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Buckling Analysis of Cylindrical Steel Fuel Storage Tanks under Static Forces

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Abstract **–** Developing sustainable fuel containers to store energy resources is essential because of the worldwide energy crisis. The sustainability of fuel storage tanks is more necessary than any other infrastructure because of its contents' toxic and inflammable nature. The primary design problem that requires full attention is the prevention of buckling and large magnitude displacement against static and dynamic forces. A detailed analytical program is needed to evaluate the buckling strength of fuel storage tanks. Initially, as a starting point, a simple axial linear buckling analysis of an empty steel cylindrical storage tank with different *H/D* and *R/t* ratio are considered for the present work. To cover all ranges of steel cylindrical fuel storage tanks (i.e., short, medium, and tall), twelve sizes were selected from the literature with diameter to thickness (*D/t*) ratios of 1000, 1500, and 2000 and the height to diameter (*H/D*) ratios of 0.5,1,1.5 and 2.0. This study used two commercially available software, ABAQUS 6.5 and ANSYS workbench 2021. The results are compared with the theoretical axial buckling stress equation. Finite Elements results obtained from both software showed good agreement with the theoretical results.

Keywords**:** Fuel Storage Tanks, Buckling Strength, Steel, Analysis, Diameter to Thickness Ratio, Height to Diameter Ratio, Finite Element Analysis

1. Introduction

Nowadays, thin-walled steel cylindrical shell structures are remarkably used as storage vessels because of their economical and efficient support system. Due to the very slim and thin-walled cylindrical nature, the buckling response of the cylindrical tanks results in an abrupt and significant change in the structural shape. This unstable buckling response of cylindrical tanks results in a large deflection and a substantial reduction in load-bearing capacity and stiffness of the tanks. Furthermore, stability issue arises due to the initial geometric imperfection, which is the small unavoidable variations in the geometry resulting from its manufacturing process. Therefore, the primary design problem that requires full attention is preventing buckling and large magnitude displacement against static and dynamic forces. The critical or buckling load of a cylinder depends on the geometrical configuration, loading and boundary conditions, the way it is stiffened, and the material properties [1].

Significant progress has been made in developing improved theories and computational analysis to understand the behavior of shell structures. The classical theory of stability of cylindrical shells was developed in the early 20th century. But the early experimental works showed different and scattered results from the earlier theoretical studies done by Lorenz [2] and Timoshenko [3]. From the 1920s to the early 1960s, many researchers conducted experiments to find the discrepancies between the classical predictions and the experimental buckling loads. Based on the initial works of von Kármán and Tsien [4], Donnell and Wan [5], and Koiter [6], it was clear that the primary factor causing the reduction of the experimental buckling load from the classical is imperfections.

Besides these experimental works, significant progress in numerical solutions was made by developing computational sources. A.M Abd-Elbase [7] emphasized the importance of soil-structure interaction and Time History Analysis to better understand the seismic response of above-ground storage tanks. This study performed a nonlinear implicit dynamic analysis using ADINA software. Mainly Loma Prieta earthquake was adapted. In addition, a Comparison between Pile Raft Foundation (PRF) and Stone Column Foundation (SCF) was conducted in both static and dynamic analyses to investigate the effectiveness of SCF as an alternative to PRF because of its economic nature. Results proved that the tank aspect ratios and soil properties significantly affect the hydrostatic pressure and dynamic hoop stresses. Also, API-650 Guidelines for calculating axial compressive stresses need more studies, especially the anchorage ratio equation. Secondly, results showed that SCF is a more economical and effective alternative to PRF for soil stabilization against seismic resistance. Sobhkhiz and

Mardookhpour [8] studied and analyzed the seismic behavior of unanchored metal tanks via time history analysis with a focus on the uplift mechanism. This study explored the relationship between hydrodynamic loads and the bottom sheet uplift and their effects on the structural deformation, stress, and fluid movement through the tank. The results showed that the Bottom uplift occurs only when the fluid-induced overturning moment exceeds the critical value. Roopkumdee and Mamaghani [9-11] studied and proposed a solution to improve the seismic response of the liquid-filled cylindrical tanks under the earthquake excitation by using ANSYS [12]. They studied the seismic behavior of liquid-filled steel cylindrical tanks under different diameter-to-thickness (*D/t*) and height-to-diameter (*H/D*) ratios and proposed a design equation. Results showed that the dynamic buckling capacity of the tank decreased significantly when the *D/t* and *H/D* ratio increased, but the effect of the *H/D* ratio was less significant than the *D/t* ratio.

Extensive research conducted so far has contributed much to understanding the behavior of the cylindrical shell structure; numerical works on the buckling resistance of thin-walled cylindrical tanks are still rare. Therefore, a numerical study has been proposed to evaluate the buckling strength of thin-walled cylinders subjected to static forces.

2. Preliminary Linear Elastic and Buckling Analysis

A linear elastic stress analysis was initially performed to verify the overall performance and quality of the numerical modeling approach, and computational analysis to calculate the linear buckling behavior of empty cylindrical shells with different H/D and D/t ratios using commercial engineering software ABAQUS 6.5 [13] and ANSYS workbench 2021 [12]. The theoretical results were compared with FE analysis results to substantiate the model.

2.1. Material Description and Geometry of the Cylindrical Tanks

Twelve different geometries of the tanks are analyzed with height to diameter (H/D) ratios of 0.5, 1.0, 1.5, and 2.0 and the diameter to thickness (D/t) ratios of 1000, 1500, and 2000 to investigate the buckling behavior of various sizes of the cylindrical tanks. These twelve cylindrical tanks are modeled as above-ground storage tanks open at the top, as shown in Figure 1.

Fig. 1: Cylindrical Tank Dimension

The geometries of the cylindrical tanks analyzed are listed in Table 1. The material for all cylindrical storage tanks is steel with a modulus of elasticity, E = 200 GPa. (29×10^6 psi), Poisson's ratio, $\nu = 0.3$.

Table 1: Summary of twelve geometries of cylindrical shells.

Model	D	H	t	D/t	H/D
1	9.144 m (360 in.)	4.573 m (180 in.)	9.144 mm (0.360 in.)	1,000	0.5
2	9.144 m (360 in.)	4.573 m (180 in.)	6.096 mm (0.240 in.)	1,500	0.5
3	9.144 m (360 in.)	4.573 m (180 in.)	4.572 mm (0.180 in.)	2,000	0.5
4	9.144 m (360 in.)	9.144 m (360 in.)	9.144 mm (0.360 in.)	1,000	1.0
5	9.144 m (360 in.)	9.144 m (360 in.)	6.096 mm (0.240 in.)	1,500	1.0
6	9.144 m (360 in.)	9.144 m (360 in.)	4.572 mm (0.180 in.)	2,000	1.0
7	9.144 m (360 in.)	13.716 m (540 in.)	9.144 mm (0.360 in.)	1,000	1.5
8	9.144 m (360 in.)	13.716 m (540 in.)	6.096 mm (0.240 in.)	1,500	1.5
9	9.144 m (360 in.)	13.716 m (540 in.)	4.572 mm (0.180 in.)	2,000	1.5
10	9.144 m (360 in.)	18.288 m (720 in.)	9.144 mm (0.360 in.)	1,000	2.0
11	9.144 m (360 in.)	18.288 m (720 in.)	6.096 mm (0.240 in.)	1,500	2.0
12	9.144 m (360 in.)	18.288 m (720 in.)	4.572 mm (0.180 in.)	2,000	2.0

2.2. Theoretical Buckling Stress for the Cylindrical Shell

The theoretical static buckling stress for the cylindrical shells using the English unit is given by Timoshenko [3] theory of elastic stability is,

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-v^2)}}\left(\frac{t}{R}\right) \tag{1}$$

Where R is the radius of the cylindrical shell.
E is the modulus of elasticity.
t is the thickness of the cylindrical shell.
v is the Poisson's ratio.

2.3. Buckling Analysis of Cylindrical Shells using ABAQUS:

The linear buckling analysis has been performed by using a commercial ABAQUS code. The way of applying load, boundary conditions and meshing for Model 01 geometry in ABAQUS are shown in Figures 2,3 and 4 respectively.

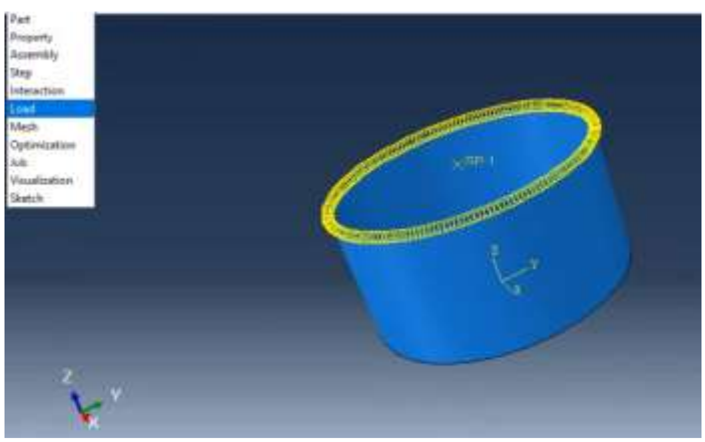

Fig. 2: Model 01 Geometry with Load Application

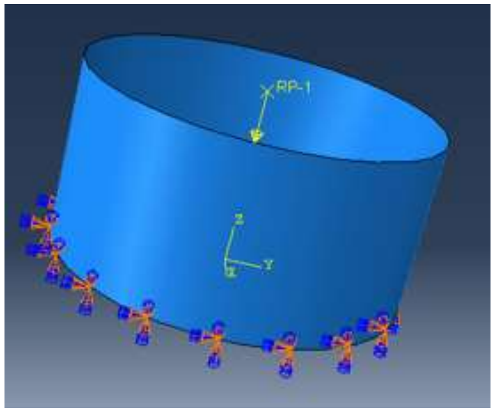

Fig. 3: Model 01 Geometry with B.C.

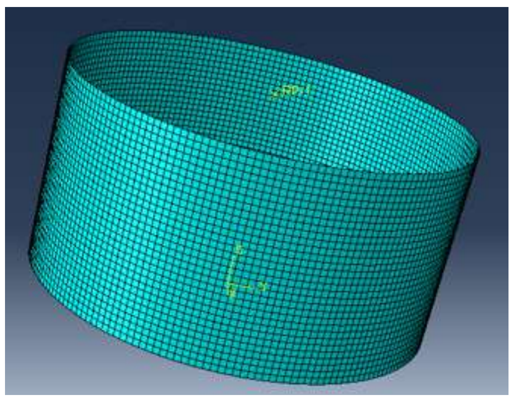

Fig. 4. Model 01 Meshing

Figure 5 shows the Model 01 ABAQUS buckling load is 6.397×10^{7} N.

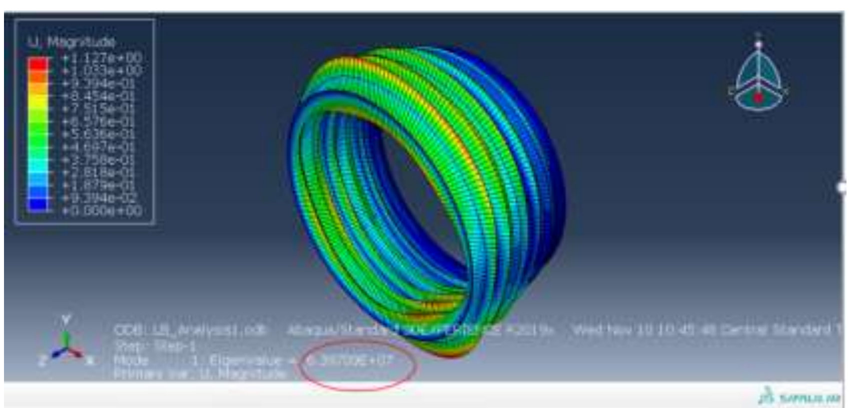

Fig. 5: Model 01 Buckling Load

2.4. Buckling Analysis of Cylindrical Shells using ANSYS:

For comparison, another FE software ANSYS has been used for linear buckling analysis of cylindrical tanks. The asymmetric tool option was used in the Design Modeler window to reduce the computational time, as shown in Figure 6.

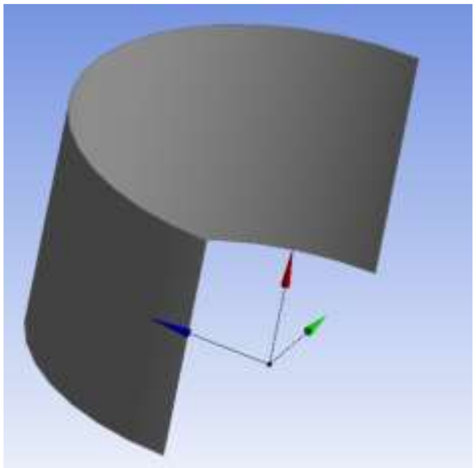

Fig. 6: Model 01 Geometry in ANSYS Workbench

For FEA buckling stress in ANSYS, the compressive pressure line of 1 N/mm was applied at the top to be a unit load, as shown in Figure 7. Thus, from ANSYS, the compressive pressure line of l N/mm multiplied by the multiplier is the critical value of buckling load. Figure 8 shows the Model 01 ANSYS multiplier of around 2336.3 N/mm.

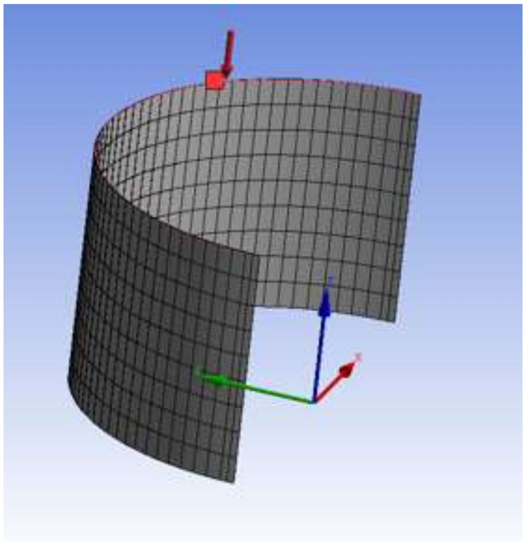

Fig. 7: Model 01 Compressive Pressure Line in ANSYS Workbench

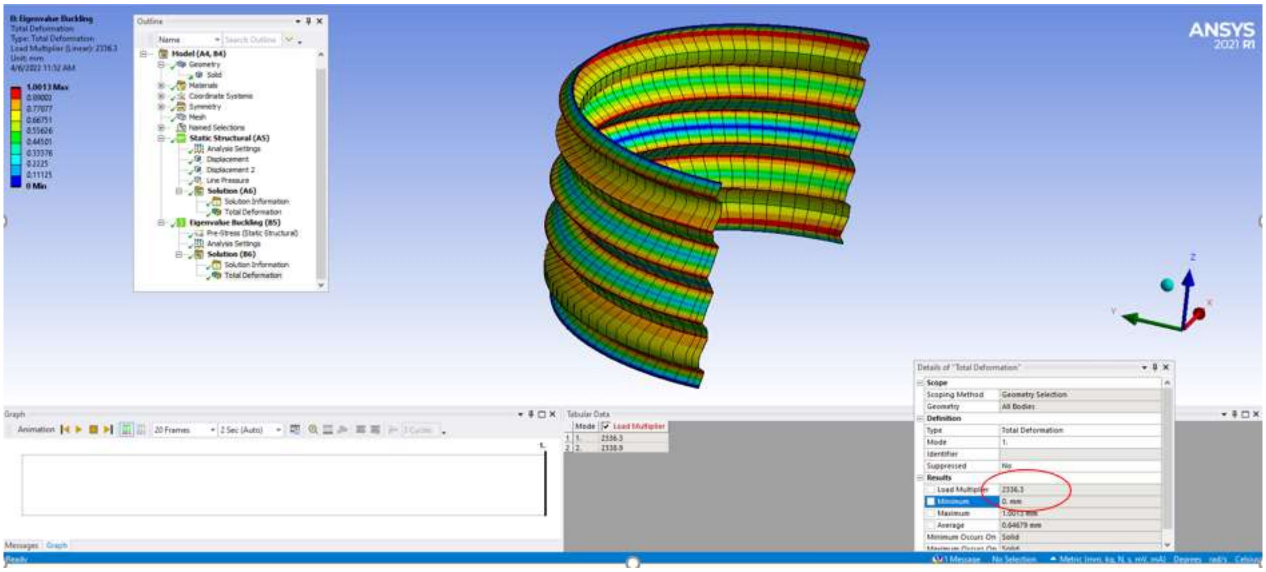

Figure 8. Model 01 Buckling Load Multiplier

3. Results

Calculations for Model 1 as an example are presented below to calculate the linear buckling stress values.
The theoretical, critical stress (σ_{cr}):

$$\sigma_{cr} = \frac{E}{\sqrt{3(1-\nu 2)}.} \cdot \frac{t}{R}$$

$$\sigma_{cr} = \frac{200000}{\sqrt{3(1-0.32)}.} \cdot \frac{9.144}{4573} = 242.03 \text{ MPa}$$

the buckling stress from FEA by using ABAQUS:

$$\sigma_{cr}(FEA) = \frac{\text{Buckling Load}}{\text{Area}} = \frac{6.39 \text{ x } 10e7}{2\pi(4573).(9.144)} = 243.211 \text{ MPa}$$

and, the buckling stress from FEA by using ANSYS:

$$\sigma_{cr}(FEA) = \frac{\text{Multiplier}}{\text{t}} = \frac{2336.3}{9.144} = 255.5 \text{ MPa}$$

The comparison of both FE axial buckling stresses with the theoretical values for all models is presented in Table 2. These results show that the critical compressive (buckling) stress mainly depends on the D/t ratio. The value of buckling stress decreases with the increase of the D/t ratio. These variations remain the same for any H/D ratio, as shown in Figure 9. In addition, FE results showed good agreement with theoretical values.

Table 2: Summary of Results.

Model No.	D (m)	H (m)	t (mm)	D/t	H/D	$\sigma_{cr.}$ Theoretical (MPa)	$\sigma_{cr.}$ ANSYS (MPa)	$\sigma_{cr.}$ ABAQUS (MPa)
1	9.144	4.573	9.144	1,000	0.5	242.03	264.98	243.211
2	9.144	4.573	6.096	1,500	0.5	161.37	176.84	162.14
3	9.144	4.573	4.572	2,000	0.5	121.02	132.11	121.77
4	9.144	9.144	9.144	1,000	1.0	242.03	265.42	242.45
5	9.144	9.144	6.096	1,500	1.0	161.37	177.00	161.57
6	9.144	9.144	4.572	2,000	1.0	121.02	132.33	121.73
7	9.144	13.716	9.144	1,000	1.5	242.03	249.34	243.11
8	9.144	13.716	6.096	1,500	1.5	161.37	174.05	161.33
9	9.144	13.716	4.572	2,000	1.5	121.02	132.33	121.22
10	9.144	18.288	9.144	1,000	2.0	242.03	248.25	243.11
11	9.144	18.288	6.096	1,500	2.0	161.37	172.24	162.14
12	9.144	18.288	4.572	2,000	2.0	121.02	132.33	121.22

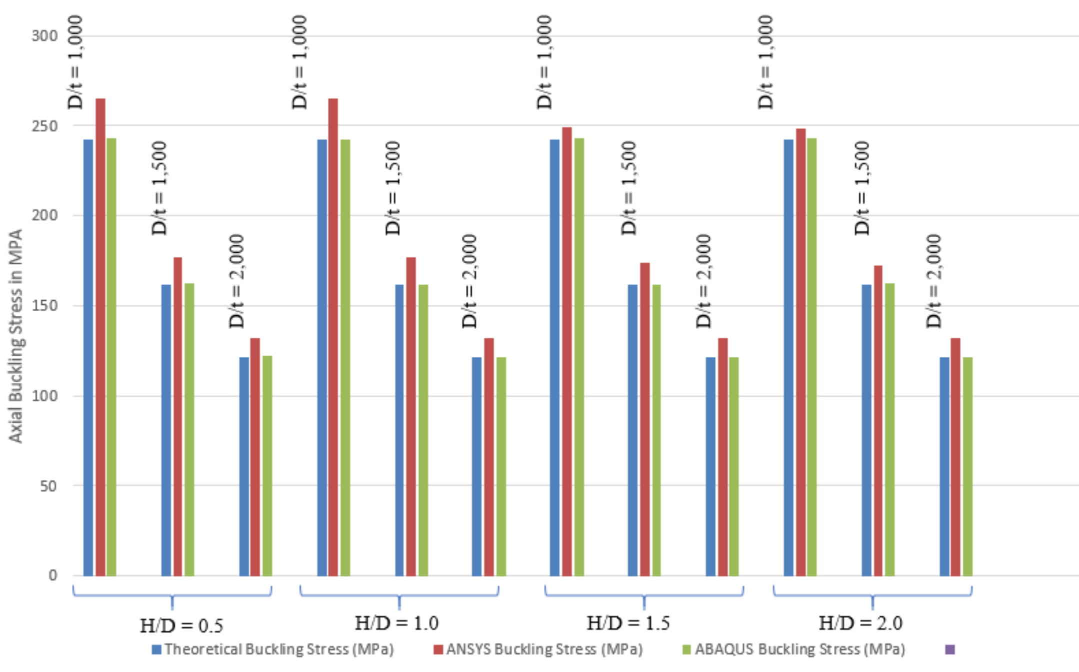

Fig. 9: Comparison of FE axial buckling stresses with theoretical buckling stresses for all Models

4. Conclusion

These results show that the FEA models accurately predict static critical buckling stress. Results show good agreement of ABAQUS software with theoretical values compared to ANSYS. The solution of the buckling analysis provides multiple buckling mode shapes and critically buckling load values. Those mode shapes (eigenvectors) can indicate the expected buckling modes during the nonlinear analysis.

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