0.0
			B	Dynamic Liquid Pressure of Content	2.8	1.313×10^5	0.0
Load Combinations	7	Design Condition: LC. 1.A + LC. 2 + LC. 3			1.989×10^7	0.0	7.479×10^5
	8	Design Condition with Seismic Load: LC. 1.A + LC. 2 + LC. 3 + LC. 6.A/B			1.989×10^7	1.680×10^5	7.476×10^5
	9	Hydrotest Condition with Wind Load: LC. 1.B + LC. 2 + LC. 4 + 1/3×LC. 5			2.583×10^7	5.317×10^3	1.320×10^6

3.2 Numerical Results of Stress Intensities

3.2.1 Numerical Results of Shell

The numerical results of stress intensities of global analysis for all load cases are summarized in Table 6. The stress intensity is defined as twice the maximum shear stress of evaluation point of interest.

In the cases of the design condition and the hydrotest condition with wind load, the maximum stress intensity occurs in the vicinity of the equator plate. The stress intensities of the junction part of shell-to-supporting structures are relatively low due to the effect of rigid links between shell and supporting structures. But in the case of the design condition with seismic load, the maximum stress intensity occurs in the junction part of shell-to-supporting structures.

The detailed stress evaluations for the junction part will be separately conducted in accordance with the ASME code and pressented in Chapter 4.

Table 6 Stress Intensities of Shell for Global Analysis (kg/cm²)

Load Case	Stress Catagory	Stress Intensity	Locations										Remark
			1	2	3	4	5	6	7	8	9	10	
Design Condition	P_m	1628.7	1548.0	-	1590.3	-	-	1622.3	-	-	-	-	
	P_L	2443.0	-	1540.3	-	1640.2	1626.5	-	1562.0	1579.4	1660.8	1611.8	
	$P_L + P_b$	2443.0	1551.8	1536.3	1590.6	1666.2	1621.5	1630.3	1518.7	1588.8	1604.7	1587.6	Inner
			1153.2	1545.5	1590.0	1614.2	1634.3	1614.3	1605.3	1571.5	1717.0	1636.1	Outer
Design Condition with Seismic Load	P_m	1954.4	1547.8	-	1626.0	-	-	1628.4	-	-	-	-	
	P_L	2931.7	-	1543.1	-	1649.0	1632.3	-	1594.3	1616.5	1695.2	1628.3	
	$P_L + P_b$	2931.7	1551.5	1540.3	1627.0	1675.3	1635.4	1636.8	1550.1	1628.7	1637.9	1602.4	Inner
			1554.4	1545.8	1625.0	1623.1	1638.5	1620.1	1638.5	1605.7	1753.1	1655.9	Outer
Hydrotest Condition with Wind Load	P_m	2404.5	1949.2	-	2078.7	-	-	2142.5	-	-	-	-	
	P_L	2404.5	-	2006.4	-	2159.6	2146.5	-	2049.5	2077.7	2180.4	2119.7	
	$P_m + P_b$	2858.7	1948.9	2000.1	2078.7	2194.6	2139.4	2152.2	1992.5	2095.0	2108.9	2087.1	Inner
			1966.2	2012.9	2078.7	2124.6	2156.2	2132.9	2106.8	2062.4	2252.2	2152.5	Outer

3.2.2 AISC Code Check of Supporting Structures

For the supporting structures, the AISC Code Check is used to examine the structural integrity.

The allowable stresses for axial and bending are increased to one and one-third of the calculated allowable stress by the regulation of the AISC code in case of the short-time loadings such as the design condition with seismic load and the hydrotest condition with wind load. The effective length factor K is assumed as 1.0 and the effective lengths of columns and bracings are their full lengths in consideration of the buckling mode. In spite that the bracing is connected with the other in the middle point, the effective length of the bracing is taken as the full bracing length because the buckling mode of bracing is not affected significantly by the middle joint point.

The maximum Unity Check is 0.695 for column in the hydrotest condition with wind load and 0.867 for bracing in the design condition with seismic load.

4. Local Analysis for Junction Part of Shell-to-Supporting Structures

4.1 Finite Element Modelling

4.1.1 Geometrical Modelling

For detailed analysis of the junction part of shell-to-supporting structures, the only one equator plate and one-ninth of the support sturcutres are modelled. The equator plate and the junction part of the column are more finely meshed with 3-D plate elements. The rest of the junction part, the column and the bracings, are simply modelled with the 3-D plate element and the beam element because the column and the bracings are not of major interest in local analysis. The finite element model for the local analysis is shown in Fig. 4.1.

4.1.2 Boundary Conditions

The displacements computed in the global analysis are loaded on the boundary nodes of local equator plate model as forced displacements. For the unmatched boundary nodes due to refinement, a linear interpolation is needed to obtain the forced displacements for the added nodes between two adjacent nodes for the global analysis. The displacement results of the global analysis are also imposed on the other boundary nodes of supporting structures in the local analysis. The boundary conditions for the local analysis are shown in Fig. 4.2.

4.1.3 Loading Conditions

The loads and their load combinations for the local analysis are identical to those for the global analysis. Each load is applied along with the displacements computed in the global analysis.

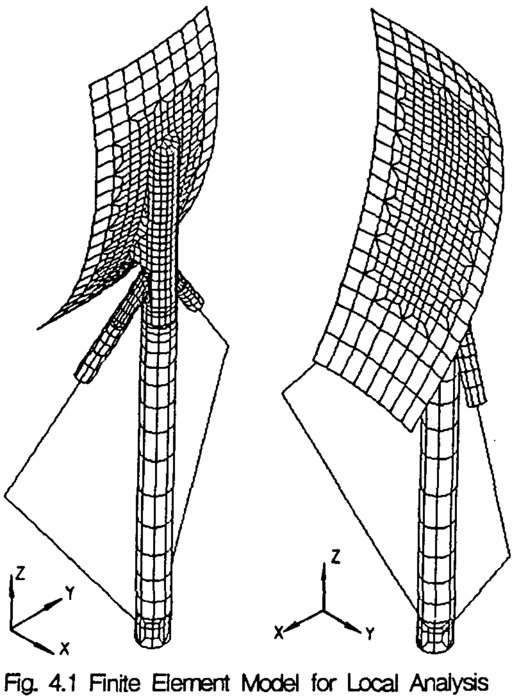

Fig. 4.1 Finite Element Model for Local Analysis

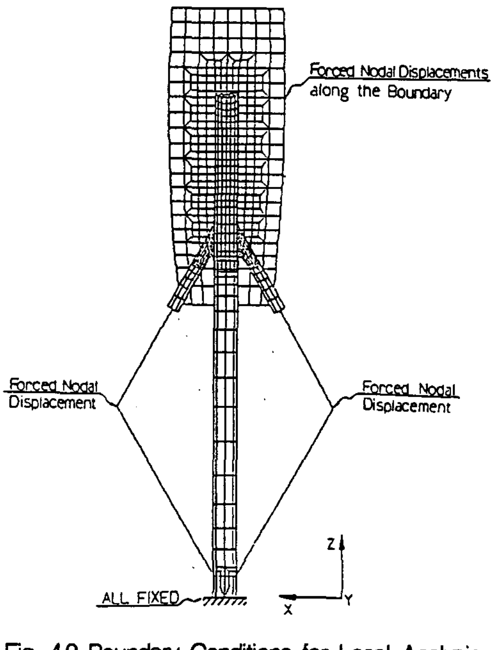

Fig. 4.2 Boundary Conditions for Local Analysis

4.2 Numerical Results of Stress Intensities

For all load cases, the maximum stress intensity occurs in the upper corner of the junction part of shell-to-supporting structures in contrast that the column and bracings show relatively lower stress intensities due to their sufficient strengths.

The stress intensities in all load cases are evaluated in compliance with the criteria in AD-150, AD151-1 and Appendix 4-130 of the ASME Sec. Ⅷ, Div. 2, prescribed in Chapter 2. The stress intensities at stress evaluation points for all load combinations are summarized in Table 7.

Table 7 Stress Intensities for Local Analysis (kg/cm^2)

Load Case	Stress Catagory	Stress Intensity	Location										Remark
			1	2	3	4	5	6	7	8	9	10	
Design Condition	P_L	2443.0	1303.6	1388.6	1184.4	1324.2	991.6	1241.7	183.8	415.9	197.6	1703.9	
	P_L+P_b	2443.0	1376.9	1310.0	1316.2	1247.3	1416.4	1246.0	215.4	384.5	160.7	1576.8	Inner
			1211.9	1467.1	1055.8	1352.6	771.2	1322.7	196.0	447.4	234.5	1865.6	Outer
Design Condition with Seismic Load	P_L	2931.7	1345.8	1412.5	1139.6	1364.3	1006.3	1243.6	194.1	461.5	183.6	1753.2	
	P_L+P_b	2931.7	1421.6	1316.0	1293.8	1293.3	1472.2	1318.4	223.7	427.4	167.3	1625.9	Inner
			1252.2	1508.9	993.8	1376.4	709.4	1153.3	209.5	495.7	218.7	1908.3	Outer
Hydrotest Condition with Wind Load	P_L	2404.5	1694.5	1795.9	1539.1	1725.9	1280.7	1641.4	216.1	765.2	407.2	2214.0	
	P_m+P_b	2858.7	1784.0	1675.6	1736.3	1730.3	1879.5	1615.7	244.0	719.8	323.6	2131.6	Inner
			1584.7	1916.2	1354.1	1649.7	935.3	1761.6	233.7	810.7	490.7	2329.1	Outer

5. Conclusion

As a result of the analysis, it is found that the higher stress intensities occur in the vicinity of the equator plate and the junction part of shell-to-supporting structures, more specifically at the equator plate region just out of the junction part. These higher stress intensities are seemed to be due to the structural discontinuity and the stress concentration.

From the results of the analysis, the conclusions are drawn as the stress intensities of the spherical shell meet the criteria of the ASME code for all loads and their combinations, and the Unity Check for the supporting structures also meet the criteria of the AISC code.

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