Post-Buckling Analysis of Steel Silo Subjected to Internal Pressure

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Abstract— Silos are used to store granular solids, liquids, and metal ores. Due to high height to diameter ratios, silos are prone to failure due to buckling. This research work aims to assess the buckling strength of steel silos containing liquid (water). The silo is designed as per ASME codes for the requirements given in problem, and then validated the design for safety by performing linear and nonlinear analysis using software ANSYS. Water stored in silo acts as loading on surfaces of it. Hence in addition to above analyses, hydrostatic analysis is also performed on silo.

Key words: Post-Buckling, Silo, Linear Finite Element Analysis, Nonlinear Finite Element Analysis, Cylindrical Shell, Buckling

I. INTRODUCTION

A silo is a structure which is used for storing bulk solids such as grains, coal, cement, woodchips and food products. These are used in mining, agricultural and manufacturing industries to store grains, fluids and cement and platinum ores. These industrial silos often experience some degrees of failure due to buckling, which causes economical loss, material losses and maybe loss of human life. In this research project, our aim is to design steel silo and to verify its safety against buckling failure.

Buckling is a phenomenon which causes sudden failure of structure. Eigen value linear buckling analysis is generally used to estimate the critical buckling load of ideal structures. Such an analysis will not, however give any information about what happens after critical buckling load. Tracing the load after critical buckling load is called post-buckling analysis.

II. PROBLEM DEFINITION

To design a vertical steel silo, to be supported on ground, this will be used for storing water. Silo has 6 openings (nozzles), 3 openings in top portion and 3 openings in bottom portion of shell, separated by 120 degree each, to intake and outflow of water. Other inputs are given in next table.

Process volume V_p	500 m^3
Expected stagnant volume V_s	20 m^3
Buffer volume V_b	5 m^3
Internal pressure, P	Self weight
Vessel radius, R	3.6 m
Nozzle diameter, d	0.3 m
No. of nozzles	6
Head type	Flat
Support type	Ground support

Table 1: Input Parameters of Silo

III. MATERIAL PROPERTIES

The material to be used for cylindrical shell, nozzle, flat heads, reinforcing pads is same and is SA516 Grade 70 (carbon steel plate).

Description	Values
Material	SA 516 Grade 70
Modulus of elasticity	200 GPa
Poisson's ratio	0.29
Maximum allowable stress	137.8951 MPa

Table 2: Material Properties

IV. DESIGN CALCULATIONS

From calculations, the maximum pressure acting on silo wall due to water height (h) obtained is equal to P = 0.2478 MPa.

By using this value of internal pressure, following dimensions are obtained according to ASME code for pressure vessel; section VIII, division I, shown in TABLE III.

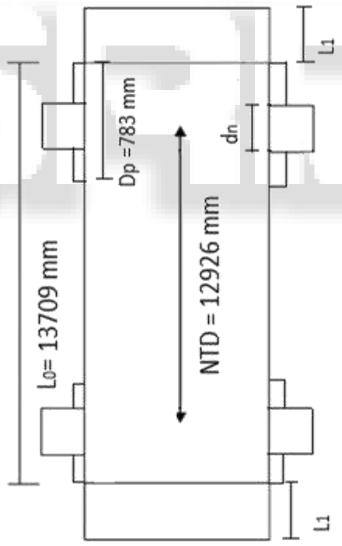

Fig.1: SILO DIMENSIONS

Nozzle to nozzle distance, NTD	12926 mm
Main stock cylindrical length, L_0	13709 mm
Buffer stock cylindrical length, L_1	714 mm
Thickness of shell, t	12 mm
Diameter of shell, D	7200 mm
Thickness of nozzle, t_n	6 mm
Diameter of nozzle , d_n	300 mm
Thickness of reinforcing pad, t_p	6 mm
Diameter of reinforcing pad, D_p	783 mm
Thickness of flat head, t_h	150 mm
Total Height, H= $L_0+2L_1+2t_h$	15437 mm

Table 3: Silo Dimensions

V. MODELING OF COMPONENTS

Advanced FEA tools can be vital in the assessment of safety and serviceability of proposed design. Safety and serviceability assessment of silo structures are important in the development of accurate and reliable methods and in modeling of silo. In this case we are using modeling and analysis software ANSYS workbench which is easy and accurate. From the dimensions given in above table, the 3D modeling of silo is done in ANSYS workbench. As meshing of component is easy in surface model, the surface model of silo is created first instead of solid model. The thickness is provided later during setting up the model for meshing.

Fig. 2: SURFACE MODEL OF SILO

Diagram shown above indicates surface model of silo with nozzles and reinforcing pads. Since silo to be supported on ground, there is no need to do design calculations as well as modeling of support.

VI. MESHING OF COMPONENTS

The meshing is done with quadrilateral dominant method using quad/ tria elements with midside nodes. The element size for shell and heads is kept 100 mm while for nozzles and reinforcing pads it is kept as 50 mm. Additionally, mapped face meshing command used to remove non-regularity in meshing of nozzles and reinforcing pads, which has significant effect on end results. The number of nodes obtained are 156500 and number of elements are 51692. The connections were formed between shell-nozzles and shell-reinforcing pads. Fig.3 indicates top portion of meshed silo.

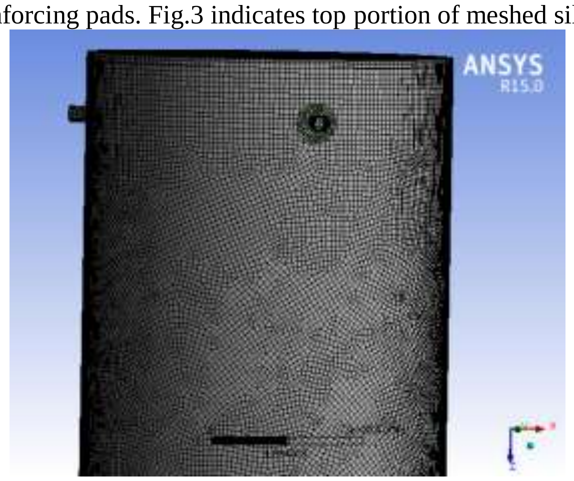

Fig. 3: Top Portion of Meshed Silo

VII. ANALYSIS AT DIFFERENT LOADING CONDITIONS

A. *Dead Weight Loading:*

In static structural, standard earth gravity is added as input by entering value as 9806 mm/s^2 is applied in downward direction. The bottom surface of silo is kept fixed. In this case, self-weight of shell, head, and nozzles acts as load on silo.

Fig. 4: self weight loading

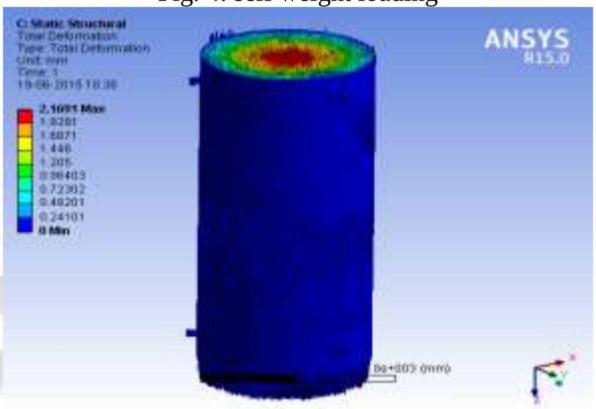

Fig. 5: Self weight deformation

B. *Hydrostatic Loading:*

The water stored in the silo would create hydrostatic forces on the surface of shell, which would cause deformation in shell. In static structural, in addition to standard earth gravity, hydrostatic pressure is added by giving fluid density 10^{-6} kg/mm^3. Fig. 6 shows the hydrostatic loading on shell and stresses obtained after analysis. Maximum stress obtained (from fig. 7) is equal to 59.734 MPa which is less than allowable stress (137.895 MPa) of steel.

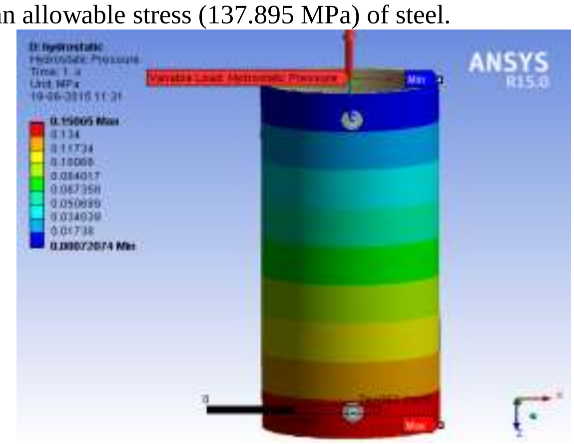

Fig. 6: Hydrostatic loading

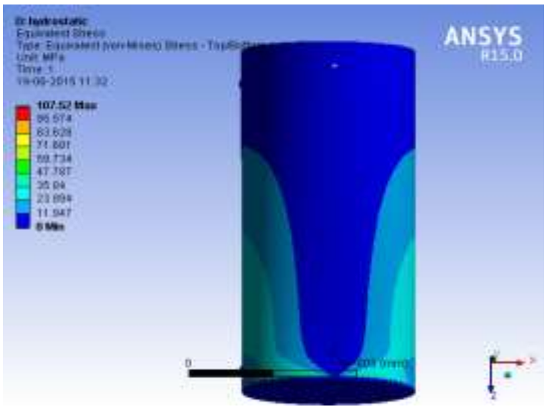

Fig. 7: Hydrostatic stress

C. *Eigen Linear Buckling:*

The silos are prone to failure by buckling due to internal pressure loading. Hence it is necessary to determine the buckling strength of silo. Eigen value buckling analysis predicts the theoretical buckling strength of an ideal elastic structure. By performing linear buckling analysis in workbench, we get load multiplier as output, which indicates the critical (buckling) load capacity of shell. Higher the load multiplier, higher the buckling strength and safer is design. When loading on silo reaches the value of load multiplier, then there is possibility of failure due to buckling. Internal pressure of some random magnitude, which causes buckling, is applied to the structure. This magnitude of loading (F) will be multiplied by load multiplier (λ) to obtain the critical (buckling) strength.

$$F \times \lambda = \text{Buckling } load$$

In our case, we have applied internal pressure of 2.107 MPa. Fig. 8 shows the loading in eigen value buckling.

Fig. 8: Loading in linear buckling

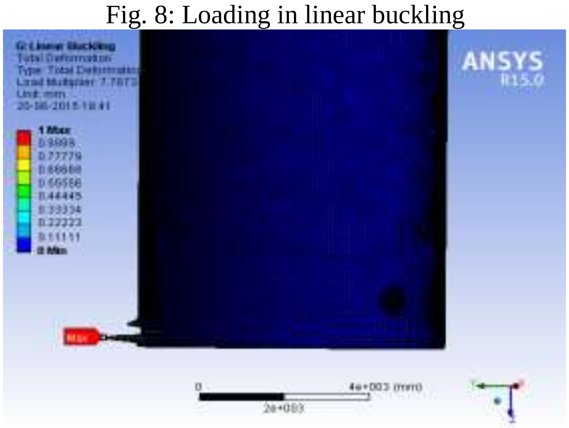

Fig. 9: Buckling deformation

Fig.9 shows the deformation obtained in the bottom portion of silo. For input pressure of 2.107 MPa, we obtain load multiplier (λ) equal to 7.7673. From these values we get,

Buckling strength = 2.107 × 7.7673 MPa
= 16.3657 MPa

Thus, we found the critical buckling load is 16.3657 MPa.

D. *Nonlinear Analysis:*

Nonlinear buckling analysis is more accurate than eigen value analysis, because it employs nonlinear, large – deflection, static analysis to predict buckling loads. Its mode of operation is very simple: it gradually increases applied load until a load level is found whereby the structure becomes unstable (ie. Suddenly, a very small increase in load will cause large deflections.) For this type of analysis, small off-axis loads are necessary to initiate the desired buckling mode. Fig.11 indicates loading on silo for nonlinear analysis. From linear analysis, we know that buckling will occur near 16.3657 MPa, hence we will apply internal pressure of different values from 16 MPa to 17 MPa with the steps of 0.05 MPa. An off-axis load 1 N of force is applied on reinforcing pad to insert nonlinearity in silo, shown at point D in fig.11. The load at which there is sharp change in slope of load- deflection curve will be output in nonlinear analysis. Fig.10 shows the table in which pressure is applied in no. of steps.

Steps	Time [s]	Pressure [MPa]
1	0	0
1	1	-16
2	2	-16.05
3	3	-16.1
4	4	-16.15
5	5	-16.2
6	6	-16.25
7	7	-16.3
8	8	-16.35
9	9	-16.4
10	10	-16.45
11	11	-16.5
12	12	-16.55
13	13	-16.6
14	14	-16.65
15	15	-16.7
16	16	-16.75
17	17	-16.8
18	18	-16.85
19	19	-16.9
20	20	-16.95
21	21	-17

Fig. 10: Pressure loading in no. of steps

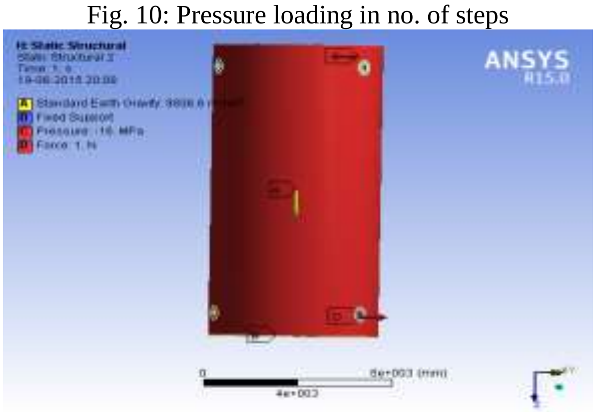

Fig. 11: Loading in nonlinear analysis

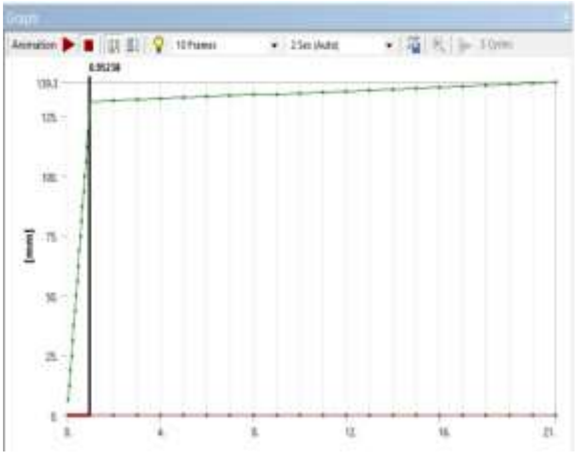

Fig. 12: Graph of deflection Vs no. of steps

The graph of Load Vs number of steps shown in fig. 12 is equivalent to load- deflection curve. It shows that at the first step there is sharp change in slope of curve. Hence, load at first substep, 16 MPa is the critical buckling load.

VIII. Conclusion

1) The silo is designed as per ASME codes and then modeled and analysed under different loading conditions by using ANSYS Workbench.
2) In hydrostatic analysis, von-mises stress obtained is 59.734 MPa, which is less than allowable stress of steel (137.895 MPa). Hence, design is safe for hydrostatic conditions.
3) After performing linear buckling analysis, we calculated critical buckling capacity of silo equal to 16.3657 MPa, which is very high than our calculated value of internal pressure 0.2478 MPa, hence, our design is safe with high factor of safety.
4) In nonlinear analysis, we found out critical buckling capacity equal to 16 MPa, which shows that design is safe in nonlinear case also.

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