Investigation on Buckling Behaviour of Anchored Steel Tanks

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Abstract : Vertical above ground steel tanks are employed in several industries to store water, oil, fuel, chemicals, and other fluids. Because of their geometric slenderness, steel tanks are prone to fail by buckling, and frequently this failure initiates in the form of elastic buckling. Interest in this study is due to failure of steel tanks in the cases of accidents or natural disasters with huge economic, environmental and social losses. The main objective is to investigate the buckling behaviour of steel tanks under static and dynamic loading conditions and to understand the various factors influencing buckling behaviour. Influences of aspect ratio, material and geometric non linearity on buckling characteristics of steel tanks were considered for the study. Buckling analysis of cylindrical anchored steel tanks with different aspect ratios (H/D) 0.43, 0.5, 0.6, 1.0, 1.5 under uniform external pressure and earthquake load were carried out using finite element analysis software ANSYS. Transient buckling analyses of the empty tank and liquid filled up to 90% of the height of the tank has been undertaken to examine the dynamic buckling behaviour of steel tanks. Study shows that the empty tanks are safe from the buckling consideration when subjected to earthquake loading whereas water filled tanks may buckle under the influence of any possible real world earthquake.

Index Terms - Steel tank, Buckling analysis, Aspect ratio, Nonlinear analysis, Time history analysis

I. INTRODUCTION

Vertical above ground steel tanks are used in many industries to store water, fuel, oil, chemicals, and other fluids. Tanks are thin walled short cantilever shells, and have geometrical and structural differences with other storage shells, such as silos or pressure vessels which tend to be taller. Storage tanks are constructed using curved steel sheets, commonly known as courses, with dimensions depending on the local steel industry, and which are welded together to form the cylinder. Because of their geometric slenderness, tanks are prone to fail by buckling.

The buckling strength of the cylindrical shell of tanks mainly depends on two geometric parameters: the aspect ratio, as defined by the ratio between the height H and the diameter D of the cylinder (H/D), and the slenderness (R/t) calculated as the ratio between the radius R of the shell and its minimum thickness t. Increasing sizes of tanks are reported in China, reaching D = 100 m, with volumes of fluid storage in the order of 100,000m^3. Similar trends are informed in France, with tanks reaching D = 80 m; to illustrate different sizes, volume capacities have been classified as 100,000m^3 , 10,000m^3 , and 1,000m^3[1]. An increase in volume capacity is accompanied by an increase in D and a decrease in the aspect ratio H/D.

Despite of many studies in buckling behaviour of thin shells, so far few investigations have been undertaken to examine static and dynamic buckling behaviour of anchored cylindrical empty steel tanks. Dynamic buckling of above the ground steel storage tanks with conical roofs was investigated by Virella et al. [2] subject to the horizontal components of real earthquake records. The study consisted of three finite element models with height to diameter (H/D) ratios of 0.40, 0.63, and 0.95with a liquid level at 90% of the height of the tank. Accelerograms of 1986 El Salvador and the 1966 Parkfield earthquakes were chosen. It was found that the critical peak ground acceleration (PGA) lied between 0.25g to 0.35g. Rofooeia et al. [3] investigated the static and dynamic buckling of an anchored, shallow, steel cylindrical tank under the horizontal-only and both horizontal and vertical ground excitations using nonlinear static pushover and incremental dynamic analysis. He had considered both geometric and material nonlinearities for the analysis with tank of aspect ratio of 0.4 for the analysis. The Budiansky and Roth buckling criterion was used to evaluate the critical PGA and load pattern for elasto-plastic buckling of the tank shell. Finally, they had concluded that the mean maximum radial displacement of the tank wall due to bi-directional excitations was more significant than the uni-directional one for various PGA levels. Abedi et al. [4] have studied the buckling and post-buckling behaviour of thin walled cylindrical steel shells with varying thickness subjected to uniform external pressure. Study shows that the numerical behaviour predicted by the non linear finite element collapse analysis is close to the experimental results. Consequently, finite element modelling was found to be reliable enough to be used to perform non linear analysis for the study of buckling and post buckling behaviour. In this investigation the stability effects were studied by subjecting the tanks to static and dynamic loads.

The objectives of the present study are: (i) To find the critical buckling pressure and to investigate the influence of aspect ratio on buckling pressure for anchored empty steel tanks under uniform external pressure by linear and non linear static buckling analyses. (ii) To find the dynamic buckling load for anchored empty and water filled steel tanks under earthquake loading, by performing nonlinear transient buckling analysis. (iii) To find the influence of aspect ratio on buckling behaviour of empty steel tanks subjected to earthquake loading conditions and to suggest the best aspect ratio of anchored steel tank from static and dynamic loading conditions.

II. FINITE ELEMENT MODELLING

The study is conducted on cylindrical anchored steel tanks to investigate the influence of aspect ratio (height to diameter ratio) on buckling strength under static and dynamic loading conditions and to suggest the best aspect ratio of steel tank. Anchored steel tanks of constant wall thickness and height are considered for the study. Eigen buckling analysis and non linear static buckling analyses are carried out to find the influence of aspect ratio on buckling strength of tanks. Nonlinear transient buckling analyses of the empty and liquid filled tanks up to 90% of their height have undertaken to examine the dynamic buckling behaviour of steel tanks. The finite element analysis was conducted by using ANSYS [5] computer program. SHELL 181, FLUID 30 were the elements used for the modelling the tank and fluid.

Only anchored tanks are considered and primary interest is only in the buckling of the cylinder shell, since the tank bottom was not modelled. All models have fixed condition at the base thereby restricting the translations and rotations in x, y and z directions and top is free.

2.1 Material Modelling

The linear material properties used for all steel tank models including modulus of elasticity, Poisson's ratio and mass density are shown in table 1. For performing nonlinear static buckling analysis and nonlinear dynamic buckling analysis, it is necessary to consider material nonlinearity. Large deformation and elasto-plastic stress-strain properties were assumed for the cylindrical shell. Plasticity was included using bilinear isotropic hardening with yield stress of 345 MPa and a tangent modulus of 13,790 MPa. Table 2 represents the nonlinear material properties used in the present study.

Table 1 Linear Material Properties

Density	7857 kg/m³
Poisson's ratio	0.3
Young's modulus	210 GPa

Table 2 Nonlinear Material Properties

Yield stress	345 MPa
Tangent modulus	13790 MPa

2.2 Geometric Modelling

The study aims to suggest best aspect ratio of anchored cylindrical steel tank under uniform external pressure (static loading condition) and earthquake loading (dynamic loading) condition. Buckling load of the empty steel tanks under varying aspect ratios 0.43, 0.5, 0.6, 1.0 and 1.5 were studied and compared. The Eigen buckling analysis and nonlinear static buckling analysis were carried out for empty steel tanks under uniform pressure. Nonlinear dynamic buckling analyses under earthquake loading were carried out on empty and water filled cylindrical steel tanks. Transient buckling analysis was also carried out for water filled tank (90% of the height) with aspect ratio 1.5 to find the dynamic buckling load.

Table 3 Geometrical Characteristics of Tanks

Model	Height (m)	Diameter (m)	Aspect ratio(H/D)
A	15	35	0.43
B	15	30	0.5
C	15	25	0.6
D	15	15	1.0
E	15	10	1.5

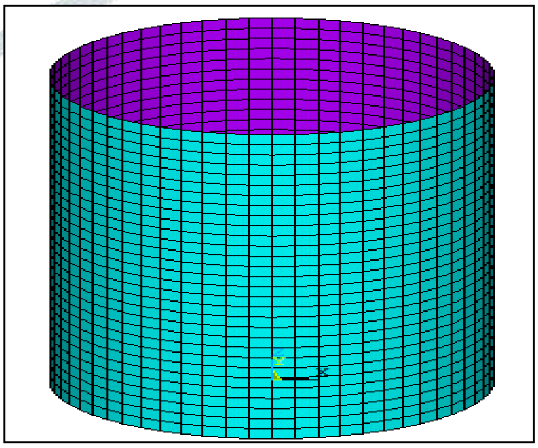
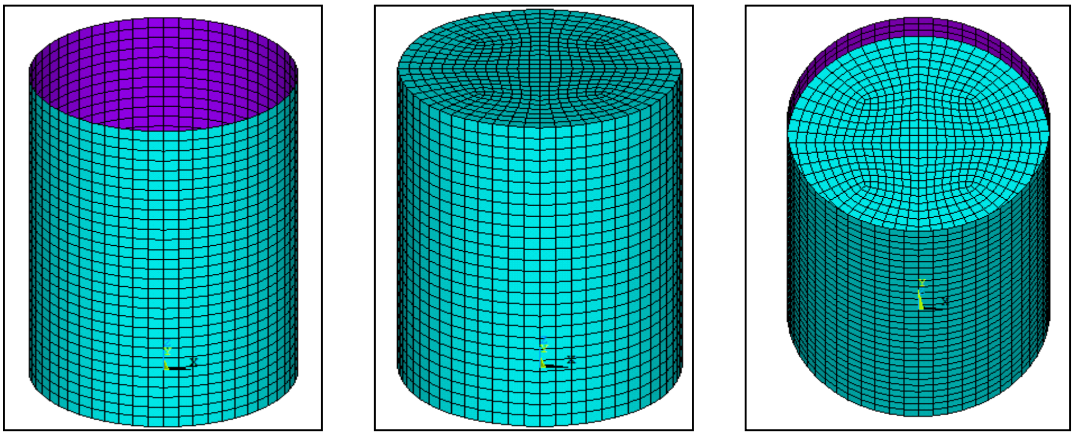


Fig.1 FE model of tank E (H/D -1.5)



(a) (b) (c)

Fig.2 FE Model-E of (a) tank wall, (b) water and(c) water filled tank

Table 4 Properties of Water

Density	983 kg/m³
Bulk modulus	2.07GPa
Boundary admittance	0.5
Height of water	13.5m

III. STATIC BUCKLING ANALYSIS UNDER UNIFORM EXTERNAL PRESSURE

Geometrical characteristics of anchored cylindrical empty steel tanks of five different aspect ratios 0.43, 0.5, 0.6, 1.0 and 1.5 considered in the study are given in table 3. All tanks are of height 15m and thickness 10mm. Finite element model of tank E (H/D-1.5) is shown in Fig.1 Geometrical imperfections are included in models in order to provide geometrical nonlinearity. For performing linear static buckling (eigen value buckling) analysis and nonlinear static analysis, uniform external pressure was applied on the outer surface of the tank wall.

IV. DYNAMIC BUCKLING ANALYSIS UNDER EARTHQUAKE LOADS

Transient dynamic buckling analyses were performed using horizontal earthquake accelerations from the 1940 El Centro earthquake with peak ground acceleration (PGA) of 0.348g shown in Fig.3. The first 3 seconds of the earthquake record was used because the maximum amplitudes of the earthquake occurred before that period.

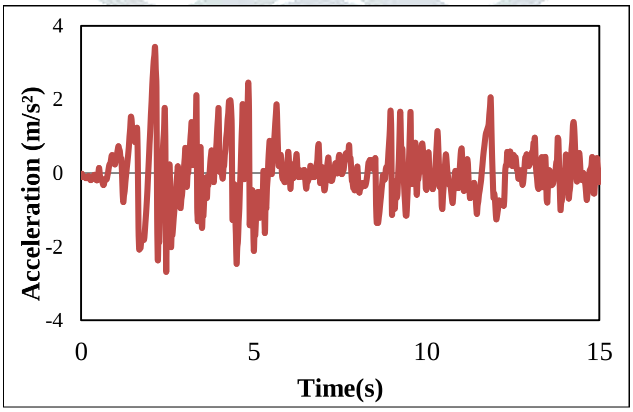


Fig.3 El Centro earthquake 1940 accelerogram

4.1 Dynamic Buckling Criteria

The Budiansky and Roth criterion (1962) was used for determining the dynamic buckling load. According to this criterion, different analyses of the structure for several load levels need to be done, and the value for which there is a significant jump in the response for a small increase in the load indicates that the structure passes from a stable state to a critical state [6].

4.2 Analysis of Empty Steel Tanks

In the study five different sizes of tanks, Model A, model B, model C, model D and model E with different aspect ratios were modelled in ANSYS 16. Aspect ratios of the tank considered are 0.43, 0.5, 0.6, 1.0 and 1.5. Geometrical properties are considered given in table 3.

4.3 Analysis of Water Filled Steel Tank

In the study model E with aspect ratio 1.5 was selected. Water was filled in the tank up to 90% of the height of the tank. Bilinear isotropic hardening material properties were included with yield stress and tangent modulus are similar to empty steel tanks. Properties of water within the steel tank are given in table 4. Figure 2 represents the modelling details of water filled tank E.

V. RESULTS AND DISCUSSIONS

5.1 Linear Static Buckling Analysis of Tanks under Uniform Pressure

Critical buckling pressure for each tank models was determined from linear static buckling analysis. Eigen value buckling analysis of tanks under uniform external pressure shows that maximum deformation occurs at the top of the tank wall. First buckling mode shape for each model are shown in Fig. 4, Fig. 5, Fig. 6, Fig.7 and Fig.8.

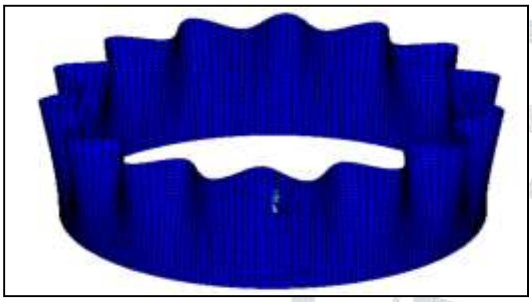


Fig. 4 First mode shape- model A

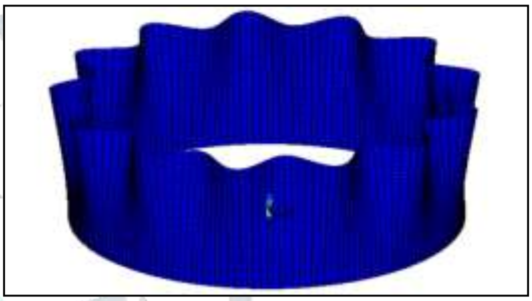


Fig. 5 First mode shape- model B

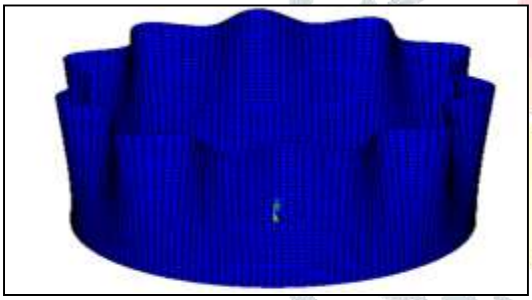


Fig. 6 First mode shape- model C

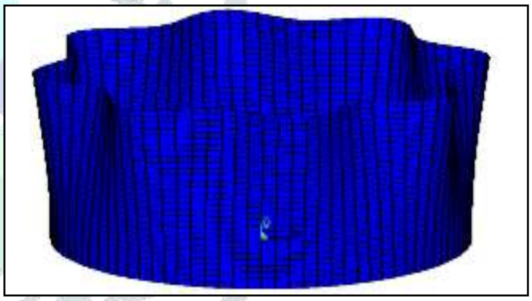


Fig.7 First mode shape- model D

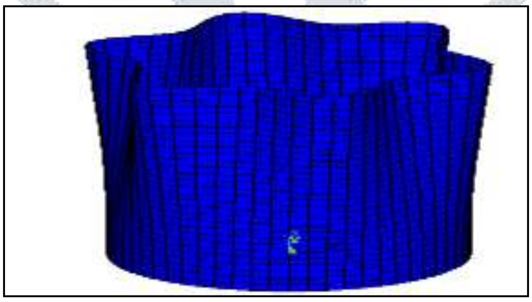


Fig.8 First mode shape - model E

5.2 Non linear Static Buckling Analysis of Tanks under Uniform Pressure

Critical buckling pressure for each tank models was determined from non linear static buckling analysis. Critical buckling pressure results are obtained from the load deflection diagram of non linear static buckling analysis for different tanks shown in Fig.9 and Fig.10.

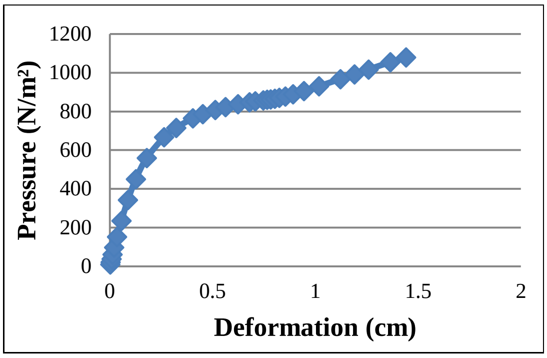


Fig.9 Load deflection diagram - Model A

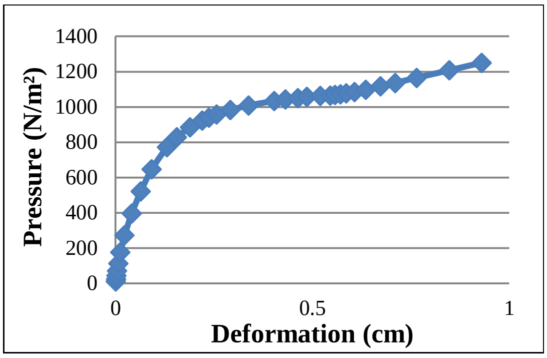


Fig.10 Load deflection diagram - Model B

Table 5 Critical Buckling Pressure Results From Static Analysis

Model	H/D	Critical buckling pressure (N/m^2)	
		Eigen value analysis	Non linear static analysis
A	0.43	1079	855
B	0.5	1352	1062
C	0.6	1788	1200
D	1.0	3880	3270
E	1.5	7210	5933

Table 5 illustrates comparisons of critical buckling pressure for eigen value buckling analysis and non linear static analysis. The value obtained from eigen buckling analysis is much greater than the non linear static analysis. For both eigen value and nonlinear static analysis, critical buckling pressure increases with increase in aspect ratio. So, eigen buckling analysis can be used to predict the nature of buckling pressure and the position at which maximum deformation of structure occurs. This is essential for monitoring load deflection curve by nonlinear analysis.

5.3 Dynamic Analysis

5.3.1 Nonlinear Dynamic Analysis of Empty Steel Tanks

The displacements at the critical node versus PGA (varying PGA for the El Centro earthquake) are plotted to form the “pseudo equilibrium path” for the Model A and is given in Fig.11. The curve follows an initially stable path and then the slope of the curve changes at the critical load because of reduction in the stiffness of the tank.

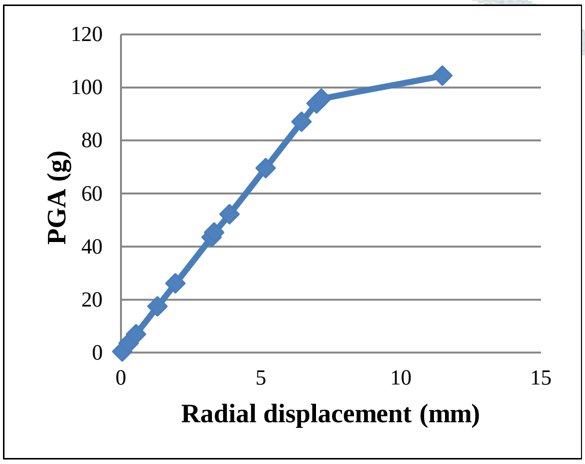


Fig. 11 Pseudo equilibrium path for critical node - model A

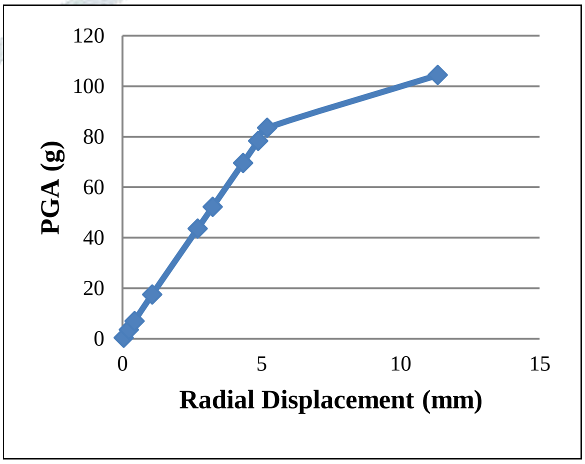


Fig.12 Pseudo equilibrium path for critical node - model B

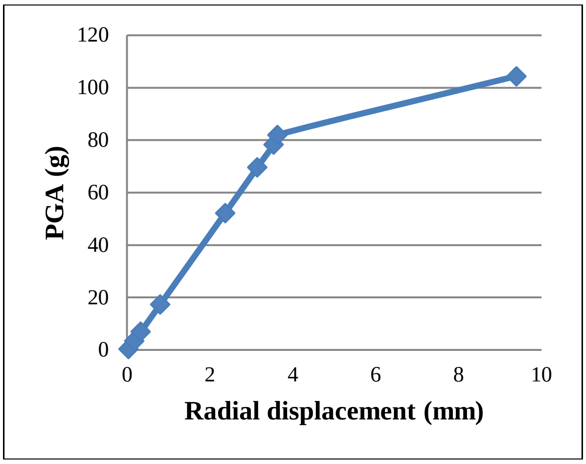


Fig.13 Pseudo equilibrium path for critical node - model C

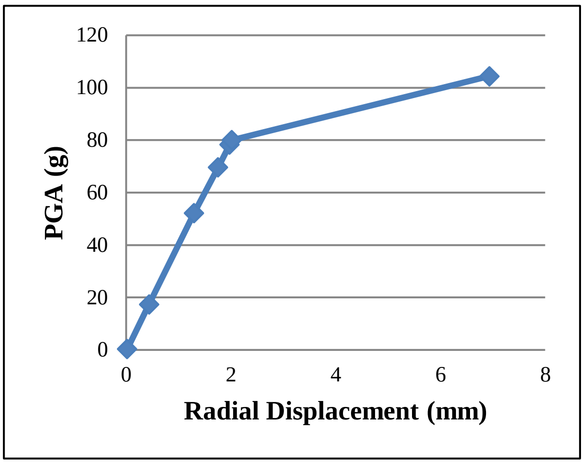


Fig.14 Pseudo equilibrium path for critical node - model D

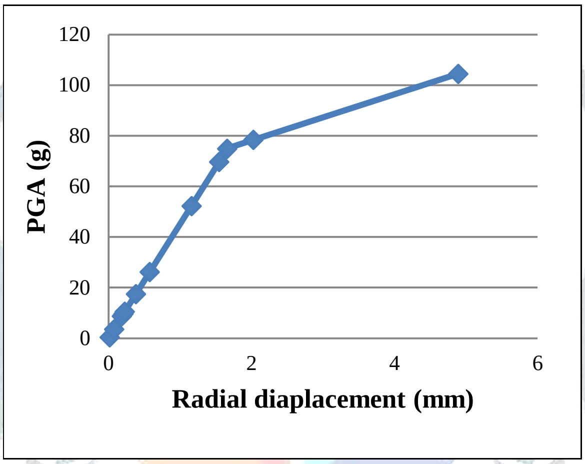


Fig.15 Pseudo equilibrium path for critical node - model E

Critical PGA for the Model A is 93.9g as shown in Fig.11. Transient response of model A for different peak ground acceleration shown in Fig.16 also helps to identify jump in radial displacement for small increase in the peak ground acceleration. The critical PGA value for the Model B is 85g shown in Fig.12 and corresponding transient response for model B is given in figure 17. The Model C, D, and E buckled at PGA values of 82g, 80g, and 75g are shown in Fig.13, Fig.14 and Fig.15 respectively. This means that the empty tanks will not buckle under the influence of any possible real world earthquake. Transient response of tank model C, D and E are shown in Fig.18, Fig.19and Fig.20 respectively.

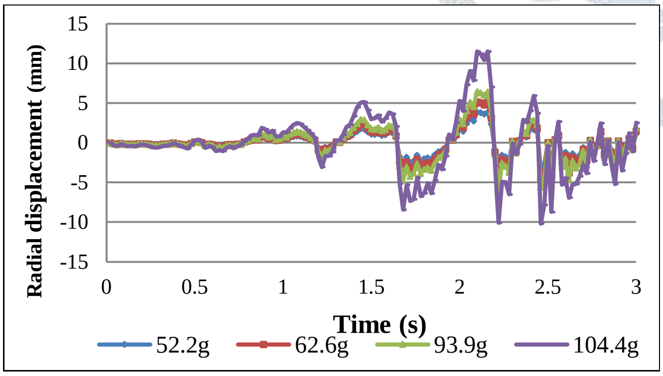


Fig.16 Transient response- model A

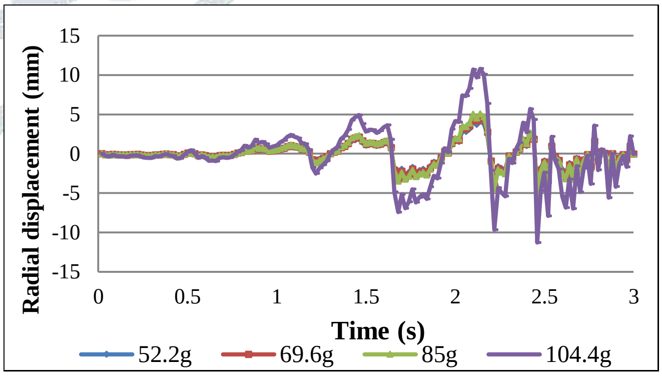


Fig.17 Transient response- model B

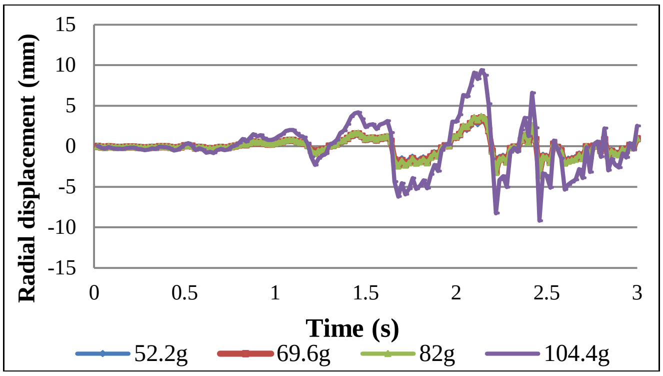


Fig.18 Transient response- model C

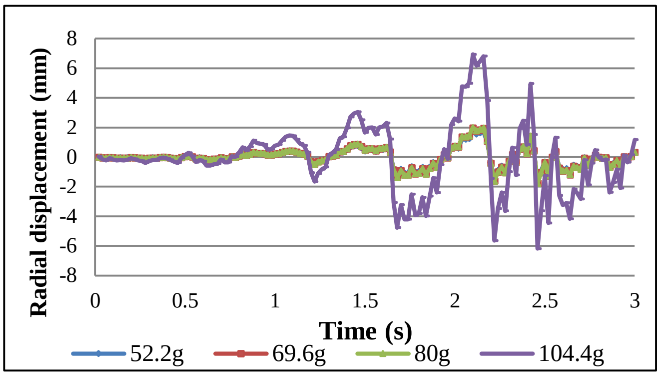


Fig.19 Transient response- model D

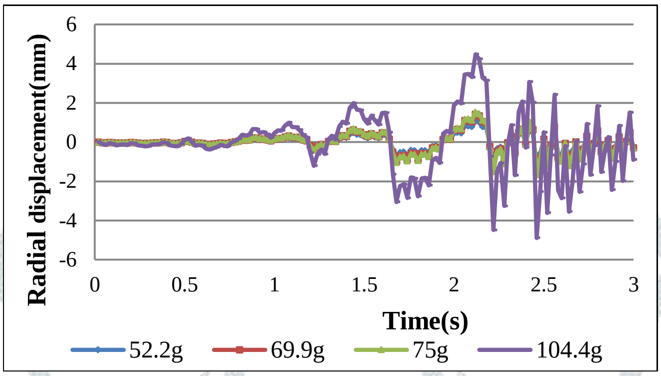


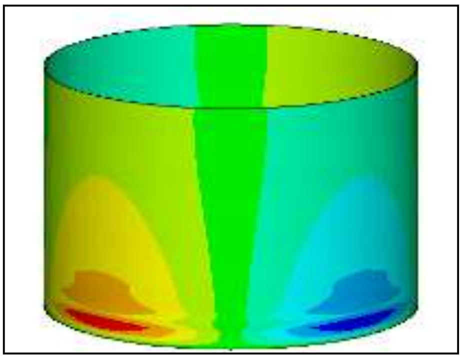
Fig.20 Transient response- model E

Table 6 represents the critical peak ground acceleration for each tank model. Results show that critical PGA for empty tank under dynamic earthquake loads decreases with increase in aspect ratio. Critical PGA for earthquake loading is very high for empty cylindrical steel tanks to fail by buckling. So, empty steel tanks are safe from buckling consideration under earthquake loading.

Table 6 Critical PGA for Tank Models

Model	Aspect Ratio (H/D)	Critical PGA (g)
A	0.43	93.9
B	0.5	85
C	0.6	83
D	1.0	80
E	1.5	75

Figure 21 shows the deformed configuration of the tank, subjected to earthquake load. Figure 22 gives the variation of radial displacement along the height of the tank wall corresponding to critical PGA. The maximum deformation occurs just above the base of the tank in the form of an elephant foot shape. It means that the structure undergo elephant foot buckling. Elephant foot buckling is an outward bulge, occurs just above the tank base. From the figure, it can be seen that maximum radial displacement of tank wall for each model occurred within the height of 2m above the tank base. So, the analyses indicate that the critical buckling of tank wall occurs at a region near the base of the tank.



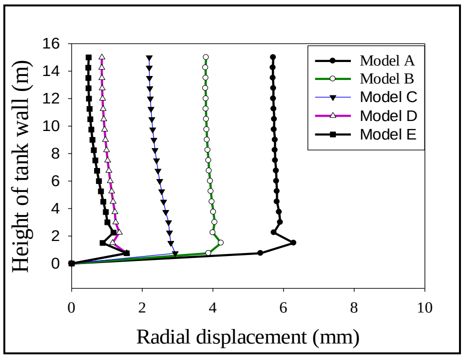


Fig.21 Deformed shape of the tank Fig.22 Radial displacement v/s height

From Fig.21 and Fig.22, it is clear that all five tank models undergo elephant foot buckling when it is subjected to earthquake load.

5.3.2 Nonlinear Dynamic Analysis of Water Filled Steel Tank

Figure 7.23 and 7.24 shows the pseudo equilibrium path and transient response diagram for water filled tank model E. Both the figures are formed based the Budiansky and Roth (1962) criterion in order to find the critical peak ground acceleration for tank model.

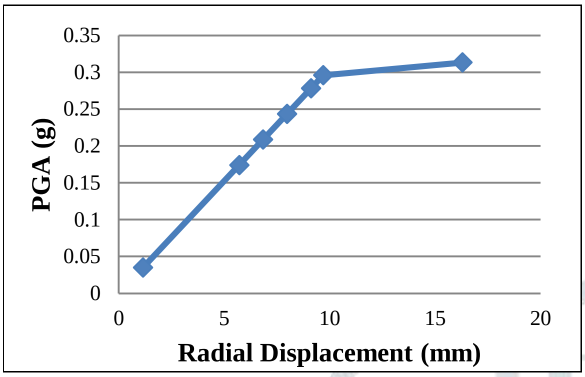


Fig.23 Pseudo equilibrium path at critical node –model E

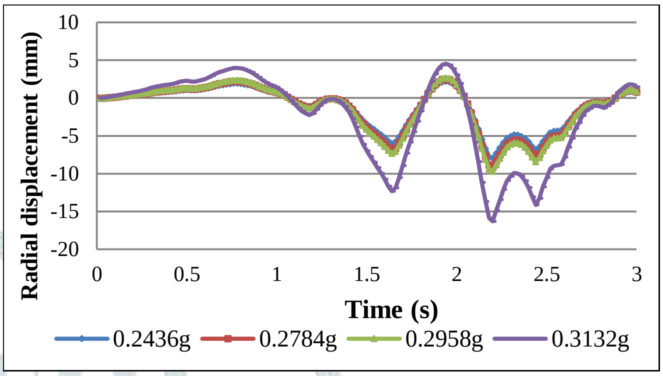


Fig.24 Transient response of water filled tank-model E

Critical peak ground acceleration for water filled tank model E is 0.2958g from Fig. 23. The peak ground acceleration value is very small for the water filled tanks. So the water filled tanks will buckle under the influence of any possible real world earthquake. Fig.24 shows the jump in displacement after critical peak ground acceleration 0.2958g.

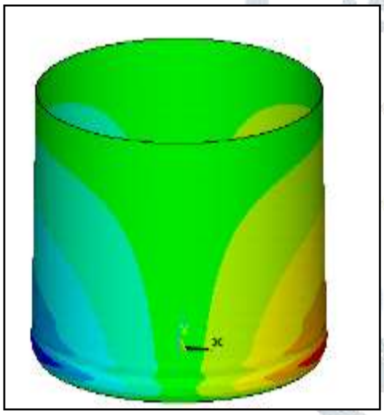


Fig.25 Deformed shape of water filled tank

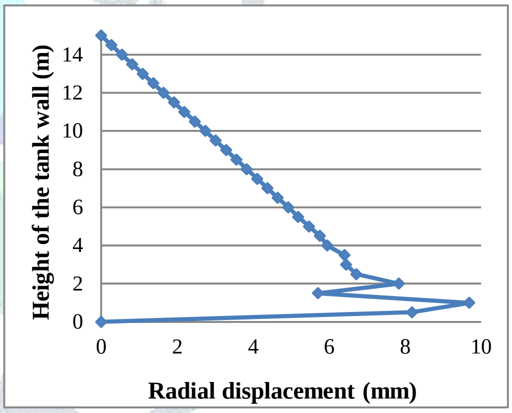


Fig. 26 Radial displacement versus height of the tank

Radial displacement at critical PGA for water filled tank model E is shown in Fig.25. Fig.26 gives the variation of radial displacement along the height of the tank wall corresponding to critical PGA. Similar to empty steel tanks under dynamic loading, maximum deformation occurs just above the base of the tank in the form of an elephant foot shape. It means that the structure undergo elephant foot buckling. From the figure, it can be seen that maximum radial displacement of tank wall for each model occurred within the height of 2m above the tank base.

VI. CONCLUSIONS AND RECOMMENDATIONS

In this study an effort was taken to find the critical buckling load under static uniform external pressure and dynamic earthquake loading conditions by analysing anchored cylindrical steel tanks based on different aspect ratios. Empty steel tanks are considered for obtaining critical buckling pressure under uniform external pressure. Both empty and water filled up to 90% of the height are considered for finding critical peak ground acceleration under dynamic earthquake loading. Linear static buckling analysis (Eigen buckling), nonlinear static buckling analysis and nonlinear transient buckling analysis were carried out using ANSYS 16 software. Tank wall was modelled as a shell element and water body was modelled as an acoustic element. Following conclusions were reached from the result obtained:

1. Influence of aspect ratio on critical buckling pressure was similar for both eigen value and nonlinear static buckling analysis of empty tanks under uniform external pressure
2. Eigen buckling analysis can be used to predict the nature of buckling pressure and the position at which maximum deformation of the structure take place

3. Linear and nonlinear static buckling analyses results under uniform external pressure shows that buckling strength increases with increase in aspect ratio. Model E with aspect ratio 1.5 is having the maximum buckling strength under uniform external pressure. Model E is the best model under static loading condition
4. In the case of dynamic buckling the peak ground acceleration (PGA) for the earthquake loading is very high for the empty cylindrical tanks to fail by buckling. It is concluded that the empty tanks are safe from the buckling consideration when subjected to earthquake loading
5. Nonlinear dynamic buckling analysis under earthquake loads shows that critical PGA for empty tank under dynamic earthquake loads decreases with increase in aspect ratio. Model A with aspect ratio 0.43 is (H/D =0.43) is the best model under dynamic buckling
6. For water filled tank, critical PGA is very small. Water filled tanks may buckle under the influence of any possible real world earthquake.
7. Dynamic buckling analyses on steel tanks with different aspect ratios indicate that the maximum radial displacement of the tank wall corresponding to critical PGA occurred within the height of 2m above the tank base and it is in the form of elephant foot buckling

Hence it is concluded that, tanks fail by static buckling when they are empty, whereas for dynamic buckling they fail when they have liquid in them, because of added mass. Tank with higher aspect ratio are more unsafe under earthquake loading conditions.

6.1 Scope for Future Study

In this study buckling behaviour anchored steel tanks are considered under uniform external pressure and earthquake loading conditions. The present study can be extended by including the buckling behaviour of tanks farms with group effects under wind and thermal loading, effects of tank components on buckling, such as ring stiffeners or ladders, which modify the flow around the axisymmetric shell and topographic effects etc. Researches on these areas will helpful for providing much safety to the tanks hence reduce the damages to the life and properties.

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