NOVEMBER 2017 M.Sc. in Civil Engineering MAHMOOD HUNAR DHEYAALDIN

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GRADUATE SCHOOL OF

NATURAL & APPLIED SCIENCES

EFFECT OF STIFFENERS ON STRUCTURAL BEHAVIOR OF STEEL LIQUIDS TANK

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MAHMOOD HUNAR DHEYAALDIN

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Effect of Stiffeners on Structural Behavior of Steel Liquids Tank

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Prof. Dr. Mustafa ÖZAKÇA

By

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Mahmood Hunar DHEYAALDIN

ABSTRACT

EFFECT OF STIFFENERS ON STRUCTURAL BEHAVIOR OF STEEL LIQUIDS TANK

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M.Sc. Thesis in Civil Engineering

Supervisor: Prof. Dr. Mustafa ÖZAKÇA

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The finite element method is used to conduct the analysis of liquid storage tanks. This research has focused on the structural behaviors, under static condition, free vibration and buckling of steel liquid tanks which are designed according to American Petroleum Institute (API) 650 standards. The materials properties and the real geometrical and load measures have been considered in the numerical model. These storage tanks are stiffened with standard steel profiles. The equivalent stress (Von-Mises) distribution, deformation in circular wall of liquid tank, buckling load and fundamental frequency are computed using finite element method in order to investigate the effect of type of the stiffener, number of course and location of stiffener on structural behavior of liquid tanks. The uses of the stiffeners decrease the stress and increase the fundamental frequency and buckling multiplier factor of wall tank and improve the other structural behaviors.

Keywords: Finite element method, Stiffener, Storage tank, API-650 standard.

ÖZET

ÇELİK SIVI TANKLARIN YAPISAL DAVRANIŞINA TAKVİYE ELEMANININ ETKİSİ

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71 Sayfa

Sıvı depolama tanklarının analizinde sonlu elemanlar yöntemi kullanılmıştır. Bu araştırmada, Amerikan Petrol Enstitüsünün API 650 standartlarına göre tasarlanan çelik sıvı tanklarının statik, serbest titreşim ve bükülme davranışları üzerine yoğunlaşmıştır. Sayısal modelde malzemelerin mekanik özellikleri, gerçek geometrik ve yük değerleri dikkate alınmıştır. Bu depolama tankları standart çelik profillerle takviye edilmiştir. Sıvı deponun dairesel duvarda deformasyonu, burkulma yükü ve doğal frekansı, eşdeğer gerilim (Von-Mises) dağılımı, sonlu elemanlar yöntemi kullanılarak hesaplanmış ve takviye tipinin, bölüm sayısının ve takviye yerinin sıvı tankların yapısal davranışına etkisini araştırılmıştır. Profil takviye kullanılması, tank duvarındaki gerilmeyi azaltmakta, doğal frekansı ve bükülme katsayısını artırmakta ve diğer yapısal davranışları iyileştirmektedir.

Anahtar kelimeler: Sonlu elemanlar yöntemi, Profil takviye, Depolama tankı, API-650 standardı.

To My Families

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LIST OF SYMBOLS/ABBREVIATIONS

ANSYS	American Computer-aided engineering software
API	American Petroleum Institute
A_{reqd}	Total required cross-sectional area of the stiffener region
A_{stiff}	Required cross-sectional area of stiffener
BS	British Standard
BLF	The buckling load factor
CA	Corrosion Allowance
D	Nominal tank diameter
D_L	Dead load
DOF	Degree of Freedom
EN	European Standard
E	Modulus of elasticity
f	Smallest allowable tensile stresses.
f_C	Smallest of the allowable compressive stresses
F_y	Yield strength of the component at the maximum operating temperature
FE	Finite Element
F	Force

FSI	Fluid structural interaction
G	Specific gravity of the liquid
H	Shell height
H_{safe}	Maximum height of unstiffened shell permitted, based on the calculated minimum thickness
H_{TS}	Transformed height of tank shell
$h_1, h_2 \ldots h_n$	Height of shell courses
I_{act}	The actual moment of inertia
I_{reqd}	Required moment of inertia of the stiffener ring
JE_b	Joint efficiency of bottom plate
JE_C	Joint efficiency of compression ring
JE_r	Joint efficiency of roof plate
JE_S	Joint efficiency of shell plate
JE_{st}	Joint efficiency of splice of stiffener sections
L_1, L_2	Distances between adjacent intermediate stiffeners or intermediate stiffener and top or bottom of shell
L_r	Minimum roof live load on horizontal projected area of the roof
N_S	Number of intermediate stiffeners
N	Number of waves into which a shell will buckle under external pressure
P_e	Specified external pressure
P_r	Total design external pressure for design of roof

P_s	Total design external pressure for design of shell
PC	Personal Computers
Q	Radial load imposed on the intermediate stiffener by the shell
R	Roof dish radius
r	Radius of gyration
SSI	Soil Structural Interaction
$S_d(\sigma)$	Allowable design stress
$S_t(\sigma)$	Allowable stress for hydrostatic test condition
t	Shell thickness, including corrosion allowance
t_b	Thickness of bottom plate under the shell, including corrosion allowance
t_{cone}	Required thickness of cone roof plate, including corrosion allowance
t_{dome}	Required thickness of dome roof plate, including corrosion allowance
t_{shell}	Actual thickness of shell at level under consideration, including corrosion allowance.
t_{smin}	Minimum thickness of thinnest shell course.
t_d	Design shell thickness
t_t	Hydrostatic test shell thickness
V_1	Radial load imposed on the stiffener by the shell
V	Specified design wind velocity
W_{shell}	Contributing width of shell on each side of intermediate stiffener

W	Weight
X_{dome}	Length of umbrella or dome roof within tension/ compression ring region
X_{cone}	Length of cone roof within tension/compression ring region
X_{shell}	Length of shell within tension/compression ring region
ν	Poisson's ratio
ρ	Mass density
σ	Normal stress
ε	Strain
λ	Slenderness ratio
θ	Angle between a horizontal plane and the surface of the roof plate (degrees)
2D	Two Dimensional
3D	Three Dimensional

CHAPTER 1

INTRODUCTION

1.1 General

Cylindrical liquid tanks have simple geometries, primarily storage cylindrical shell wall with/without a dome. There are usually performing as much as extra complicatedness in a structural analysis. Based on the diameter of the cylinder, tanks will have a floating roof fixed, or perhaps without a dome (which is identified as the open tank) at the top. Open top cylindrical tanks, on the other hand, are regularly created with a stiffener to give security to the shell wall, therefore, abstain from buckling. The typical structure of cylindrical open-topped steel tanks is shown in Figure 1.1 [1-3].

Cylindrical tanks have been utilized as a part of all segments of the industry. Liquid tanks have been particularly utilized for storage of water or another type of liquid. In addition to mentioned application, tanks are important components in liquid transmission and distribution systems. The design and sustaining of atmospheric and low-pressure vessels for liquid storage is becoming ever more vital as water and crude oil storage capacity utilization rises and water and oil storage capacity demands grow globally. On the other hand, failure of liquid tanks may attend to failure due to the water crisis, fire, health and environmental hazard owing to the spread of chemicals or/and liquid fuel [4,5]. As typical thin-walled structures, tanks are very susceptible to buckling under wind and seismic loads especially when they are empty or partially filled. Over the past few decades, buckling failures of cylindrical steel tanks and silos during windstorm and earthquakes have occurred in many countries and region [4]. Ground tanks, which are also known as reservoirs, can take different shapes (e.g. rectangular, cylindrical, and cylindrical with conical base). From the structural point of view, cylindrical liquid tanks have been so proper for the external tank walls in the horizontal direction have been satisfied only with pressure or tension, in another type of liquid tank, the load is connected. Storage tanks have been relevant further with

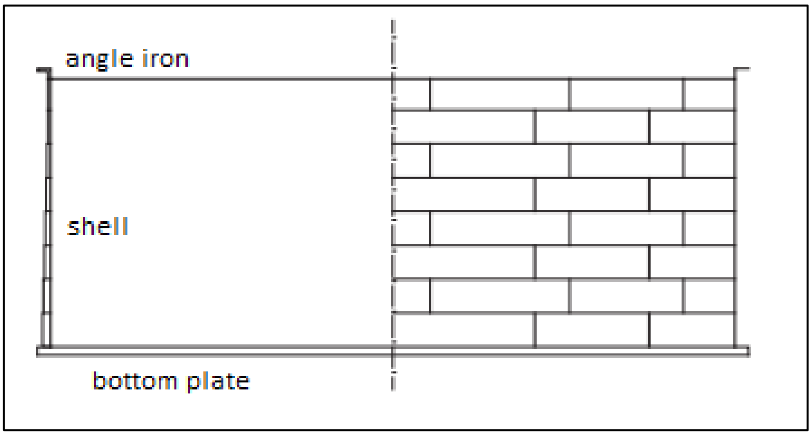

Figure 1.1 Typical structure of open topped steel tank

respect to amount of material needed for construction. Presently more than 70 % of all tanks are in cylindrical form. The cost-adequacy and safety are the essential factors in picking the sort of capacity liquid tank [6]. Cylindrical tanks can be easily constructed using concrete or steel in various sizes to satisfy the design limit necessities

The advancement of scientific examinations on structural performance of liquid tanks reflects the expanding significance of the structures as usual. As their numbers and sizes began to grow, their tendency to vibrate under wind and/or seismic loading became a matter of concern. For instance, the possible failure of large tanks containing flammable liquids in and around densely populated areas presents a critical fire hazard during severe earthquakes. In addition, the consequences of total spills of the contained liquid, as well as structural damage to the tank and its accessories, may pose a considerable economic loss. The performance of liquid storage tanks during Alaska in 1964 and San Fernando in 1971 earthquakes revealed a much more complex behavior. Thus, although the problem has been recognized, the state of knowledge of liquid-tank seismic vibrations, Soil Structure Interaction (SSI) and Fluid Structure Interaction (FSI) are, still, not entirely satisfactory.

There is considerable effort in the development of reliable liquid storage tanks since beginning of twentieth century. These tank design were based on the very simplified models which ignore the FSI and SSI. Nevertheless, the structural design and analysis of liquid tanks involves complicated shell theories and complex differential equations, which either cannot be solved at all, or whose solution requires the use of advanced calculus unfamiliar to structural engineers. Therefore, many approximate analysis and design methods have been developed, mainly on the simplified assumptions

Hence, it is not surprising that the development of the numerical methods since mid of twentieth century has led to a gradual cessation of attempts to find more accurate analysis and reliable designs. But, with today's availability of greatly increased computing power, the researcher concentrated on the completeness analysis and design rather than simplicity.

The preliminary designs are obtained according to American Petroleum Institute (API) 650 standard which to present design engineers with simple, fast, reasonably accurate and efficient instruments for the safer design. The present study develops a method of analyzing the structural performance of ground-supported, cylindrical liquid tanks by means of a digital computer such as advanced PC. The reliability of the tank design which is based on API 650 standard was confirmed by conducting static, free vibration and buckling analyses using Finite Element (FE) software.

1.2 Objectives and Scope of the Study

The principal goal of this research is to investigate the effect of the stiffener and structural performance of liquid tanks by means of an FE method. The general purpose FE software American Computer-aided engineering software (ANSYS) workbench is employed for FE modeling. The following research develops a method for analyzing the structural performance of deformable, cylindrical liquid tanks. The research was done in three stages: 1) a specific analytical approach of the system of the liquid tank 2) the preliminary design of full-scale tanks according to API 650 standard, and 3) a development of numerical model using ANSYS FE model for verifying current code values and investigation of structural performance of designed tanks.

To achieve the objectives, the following tasks will be performed:

1. Perform a comprehensive literature review on the structural behavior of liquid storage tanks.
2. Preliminary design the tanks based on API 650 standard methodology.
3. Develop a FE model which is capable of evaluation the linear elastic, buckling and free vibration behavior of cylindrical liquid tanks.

4. Investigate the effect of stiffener on the structural behavior of liquid tanks
5. Study the alternative design which is included various number of courses in order to reduce the weight of tank
6. Determine the fundamental frequency, buckling load multiplier, equivalent stress distribution and deformation of liquid storage tanks under services loads (such as weight of tank, weight of the content, hydrostatic loads due to liquid pressure, external pressure)
7. Verify the current code values (API 650 design output) for structural safety by conducting a numerical analysis based on FE method.

1.3 Organization of Chapters

This thesis consists of five chapters. An introduction to the "liquid storage tanks" and their characteristics, objective and scopes of the thesis and the organization of thesis are presented in Chapter 1.

Chapter 2 presents a comprehensive literature review on structural behavior of liquid tanks. Structural behavior of storage liquid tanks in the few past disasters (earthquakes and hurricanes) and previous research studies on structural properties of liquid tanks are discussed in this chapter. In addition, a literature review on classification of liquid storage tanks as well as introduction to current codes and guidelines related to design and analysis of tanks is included.

Chapter 3 deals with preliminary design method employed based on API 650 standard in this thesis. The general equations and formulation for design is briefly reviewed in this chapter. ANSYS FE model for static, buckling and free vibration analysis are briefly described in this chapter.

Chapter 4 presents two example in two part separately. In the first part the preliminary design of liquid storage tanks is done. A number of liquid storage tank models with various number of courses, number of stiffener and types of stiffener, (but tank capacities is kept constant in order words, high and radius of tank is constant) are developed according to API 650 standard. In the second part of each example, the structural performance of the preliminary designed tank by API 650 standard [7] is evaluated and verified by carrying out static, free vibration and buckling analysis using FE program.

Finally, Chapter 5 gives a summary and conclusions from the present study. This chapter also gives a number of recommendations for future works and further investigation. The list of references is giving, at the end of thesis.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Seismic damage of liquid storage tanks during recent earthquakes demonstrates the need for a dependable technique to assess their design safety. The Alaska earthquake of 1964 caused the first large-scale damage to tanks of modern design [8] and profoundly formed the research into their dynamic characteristics. Before that time, the development of dynamic response methods of liquid tanks estimated the container to be rigid and focused concentration on the dynamic response of the contained liquid. This topic became very important and popular in Turkey after 1997 Marmara earthquake. Some of the oil tanks damaged in Kocaeli region during Marmara earthquake.

At this point the subject appears to have been laid to rest until the seismic damage in 1964 started examinations concerning into the dynamic attributes of holders. In addition, the arrangement capacity has been upgraded by the development of the advanced PC as well as different related numerical procedures. The determination of the seismic response of tanks requires extensive and rigorous analysis, which, in most cases, demands long computational times. Despite the existing codes, the simplifying assumptions and analyses that have been performed since the early seventies, the major issue of understanding their exact seismic behavior is still incomplete and under investigation. Until recently, publications of relative research work focused on approximate procedures and simulation models in an attempt to approach the subject. However, in any case, specialized knowledge and reliable assumptions regarding the interaction between tank and contained liquid are necessary in order to simulate the complex effects of hydrodynamic loading (such as the impulsive pressure, the convective pressure component etc.) in conjunction with generating a compatible FE mesh for the shell of the steel tank. The following sections present a brief historical review of the literature, failure modes of tanks, classification of tanks, design standards and outline the methods of analysis employed in the present study.

2.2 Historical Background

One of the earliest of these studies, due to Hoskins and Jacobsen [9], reported analytical and experimental investigations of the hydro-dynamic pressure refined in rectangular tanks when subjected to horizontal motion. Later, Jacobsen and co-workers [10-11] investigated the dynamic performance of rigid cylindrical tank.

In the mid-1950's, Housner [12] proposed model, commonly applied in civil engineering practice, for guessing cylindrical tanks, rigid and rectangular excited liquid response in seismically. The hydro-dynamic pressure of the contained liquid is divided into two components; the *impulsive pressure* load originated by the part of the liquid accelerating with storage tank and the *convective pressure* load originated by the part of the liquid sloshing in the tank. The mechanical model which can be evaluated from the geometry of the tank and the attributes of the contained liquid was developed. Housner's model is broadly utilized to approximate the most extreme seismic response of storage tanks. [13-15].

The first principal utilization of a computer in analyzing and design of liquid cylindrical storage tanks had been done in 1969 by Edwards [16]. The FE method was used with a thin shell method to estimate the stresses and displacements in a circular liquid-filled container subject to seismic load. This research has been including the linked interaction between the tank elastic wall and the contained liquid.

Shaaban and Nash [17] carried out research work deal with the seismic response of elastic, circular cylindrical tanks utilizing the technique of FE method. Shortly after, Balendra and Nash [18] studied the further speculation of this investigation by including a versatile elastic dome on top of the liquid storage tank.

Veletsos and Yang [19] displayed improved recipes to get the fundamental natural frequencies of the liquid-permeated shells by the Rayleigh-Ritz method of energy. Extraordinary consideration had been provided to the $cos\theta$-type modes of vibration for which there is a single cosine wave of deformation in the circumferential regulation. More recently, a numerical study is conducted by Spritzer and Guzey [20]. The large, circular, above ground, steel, cylindrical, open-top has been investigated using FE models where liquid tanks constrained to uniform seismic forces. They include non-linear material properties and geometry deformations in the model. They investigated tanks which include height to radius ratios, or aspect ratios, between 0.4 and 2.0. They study hydro-dynamic hoop stresses, elephant's foot buckling, and uplift.

The FE method and the boundary element method were utilized by many researchers, such as Grilli et al [21], Huang et al [22] and Gedikli [23] to examine the problem. Gedikli [23] has studied the dynamic properties of liquid storage tanks which has rigid baffle. Hwang and Ting [24] used the boundary component technique to estimate the hydrodynamic pressures load correlated with small amplitude excitations in the liquid domain.

In 2003, Nachtigal et al [25] suggested that the common basic assumption, adopted from Housner [26] and Veletsos [27], They contrasted their results with the design codes, API 650 and EC8. They suggested that the fundamental frequency for current design requirements which were no longer tenable under the immediate hypothesis of shell hypothesis and shell design. Accordingly, ought to be reevaluated which a cylindrical liquid tank performs like a cantilever beam without deformation of its cross-section had been obsolete. Accentuation was on the examination of the fundamental frequencies for the tank liquid technique.

Extensive study on the dynamic performance of liquid tanks has also been carried on in the aerospace industry. With the advent of the space age, attention was focused on the behavior of cylindrical fuel tanks of rockets, the motivation being to investigate the influence of their vibrational characteristics on the flight control system. However, the difference in support conditions between the aerospace tanks and the civil engineering tanks makes it difficult to apply the aerospace analyses to civil engineering problems, and vice-versa. A comprehensive review of the theoretical and experimental research of the dynamic performance of liquid tanks of space vehicles could be found in [28].

Several experimental studied have been conducted in addition to analytical and numerical research work in past years. Those combine forced and ambient vibration tests on full-scale liquid storage tanks [8], tries different things with recreated seismic ground movements of numerous aluminum tank models [29] seeks on built lapped welded steel liquid tanks which thought to be the extremely enormous of its kind in the world [30].

2.3 Types of Liquid Tank

For the true objective of thesis, we concentrate on the air or low-pressure storage tank broadly utilized from the production fields to the refinery. Corresponding tank sizes range from around 3 m in diameter to over 125 m diameters for any of the tanks ever constructed. Liquid tanks develop in all sizes and shapes. Exceptional applications may expect tanks to be rectangular, in the form of horizontal cylinders, or even spherical in shape. Horizontal cylinders and spheres are generally used for full pressure storage of hydrocarbon or chemical products. The most widely recognized shape utilized is the vertical, cylindrical storage tank. Net limits can go from 100 barrel to over 1.5 million barrel in a single storage tank [31]. The common types of storage tanks in utilized as:

- Open top tanks,
- Fixed-roof tanks, external floating-roof tanks,
- Internal floating-roof tanks
- Closed floating-roof tank.

Figure 2.1 illustrates trend in industry, which has accentuated enhanced safety and enhanced item losing control. Oil Industry, for the most part, depend on either fixed-roof tanks or open-top tanks.

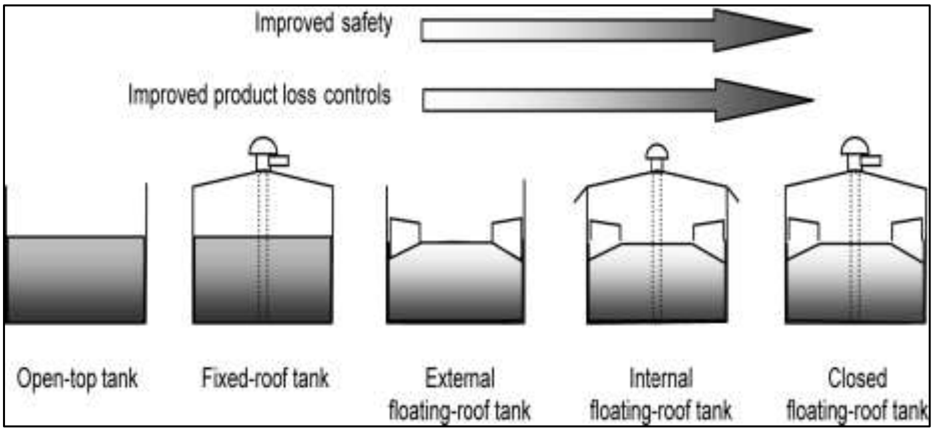


Figure 2.1 Type of storage tank [31]

2.3.1 Open top tanks

This class of tank is open to the air suddenly it was interested in the environment; subsequently, it is called an atmospheric tank. They can't be used for petroleum or chemical compound industry be that as it may, might be utilized for fire water/cooling water. While it gives liquid control, direct introduction of the liquid surface to the environment assures high evaporative misfortunes, item scents, and expanded potential for fires [32-33].

2.3.2 Fixed-roof tank

The fixed-roof tank gives improved regulation of item it means product vapors and lessens the potential for hazards for example fire. The fixed-roof tank uncovered the liquid surface to the tank vapor period, delivering certain amount evaporative misfortunes. is expands the likelihood of forming an excitable gas mix-up in the vapor space. Thus, fixed roof tanks in refineries are commonly utilized for products with vapor pressures less than 10 kPa [34]. Fixed roof tanks are composed as [34]

- Low pressure tanks (internal pressure less than 2 kPa).
- High pressure tanks (internal pressure less than 5.6 kPa).
- Atmospheric tank (free vent).

2.3.3 Floating roof tanks

Floating roof tanks are another types of the storage tank which the roof floats immediately on top of the product. There are two sorts of the floating roof:

- external floating roof.
- internal floating roof.

The internal floating roof has roof floats in a fixed rigid roof tank. External Floating roof has roof floats in an open tank [34]. They are for the most part not utilized as a part of generation operations. These tanks are principally utilized as a part of pump stations where the crude oil has balanced out to the pressure of not exactly less than, 76 kPa.

2.4 Tanks Failure Modes

Failure of atmospheric liquid tanks has been extensively studied in last century [35]. The structural representation of liquid tanks through past earthquakes confirms that steel liquid tanks are defenseless to collapse or damage. The involved deformed shapes of the interaction and tank separating the liquid and the structure result in a wide class of failure modes. A recent earthquakes show such as unanchored tanks and cylindrical tanks with a large height-to-diameter ratio seemed to be the most vulnerable to tank failure [36]. The weakness of most storage tanks also depends on the quantity of liquid stored. For instance, full filled tanks have subject to larger lateral forces (because of earthquake) and overturning moments because of liquid sloshing.[37]. The main failure mechanisms are [38]:

Shell Buckling: is the most popular of one of the failure in thin wall tanks. It is happened by an obvious buckling shape of the bottom shell courses (known as "elephant foot") as shown Figure 2.2. In a preliminary study [39], it was showed that this type of failure occurs due to merged effort of vertical compressive stresses surpassing the yield stress.

In this failure mode mechanism, rupture of the walls' generally rupture of weld surface is occurred and it cause to the loss of the content [40-42].

Figure 2.2 Elephant foot buckling [43]

The diamond shape buckling shown in Figure 2.3 is a different form of shell buckling. The diamond form shape buckling may occur at the top part of the tank due to sloshing of the liquid or at the bottom part of the tank due to use of thin shells [44]. The allowable buckling stress in API 650 standards is based on buckling stress value under axial load [7].

Figure 2.3 Diamond shape buckling.[45]

Roof Damage: as shown in Figure 2.4 occur mainly due to sloshing of the contained liquid. The rocking motion of the tank is another source of roof damage. If liquid tanks stay full or approximately full, this sloshing of liquid cause a higher pressure distribution against the roof of tank.

Figure 2.4 Roof damage of storage tank

This may lead to a break-up of the weld between shell wall and roof of the tank and lead to a leakage (loss) of liquid in the tank. Research of previous earthquakes explicate that floating roofs have commonly been more critical destruction than fixed roofs [46,47].

Tank Support System Failure: is particular for above-stage tanks which are leveled by steel frames or concrete (or columns). This sort of failure is less worry to huge liquid tanks [48,49].

Uplift: steel liquid tanks are powerless to base uplift and consequent damage during severe earthquake events. The deflections of the base-plate can cause substantial inelastic rotation demands between shell wall and base plate combination during uplift [50,51].

Foundation Failure: can be common in the case of weak foundation inclined to liquefaction, appearing into the base of tank revolution and settlements. On account of capacity tanks, tensile stress could likewise generate uplift displacement of the tank base, dividing shell wall from the baseplate [52,53].

Connecting Pipe Failure: it is the most well-known of one of the failure mechanism The fracture of the pipes at the connections to the tank results from differential displacement between the tank and the piping [54]. as a mentioned result known of rocking motion, buckling uplifting annular base plate of the liquid cylindrical tank rupture of the piping and its associates to the tank occurs [55].

Manhole Failure: because of fundamental worries upon the manhole vent cover, this last can come up short which brings about the loss of content within the opening [56].

Considering the above-mentioned types of failures, many research works were carried out in order to minimize hazard due to tank failure. They examined the types of damages which are reported between 1933 and 1983 earthquakes [57].

2.5 Storage Tank Design Codes of Practice

Structural design is often governed by a code of practice appropriate to the location of the structure. Whilst the basic design objectives are similar in each code, the specified stresses and factors of safety may vary. Tank design codes reflect the culmination of decades of work by many dedicated individuals. Three widely used codes are:

- API 650
- British Standard (BS) European Standard (EN) BS EN 14015:2004
- API 620.

The API 650 code is titled as *Steel Welded for Oil Storage Tanks*. This standard can be used for designs where the internal pressure is equal to or less than 17.24 kPa. These tanks have historically been used to house petroleum for use by chemical plants and power production facilities, as well as basic and strategic reserves.

BS EN 14015:2004 is the European code design and analysis for tanks. This EN code shares some similarities with the API 650 code. Such as, API 650, EN 14015 computes the shell course required thickness via a fairly straightforward equation

The API 620 code is entitled *Design and Construction of Large, Welded, Low-Pressure Storage Tanks*. After a quick review of this code, it is readily apparent that API 620 is a bit more technologically advanced than its close cousin API 650. The main difference, as mentioned earlier, is that this code has a higher range of design pressure (up to 15 psig). The difference between API 620 and API 650 is summarized by Mayeux and Miller [58].

2.6 Finite Element Method

The liquid storage tanks are modelled by using analytical or numerical modelling methods. The analytical methods are based on a streamlined show that had been examined by numerous analysts and recommended by current significant standards.

Some techniques for modeling tanks incorporated the FSI and SSI. The most popular and powerful numerical method is FE method. The are many commercial software is available based on FE analysis such as ANSYS [59] which is used in this study for analysis of tanks.

The primary purpose of any FE analysis investigation is to make a numerical model representing the engineering geometry of its actual geometry and behavior. The theory and algorithm of FE method can be found in many books. For analysis of the shell structures, the various types of the shell element and modelling option exist in FE method.

2.6.1 Modeling of the wall tank

The 3D FE model of exhaust empty tank was modeled as surfaces utilizing in the ANSYS workbench. The determination of an appropriate element for a provided application isn't an unimportant issue and will straightforwardly impact the computational time and exactness of the results.

In the ANSYS element library section has been a wide range of sorts of shell elements five of which were appropriate for modeling the tank walls. These shells are SHELL63 (Elastic Shell), SHELL43 (4-Node Plastic Large Strain Shell), SHELL93 (8-Node Structural Shell), and SHELL181 (4-Node Finite Strain Shell). SHELL143 (4-Node Plastic Small Strain Shell), These shell sorts are normally utilized by few analysts for modeling tanks with different mesh sizes.

SHELL43 has six Degree of Freedom (DOF) and it is appropriate for modeling linear, warped, moderately-thick shell structures.

SHELL63 has six DOF and has both bending and membrane capacities. In-plane and regular loads are allowed.

SHELL93 works great for modeling curved shells. The element has six DOF at each node.

SHELL143 is convenient to modeling nonlinear, flat or warped and thin to moderately-thick shell structures. The element has six DOF at each node.

SHELL181 is utilized in the analysis of thin to moderately-thick shell structures. It is a 4-node element with six DOF at each node. This research has been to identify the optimal options of shell sort and mesh size for modal analysis of steel liquid tanks whose bottom nodes are fixed in all six DOF [60].

2.6.2 Modeling of the fluid

The liquid, the ANSYS library section has been different sorts of fluid elements represented liquid that can be used to model the fluid in 2D and 3D problems. The fluid element FLUID80 is well suited for calculating hydrostatic pressure and FSI. In this research, the fluid is distributed into a number of 3D fluid elements (FLUID80) with eight nodes each node has been three DOF [60,61].

CHAPTER 3

ANALYSIS AND DESIGN OF LIQUID STORAGE TANKS

3.1 General

A considerable variety into the configuration of liquid tanks are available in civil engineering applications. Type of tanks are summarized in previous chapter. The circular cylindrical tanks with ground-support are most common type of containers because they are efficient in resisting primary loads, relatively simple in design, and easy to construct.

The cylindrical liquid storage tank comprises primarily of a cylindrical steel wall that opposes liquid pressure, a thin flat or annular base plate that lays on the ground and a fixed or floating roof that protects the contained liquid from the air The tank shell wall more frequently comprises of few courses of welded or bolted, thin plates of steel changing thickness. Since the circular cross-section isn't distorted by the outward liquid pressure of the contained material, the wall of the container gets designed such as a membrane to sustain a purely tensile hoop stress. This provides an efficient design because steel is a very economic material especially when used in a condition of tensile stress.

Several roof configurations are employed to cover the contained liquid: a cone, a dome, a plate or a floating roof. A commonly used type is composed of a system of trusses supporting a thin steel plate. In addition, enough freeboard above the maximum filling height is usually provided to avoid contact between sloshing waves and roof plate. Different types of foundation may be used to support the tank: a concrete ring wall, a solid concrete slab, or a concrete base supported by piles or caissons. The tank may be anchored to the foundation; in this case, careful attention must be given to the anchor bolts shell attachment to avoid the possibility of tearing the shell when the tank is subjected to seismic excitations. For unanchored tanks, the bottom plate may be stiffened around the edge to reduce the amount of uplift.

3.2 Design Loads

Generally, loads applied to tanks include static loads and dynamic loads and static loads include dead, live load, static pressure of the fluids, static pressure of soil, uplift and forces resulting from temperature change. In order to determine static pressure of soil, Rankine relation is used. In order to design the floors which are below static level of ground water, uplift of the groundwater should be included. Structure of the tank should be designed for changing temperature.

a) Dead load (DL): The weight of the tank and its components

b) Design external pressure (P_e): couldn't be under 0.25 kPa aside that external pressure might be considered as 0 kPa for tanks with course vents. Allude to Annex V for external pressure greater than 0.25 kPa. Tanks that meet the prerequisites of this standard might be subjected to a halfway vacuum of 0.25 kPa, without the need to give any extra additional supporting calculations.

c) Design internal pressure (Pi): couldn't be greater than 18 kPa.

d) Hydrostatic test load (H_t): due to loading the tank with water to the outline liquid level.

e) Minimum roof live load (L_r): generally taken as 1.0 kPa on the horizontal projected area of the roof. but could not be less than 0.72 kPa according to API 650.

f) Stored liquid load (F): due to loading the tank with design liquid which has specific gravity up to design level.

l) External loads: such as confined loads resulting from items such as ladders, stairs, platforms, etc., should be considered.

3.3 Storage Tank Design Specifications

In the case of storage tanks, the contractor's responsibilities include specifying the required design basis. The tank design basis includes the tank capacity, service, design code, materials, design conditions, external loads, appurtenances, and connections that are needed for a particular storage tank application. Storage tank design specifications are used to specify these requirements. The specifications consist of engineering standards and a storage tank design specification sheet.

3.4 Design Based on API 650 Standard

API-650 includes the material selection, the design, construction, fabrication, and testing specifications for cylindrical liquid, closed, welded, open top, above ground steel storage tanks for internal pressures that are generally equal to atmospheric pressure. If the supplemental requirements that are contained in Appendix F of API-650 [7] are applied, storage tanks may be designed for internal pressures up to 18 kPa. The entire tank bottom must be uniformly supported. API-650 tanks must be in non-refrigerated service and they will typically have a maximum operating temperature of 93℃.

The basic stress analyses due to internal and external loading to should be taken responsibility in tank design are:

- Tank shell plate wall
- Bottom plate/ tank flooring
- Tank roof
- Top girder
- Intermediate stiffener(s)

3.4.1 Bottom plates

According to API 650 all the base plates should include an eroded thickness of at the very least 6mm.

In the present study Min Thickness of bottom plates $= 6.0 + 3.0\ (C.A) = 9.0\ mm$ for all tanks

3.4.2 Tank shell (wall) design

Tank thickness: The API 650 code can be used for designs of welded liquid storage steel tanks where the internal pressure is equal or less than to 17.24 kPa. The calculation of the thickness of the liquid cylindrical tank is explained in Section 3.6 of

API 650 [7] In this section, there are two methods of thickness calculation for consideration:

- The 1-foot method
- The variable point method.

The one-foot method computes the wall thickness at a distance of one foot on the bottom of each shell course and is applicable to tanks 61 m and less in diameter. The basic equation in SI customary units looks something like this:

$$thickness\ required = \frac{4.9D(H-0.3)G}{(S_d)(E)} + CA \quad (3.1)$$

The variable point method can be used for tanks in excess of (61 m) in diameter and is an alternative to the 1-foot method. The variable point equation in SI units is as follows:

$$Thickness\ required = \left(1.06 - \frac{0.0696D}{H}\sqrt{\frac{H \times G}{S}}\right)\left(\frac{4.9H \times D \times G}{S}\right) + CA \quad (3.2)$$

Where: H is the height of liquid in m. D is nominal tank diameter in m. G is specific gravity of the contents. S is the tank wall material allowable tensile stress for the operating or test condition, CA is the corrosion allowance. As a result, the required wall thickness increases in a linear fashion when using the 1-foot method and in a slightly non-linear fashion when using the variable point method.

The developed shell thickness could be more prominent of the design shell thickness, including any corrosion allowance, or but the circular shell wall required thickness could not be not as much as the following:

Table 3.1 The nominal tank diameter

Tank Diameter (m)	Plate Thickness (mm)
< 15	5
15 to < 36	6
36 to 60	8
> 60	10

For special tanks ($L / H > 1000/6$), the calculation of shell wall thickness could be utilized on an elastic analysis where the calculated circumferential stress to be below the allowable stress.

3.4.3 Self-supporting dome or umbrella roofs

The required thickness of the self-supporting dome and umbrella roof plate is calculated by the following equations:

$$t_{dome} = 141\ R\sqrt{\frac{Pr}{E}} \qquad (3.3$$

The radius of the self-supporting dome and umbrella roof should be satisfying below requirement

$$Minimum\ radius\ =\ 0.8D \text{ and } Maximum\ radius\ =\ 1.2D \qquad (3.4)$$

3.4.4 Stiffener/ wind girder

As shown in Figure 3.1, the tank wall can be constrained by wind pressure that is not conducive to its action unless stiffness against deformation is given, individually or otherwise.

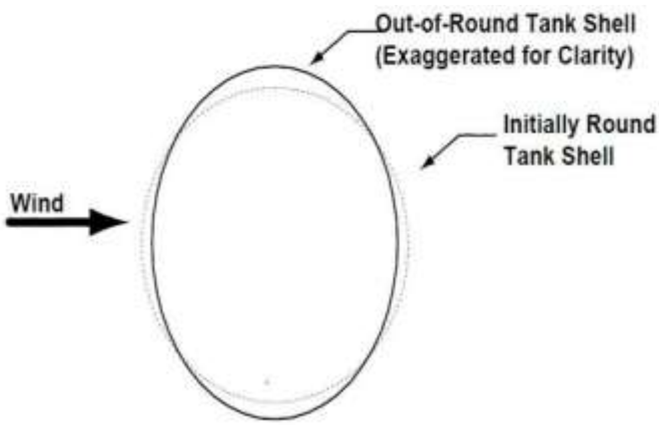


Figure 3.1 Shell out-of-roundness caused by wind

Theoretically, there are two ways to provide adequate stiffness:

- The tank shell can be made sufficiently thick to provide all the needed stiffness, or
- Some additional method of stiffening the shell can be provided.

In most cases, it is not economical to make the shell thick enough to provide all of the necessary stiffness. Therefore, additional stiffness to resist shell deformation is provided by welding circumferential stiffening rings around the outside of the tank. These stiffening rings are referred to as wind girders. Figure 3.2 shows several typical configurations for wind girders, and illustrates the general placement of a top wind girder on a tank shell.

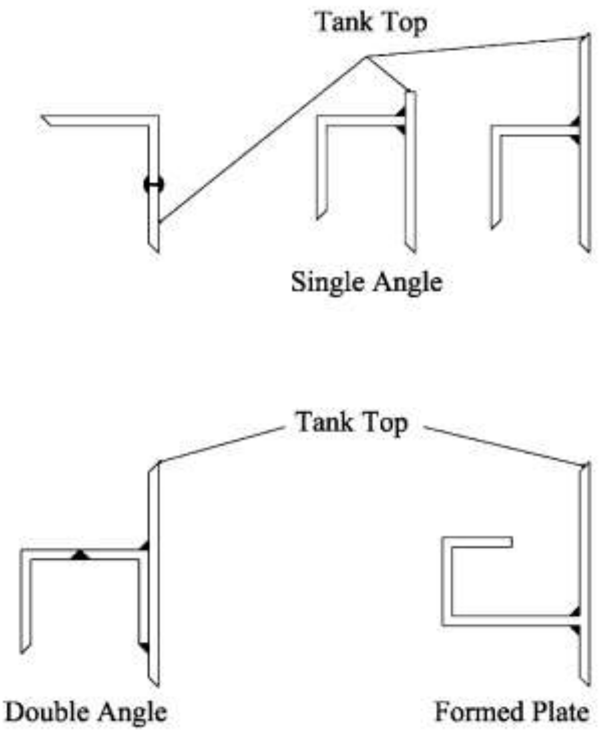


Figure 3.2 Typical top stiffener (wind girder)

API-650 requires that all open-top tanks be provided with stiffening rings (i.e., wind girders), that the stiffening rings be placed at the top of the tank, and that they preferably be located on the outer surface of the tank wall. Stiffeners will typically be made of standard sections (such as WT, C or L profiles), or will be formed from plate that are welded together and then welded to the shell. The general approach to wind girder design consists of determining the following:

- The minimum moment of inertia for the top stiffener.
- Whether a second, intermediate wind girder must also be provided at some lower elevation on the shell.
- The placed of the intermediate stiffener (if one is needed).
- The minimum inertia moment of the intermediate ring stiffener (if an intermediate wind girder is needed).

3.4.4.1 End stiffener design calculations

As previously stated, API-650 requires that all open-top tanks be provided with a stiffening ring that is placed at top or nearby the top edge of the storage liquid tank. This stiffening ring is the top wind girder. The purpose of the top stiffener ring is to ensure that the top section of the tank shell is stiff enough to prevent deformation which may be caused by the design wind velocity blowing across the entire tank.

The top stiffener (wind girder) should have a much high enough moment of inertia to present sufficient shell stiffening. Top wind girder design calculations consist of determining the minimum required section modulus, and then selecting a large enough wind girder section to provide this section modulus. API-650 contains an equation to calculate the minimum required top wind girder section modulus. The required top wind girder section modulus is based on the tank diameter and shell height. API-650 also contains a table which summarizes the section module of various structural shapes and attachment configurations to the tank shell.

I_{act} is the actual inertia moment of the end stiffener ring region, comprising of the linked inertia moment of the end stiffener and the shell inside a contributing distance on one side of the end stiffener. This inertia value should be greater than or equal to I_{reqd}, where, I_{reqd} is the total required inertia moment of this region and calculated in agreement with the computing equation below:

$$I_{reqd} = \frac{37.5\ V_l D^3}{E(N^2 - 1)} \tag{3.5}$$

Wherever the radial load calculated in following below equation that the load constrained on the end ring stiffener by the shell:

$$V_l = 250\ P_S H \tag{3.6}$$

P_s is total design external pressure for design of shell, kPa and H is shell height, m.

Where: E is Young's modulus of elasticity of the roof material, MPa., D is nominal tank diameter, m and N is waves number into which a shell will get buckle under external pressure load.

In addition to the inertia moment requirements, the end stiffener region should perform the following area requirements:

$$A_{reqd} = \frac{V_l D}{2f} \tag{3.7}$$

Where f is the allowable tensile stresses but smallest (see Table 3-2) from API 650 of the roof plate material, shell plate material or ring stiffener material at the greatest working temperature, MPa

For two of them, dome or umbrella roof top end stiffener, the required cross-sectional area of the end stiffener structural shape alone, A_{stiff}, is determined as:

$$A_{stiff} = A_{reqd} - J_{Es}\ t_{s1}\ X_{shell} - J_{Er}\ t_{dome}\ X_{dome} \tag{3.8}$$

For bottom end stiffener:

$$A_{stiff} = A_{reqd} - J_{Eb}\ t_b\ X_{btm} - J_{Es} t_{sn}\ X_{shell} \tag{3.9}$$

A_{stiff}must be more greater than or equivalent toA_{stiff} (required).

3.4.4.2 Intermediate stiffener design calculation

Circumstances exist where only a top stiffener alone won't give enough shell stiffness for a given blend of tank height, tank diameter, and tank shell course thicknesses. inauguration of an intermediate stiffener at a location between the stiffener and the tank bottom reduces the unstiffened length of the shell, and is required with a specific end goal to anticipate shell deformation in these cases. Intermediate stiffener design calculations in accordance with API-650 requirements consist of the following general steps:

- Determine if an intermediate wind girder is needed, based on design wind velocity, tank diameter, and shell course thicknesses.
- Locate the intermediate wind girder.
- Calculate the minimum required inertia moment of the intermediate ring stiffener and select a standard structural profile that provides this moment of inertia.

The perfect area of the intermediate ring stiffener is like an extent that the parts of the tank shell between the intermediate stiffener and the top stiffener, and between the intermediate stiffener and the base plate of the tank, have roughly the same stiffness. It would be mistaken, in any case, to find the moderate locate the intermediate stiffener at the mid-height between the top stiffener and the tank bottom. As we've seen from the earlier shell thickness calculations, The thickness from the bottom to the top of the tank bottom decreases. Therefore, if the intermediate ring stiffener is placed at the middle of the shell, the upper part of the shell will not become hard. As we've seen from the earlier shell thickness calculations, the thickness of the tank shell wall is diminished from the bottom to the top, as the lower courses thicker than the upper courses. Because the lower part of the tank casing is naturally harder than the upper part of the tank shell.

The API-650 procedure for locating the intermediate wind girder considers the variation in shell course thickness. As illustrated in Figure 3.3, the API-650 procedure mathematically converts the actual tank shell height to a "transformed shell" height. The shell transformation is done by accounting for the actual individual course thicknesses. The transformed shell then has the same stiffness throughout its height. Locating the intermediate stiffener at transformed shell results in equal shell stiffness both over and under the intermediate stiffener. The intermediate stiffener is then placed on the actual tank shell in the same course and in the same relative position within that course as it is on the transformed shell. Using this approach, the intermediate wind girder is located much higher than the mid height on the actual tank shell.

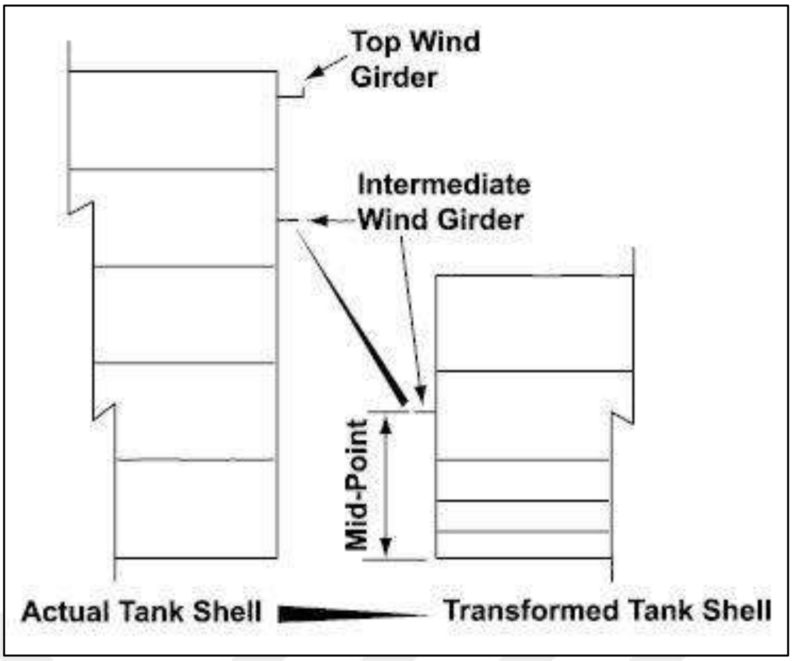


Figure 3.3 Transformed shell and intermediate wind girder

The equation V.8.1.2 from API-650 could be rewritten below to calculate the minimum shell wall thickness required for a tank subject to external pressure as:

$$t_{min} = \frac{73.05(H_{TS}Ps)^{0.4}D^{0.6}}{(E)^{0.4}} \tag{3.10}$$

The transformed shell height is calculated from the following equation below:

$$H_{TS} = H_1\left(\frac{t_{s1}}{t_{s1}}\right)^{2.5} + H_2\left(\frac{t_{s1}}{t_{s2}}\right)^{2.5} + \cdots H_n\left(\frac{t_{s1}}{t_{sn}}\right)^{2.5} \tag{3.11}$$

the maximum spacing of intermediate stiffeners:

$$H_{safe} = \frac{(ts_{min})^{2.5}(E)}{45{,}609D^{1.5}(P_S)} \tag{3.12}$$

Where t_{Smin} is minimum thickness of thinnest shell course, mm, E is Young's modulus of elasticity of the plate material MPa, D is nominal tank diameter, m, P_S is external pressure for design of shell, kPa. P_S is the greater of 1) the specified design external pressure, P_e, excluding wind or 2) $w + 0.4P_e$. The number of intermediate stiffeners required, *Ns*, based on, H_{safe}

$$Ns + 1 = H_{TS}/H_{safe} \tag{3.13}$$

and the intermediate stiffeners spacing on the transformed shell wall height can be computed using following equation:

$$Spacing = H_{TS}/ (N_S + 1) \tag{3.14}$$

The waves number of, N, within which shell will probably buckle under the uniform load external pressure which's calculated from below equation:

$$N = \sqrt{\frac{445\, D^3}{t_{smin}\, H_{TS}^2}} \leq 100 \tag{3.15}$$

For the tank design objects, the minimum amount of N is 2 and the maximum amount of N is 10. Use the same N^2 for end and intermediate stiffeners

- Determine the span between the adjacent intermediate stiffeners of the shell with uneven thickness on the actual shell Maximum spacing, Ls, on minimum shell thickness, t_{smin}

$$Ls = H_{TS}/ (N_S + 1) \tag{3.16}$$

- Maximum spacing, Ls on other shell thicknesses

$$L_s = [H_{TS} / (Ns + 1)](tsx / tsmin)^{2.5} \tag{3.17}$$

where t_{sx} is the individual shell thickness.

Where the spacing between the stiffener includes different shell wall thicknesses, the spacing is adjusted according to the transformed shell spacing.

The radial load applied to the shell on the stiffener is determined as:

$$Q = 1000 P_s L_s \tag{3.18}$$

The ring stiffener must be placed at $H_{TS}/(N_S + 1)$ spacing wherever N_S is number of intermediate stiffeners on the transformed shell.

The moment of inertia I_{act} of the intermediate stiffener region, should be greater than or equal to the total inertia moment I_{reqd}, of the region, where:

I_{act} = the actual inertia moment of the intermediate ring stiffener ring region, shaped of the linked inertia moment of the intermediate ring stiffener and the shell inside a contributing distance on each side of the intermediate ring stiffener.

In the intermediate ring stiffener ring region, the actual inertia moment, formed of the linked inertia moment of the intermediate ring stiffener also the shell inside a relevant distance on each side of the intermediate ring stiffener.

Determine contributing distance by the following equation below:

$$W_{shell} = \sqrt{D\ t_{shell}} \quad \text{on each side of stiffener} \tag{3.19}$$

where t_{shell} is the required thickness of the shell plate on which the stiffener is placed.

Determined the required inertia moment I_{reqd} of the intermediate stiffener region, is in accordance with the following equation:

$$I_{reqd} = \frac{37.5\ Q\ D^3}{E(N^2 - 1)} \tag{3.20}$$

Where Q is radial load applied to shell on the intermediate stiffener, N/m

the moment of inertia in additional requirements, the stiffener of the intermediate section will perform the following area requirements. Determined the total required cross-sectional area A_{reqd}, of the intermediate ring stiffener region: as:

$$A_{reqd} = \frac{QD}{2f_c} \tag{3.21}$$

Where f_C is the allowable compressive stress ring stiffener material but smallest at the maximum operating temperature, MPa

Determined the required cross-section area A_{stiff}, of the intermediate stiffener ring structural shape alone:

$$A_{stiff} = A_{reqd} - 26.84\ t_{shell}\sqrt{D\ t_{shell}} \tag{3.22}$$

3.5 Numerical Analysis of Tanks

The structural analysis method utilized in this research about the tank is based on the assuming that the material is linearity elastic. The control differential equation based on the above assumptions could be calculated in a closed form with a constant thickness of the shell wall.

When a nonlinear analysis or variable thickness shell wall is considered, the closed solution becomes difficult, so that structural analyses are best obtained by numerical techniques. In addition, the shell wall is considered to be a cylindrical shell whose thickness is very small compared to the diameter. Therefore, in this thesis, this work recognizes the classical thin shell theory. According to the recent thin shell theory, it is expected that the normal of the central surface of the wall remains straight and perpendicular to the deformed mid-surface.

The FE and finite-difference method are most popular numerical analysis methods for liquid tanks. Both methods can be used for the analyses of cylindrical liquid tanks. The FE method and the finite difference method both of them all involve the solution of the simultaneous equation, and the precision of the result increases as the number of equations increases, and the accuracy of results is increased with make increase in the number of equations (that is increase in the number of element or grid).

Finite difference method is simple to derive for linear analysis of regular geometry. Despite, the FE method is applicable to every shape of the axisymmetric shell. Thus, the walls, bases, and covers of the tanks could be modeled mutually and analyzed as a continuous structure without special treatment. The FE method can also be utilized for nonlinear analysis. As mention in previous chapter, they have two major failure mechanism cause to the immediate failure of a thin wall liquid tanks:

3.5.1 Static analysis

This analysis involves the solution of some unknown algebraic formulation of linear algebra such in the following equation below. For material failure, the stress of yield of the flexible material and the ultimate stress of the inelastic material should be taken into account. Elastic linear FE analysis can be utilized to predict material failure.

$$\boldsymbol{K\delta} = \boldsymbol{F} \tag{3.23}$$

Where $\boldsymbol{K}$ is stiffness matrix, $\boldsymbol{\delta}$ is displacement vector and $\boldsymbol{F}$ is force vector. The calculated of corresponding stress and the strain are compared with the allowable stress (or strain) throughout the element. If the FE solution intimates a region that exceeds these allowable values, it is assumed that the material has failed. It is worth mentioning that, for advanced material behavior modeling, we must consider nonlinear FE analysis.

Static analysis is regarded as the first step in which force resulting from mass inertia of tank, liquid and soil in static analysis is the most common method of seismic analysis. One of the most important forces is pressure resulting from fluid inside the tank and soil surrounding tank. Effect of earth gravitational acceleration causes structural response. It is very important to consider support conditions in soil boundaries for accurate determination of the problem answer

3.5.2 Buckling analysis.

The buckling multiplier load depends on the stiffness of the part. The buckling is usually confident of the material strength. The buckling phenomenon is controlled by different differential equations. Buckling refers to the destruction of stability that normally occurs in the elastic region of the material. The buckling phenomenon is controlled by different differential equations [62]. The failure of buckling isn't displayed by the typical linear FE investigation, but by a FE eigenvalue-eigenvector solution,

$$|\boldsymbol{K} + \boldsymbol{\lambda_m} \, \boldsymbol{K_F}| \, \boldsymbol{\delta_m} = \boldsymbol{0} \tag{3.24}$$

where $\boldsymbol{\lambda_m}$ is the Buckling Load Factor (BLF) for the m^{th} mode, $\boldsymbol{K_F}$ is geometric stiffness due to the stresses caused by the loading $\boldsymbol{F}$, and $\boldsymbol{\delta_m}$ is the corresponding buckling displacement mode shape for the m^{th} mode.

thin-walled structures or Thin column under compressive stress have been defenseless to buckling appearance. The buckling calculation provides a multiplier that scales the magnitude of the of that required to cause buckling.

Equation (3.24) is an eigenvalue problem. The magnitude of the scalar eigenvalue $\boldsymbol{\lambda_m}$ is called the "multiplier buckling load factor". The computed displacement eigenvector $\boldsymbol{\delta_m}$ is referred to as the "buckling mode" or mode shape. $\boldsymbol{\delta_m}$ is a relative displacement. all things considered, they have been provided in a non-dimensional design where the $\boldsymbol{\delta_m}$ range from zero to ±1. In another word, the original value of displacement or units of a mechanical mode shape aren't necessary.

BLF is a sign of the factor of safety against buckling, BLF is the ratio of the buckling load to the current applied load. Table 3.2 gives an explanation of the possible BLF values.

Table 3.2 Interpretation of buckling load factor [62]

BFL Value	Buckling Status	Remarks
>1	Buckling not predicted	The applied loads are less than estimated critical loads
=1	Buckling predicted	The applied loads are exactly equal to the critical loads. Buckling is expected
<1	Buckling predicted	The applied loads exceed the estimated critical loads. Buckling will occur
-1<BFL<0	Buckling possible	Buckling is predicted if you reverse the load directions
-1	Buckling possible	Buckling is expected if you reverse the load directions
<-1	Buckling not predicted	The applied loads are less than the estimated critical loads, even if you reverse their directions

3.5.3 Free vibration analysis

Conversance of the fundamental frequency of free vibration also the blended mode shapes is a significant first step in investigating and analyzing the dynamic response of deformable, liquid tanks. The free vibration analysis is also eigenvalue problem.

The natural, free lateral vibrational mechanism modes of a liquid tank might be divide as the $cos\theta$-type There is a pattern of a deflection waveform of a single wave cosine in the circumferential direction, and as the $cosn\theta$-type the redirection of the shell includes a majority of methods of circular waves higher than 1.

Figure 3.4a presents the vertical and circumferential modal shapes of these forms. For a high tank, the $cos\theta$ $-$type because the tank vibrates like a vertical cantilever, The pattern can be called a beam-type mode..

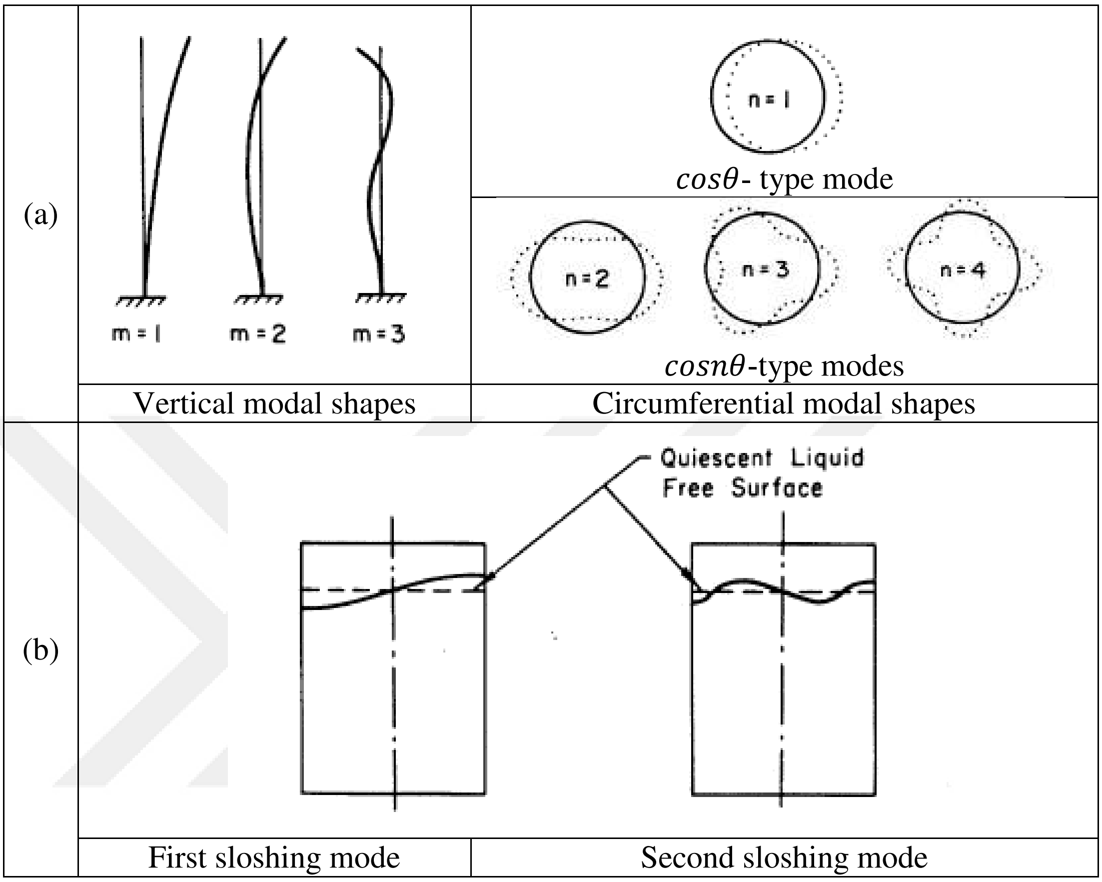


Figure 3.4 Types of vibrational modes of the liquid-shell system (a) Shell vibrational modes (b) Sloshing modes in rigid tanks

There are sloshing modes of the contained liquid in addition to vertical and circumferential modal shapes of cylindrical shell. Figure 3.7b shows the first two free surface sloshing modes of a liquid in a cylindrical tank.

The basic equations which govern the liquid motion inside the tank and the fundamental assumptions involved in the derivation of these equations can be found any textbooks. The full set of the differential equations, their associated boundary conditions and numerical solution methods are clearly presented in [62]

3.5.4 Finite element modelling and analysis of tanks

The thin shell wall structures can be admired as an assemblage of thin shell elements and investigated by the FE method. The thickness of the shell inside each element is consistent but can shift from element to element. The walls, roofs, and bases of liquids tanks, for the most part, have the shape of axisymmetric shells of substitution. For better results, fine mesh of FEs should be used, especially where singularity and high rate of change in stress are occurred.

The tank material is expected elastic isotropic; the thickness of the shell is viewed as little as with respect to the diameter and high of the tank, such an extent that shear deformation is immaterial. As a result of its successive functional event, the finite-element analysis of shells of revolution has been dealt with by many authors [63], proposing the refinement to enhance precision and diminish the amount number of FEs required in the admiration. However, in the present study, axisymmetric shell element is not used and loading is considered as axisymmetric.

The development of this research was carried out by the construction of numerical modeling of the tank with computer program ANSYS 17.2. The 3D FE model of self-supporting dome tank was modeled as surfaces using the ANSYS workbench. The determination of a reasonable element for a provided application isn't an insignificant issue and will specifically impact the computational time and accuracy of the results. FE models developed for this study consider the tank wall and base system to be represented and modeled by solid shell 190 element.

Definition of SOLSH190 Element: The element has the continuous solid element topology and emphasizes eight-node connections with three DOF at each node: interpretations in the nodal x, y, and z directions. Consequently, connecting SOLSH190 with other continuum elements needs no additional efforts. SOLSH190 is utilized for simulating shell structures with a wide variety of thickness (from thin to tolerably thick) as shown in the Figure 3.5 [64].

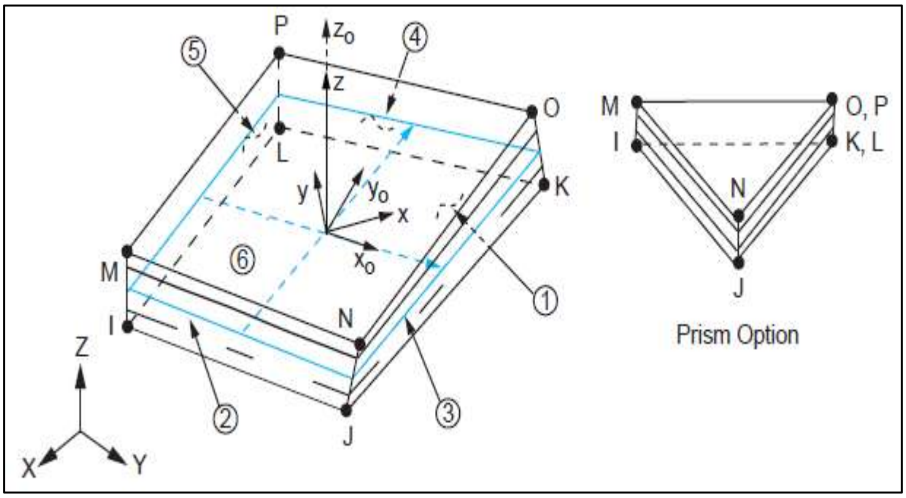


Figure 3.5 SOLSH190 geometry

Definition of CONTA174 Element: The CONTA 174 element is placed on the surfaces of 3-D shell or solid elements with mid-side nodes. The element has the indistinguishable geometric characteristics as the solid or shell element face with which it is associated. CONTA174 is used to indicate the contact and sliding between the 3-D "target" surface (TARGE 170) and the deformable surface, which is characterized by the element. The element is relevant to 3-D structural and coupled field contact analysis. (see Figure 3.6: CONTA174 Geometry) [64].

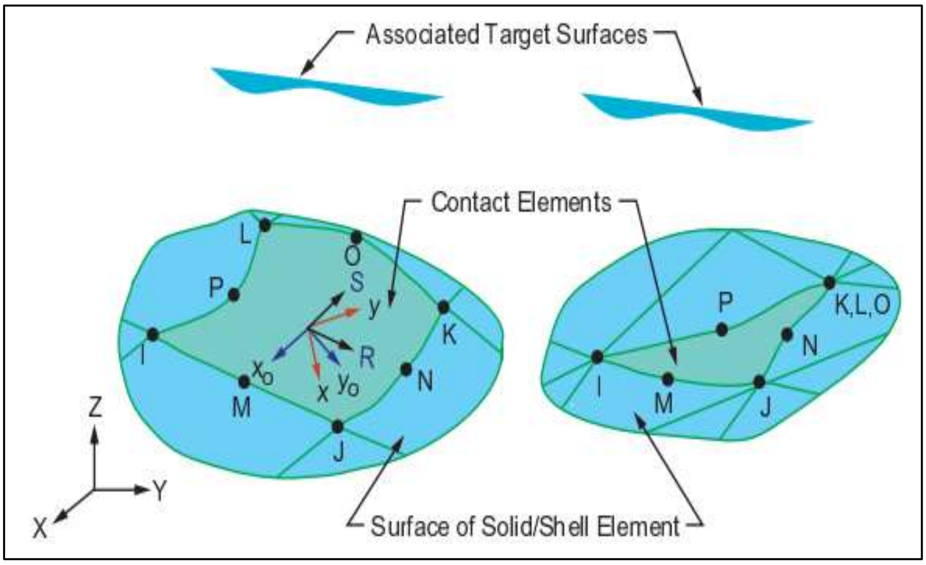


Figure 3.6 CONTA173 geometry

Definition of TARGE170 Element: TARGE170 has been utilized to delineate different 3-D "target" surfaces for the related contact elements. The contact elements themselves expand the solid, shell, or line elements representing the boundary of a deformable body shape and are potentially in contact with the objective target surface, described by TARGE170 as presented in the Figure 3.7 [64].

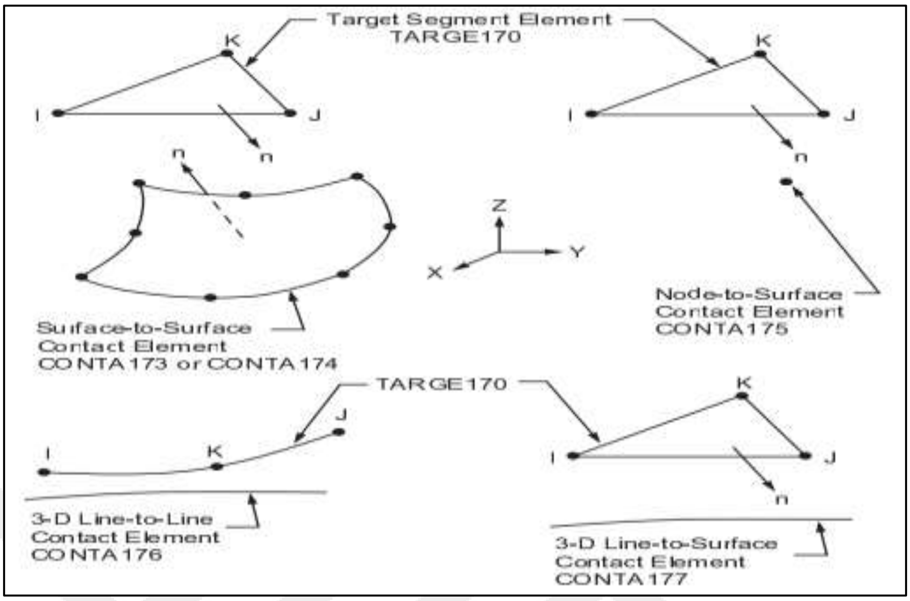


Figure 3.7 TARGE170 geometry

CHAPTER 4

ANALYSIS AND RESULTS

4.1 Introduction

The designs presented in this chapter consist of two step. In the first step, preliminary design of the tank is done based on API 650 standard. The stress, free vibration mode and buckling analysis have been carried out by utilizing FE analysis package for each preliminary design in order to the effect of various parameters on structural performance of cylindrical liquid tank. The information obtained in each of the succeeding analysis will teach a valuable lesson about the creation of a safer and economical cylindrical thin shell tank. Two types of tank are designed These are self-supporting roof tank and dome roof tank. While each of the tanks do have common design parameters, such as materials and loading conditions.

A tank design must initial be designed based on static analysis before evaluating and designing a tank for buckling and free vibration. Many different stiffener profile were picked so as with encompassing a wide range of results. These profile were selected in a way that moment of inertias nearly equal to each other. Five different courses are considered for obtaining economical and high performance tanks.

4.2 Design Example: Self-Supporting Dome (Open) Tank

4.2.1 Geometry, loading and material properties

The specific self-supporting dome tank considered in this section is shown in Figure 4.1 with inner diameter $D = 20$ m and high of the tank (liquid level) $H = 12$ m. The tank is designed for five different courses (2, 3, 4, 5 and 6 courses) and the results are compared for best solution. The courses have equal high.

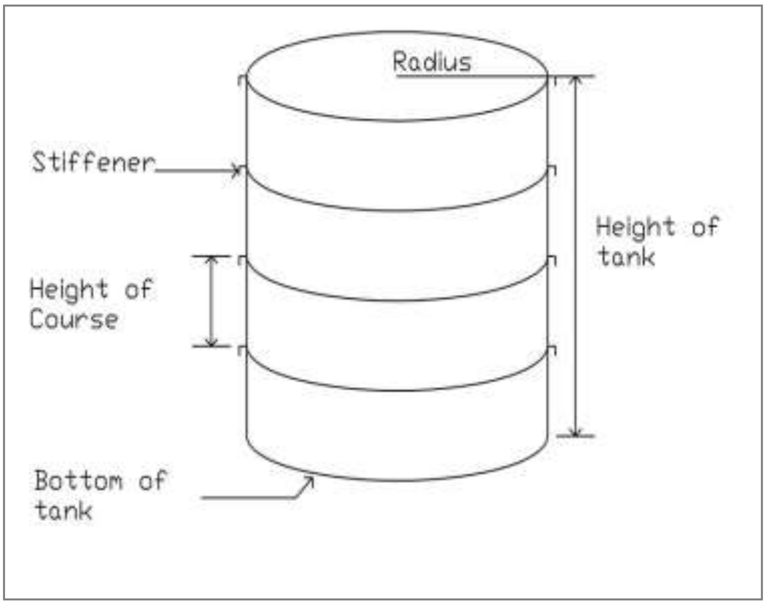


Figure 4.1 Geometry of tank

The design loading data is given in Table 4.1. The tank is subjected to hydrostatic loading of a liquid of weight per unit volume and external pressure on the shell wall as shown in Figure 4.2. The tank is only supported from bottom plate which is fixed support. The tank is made of A36 M Grade structural steel which has material properties listed in the Table 4.2.

Table 4.1 Loading data

Density of contents	988.2 kg/m^3
External pressure	3 kPa
Hydrostatic load	$\rho g h$ =0.11633
Maximum design temperature	60 C^o
High liquid level	12 m
Basic wind speed	190 km/h
Live load	1.5 kN/m^2

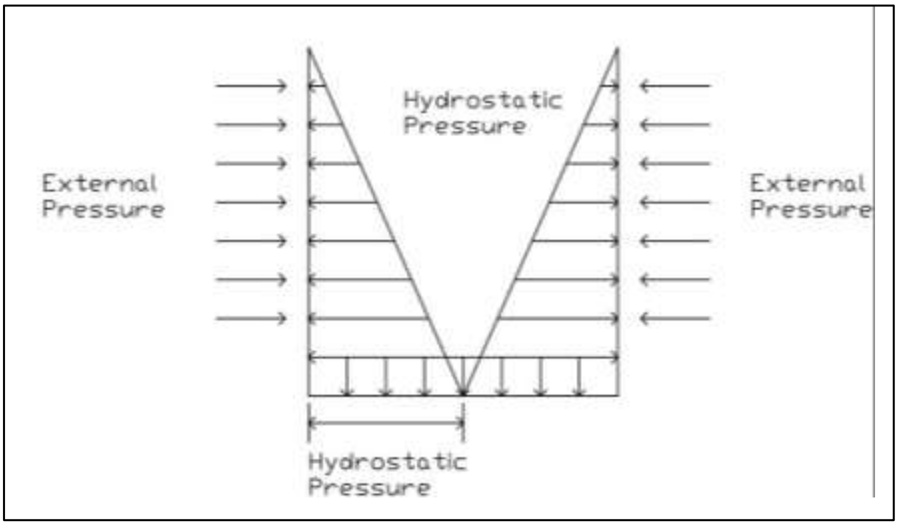


Figure 4.2 The schematic representation of tank loads

Table 4.2 Properties of the material used in tank.

Material	A36 M Grade
Material Group	Group 1
Minimum Yield Strength	250 MPa
Minimum Tensile Strength	400 MPa
Modulus of Elasticity	200000 MPa
Density	7850 kg m^3
Passion's	0.3

4.2.2 Design of tank based on API 650 standard.

The 1-foot method is used to compute the thickness of each courses. Each courses are equal height. Lap welded bottom plates is used and thickness is computed according to API 650 Section 5.4. There is a stiffener from the top to restraint displacements in the above part of the tank. This is one of the typical stiffening ring sections profile for tank shells illustrated in API 650 (see details in Figure 5.24 of API 650 standard [7]. The number, locations and dimensions of intermediate stiffeners and dimensions of the top stiffener have been computed according to API 650 Section 5.9 [7]. The details of the designed tank (according to API 650 standard) are given in Table 4.3. The thickness of the bottom plate for all courses cases is 9 mm, the location and distance measurement of stiffeners from top to bottom just top stiffener from bottom to top.

Table 4.3 The summary of tank design according to API 650

Number of Course	Thickness of courses (mm)	Number of intermediate Stiffener	Inertia of stiffener (constant stiffener) (cm^4)	Inertia of stiffeners (cm^4)	Location of stiffener (mm)
2	11	1	$I_{1,top}$=224	I_{top}= 220.14	12000
	11			I_1=468.84	6390
3	10	1	$I_{1,top}$=176	I_{top}= 173.36	12000
	10				
	11			I_1= 468.84	5030
4	9	2	$I_{1,2,top}$=176	I_{top}= 173.36	12000
	9				
	9			I_1= 223.56	3870
	11			I_2= 223.56	
5	8	3	$I_{1,2,3,top}$=142	I_{top}= 140.09	12000
	8				
	8			I_1= 134.58	2880
	9			I_2= 134.58	5760
	11			I_3= 180.66	9130
6	7	4	$I_{1,2,3,4,top}$=97.20	I_{top}= 140.09	12000
	7				
	7			I_1= 96.38	2060
	8			I_2= 96.38	4210
	9			I_3= 134.58	6250
	11			I_4= 298.35	10120

4.2.3 FE analysis of the liquid storage tank

The FE package ANSYS is employed to carry out the analyses. The 8-node, connectivity, first-order interpolation, stress/displacement continuum solid shell 190 element with reduced integration is chosen to discretize the cylindrical wall. This element has three DOF at every node: translations in the nodal x, y, and z directions Thus, associating SOLSH190 with other continuum elements requires no additional efforts. A decline prism option is accessible, but should just be utilized as filler elements in mesh generation. The element has plasticity, hyper elasticity, stress stiffening, creep, large deflection, and large strain capabilities. It also has blended u-P formulation ability for simulating deformations of nearly incompressible elastoplastic materials, and completely incompressible hyperplastic materials. The element formulation depends on logarithmic strain and true stress measures. And CONTA174 is utilized to express contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, characterized by this element. The element has an indistinguishable same geometric characteristic as the solid or shell element face with which it is connected. The element is characterized by eight nodes (the underlying solid or shell element has mid-side nodes). It can deteriorate to a six-node element relying upon the shape of the underlying solid or shell elements [64].

For stiffener, three type of profiles (see Figure 4.3) which have section details satisfying the inertia requirement stated in Table 4.3 are investigated. The tank is analyzed for following cases:

Case 1: without stiffener

Case 2: constant stiffener (unequal L angle with right orientation)

Case 3: variable stiffener (unequal L angle with right orientation)

Case 4: variable stiffener (unequal L angle with left orientation)

Case 5: variable stiffener (C section)

Case 6: variable stiffener (WT-section)

Case 1 which is tank without stiffener is considered in order to investigate the effect of stiffener. Case 1 does not satisfy the API 650 standards. In the case of constant stiffener, the minimum inertia value which is computed according to API 650 is used in all stiffener. In case of variable stiffener, the inertia of each stiffener is computed individually according to API 650. In this case, C, Unequal L angle with two different orientations and WT profile sections are investigated. In order to get meaningful comparison, the inertial values of different types of profiles are selected from catalogue in a way that they approximately equal to each other.

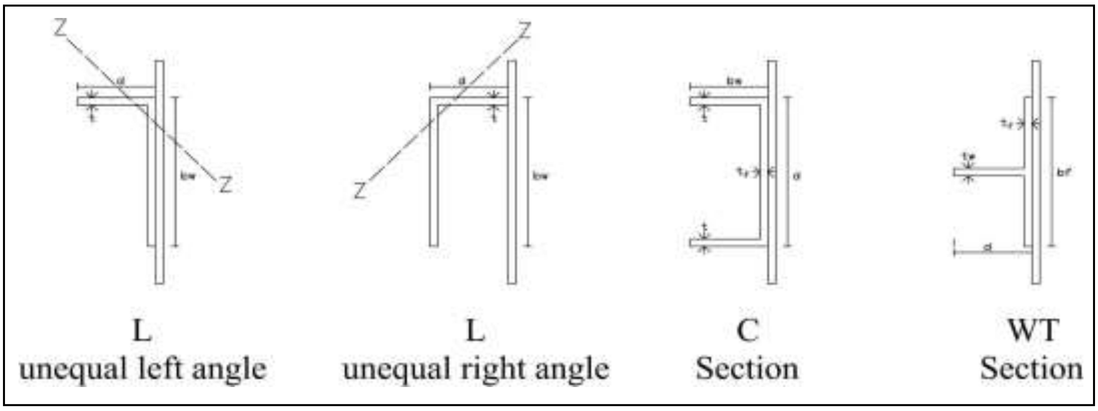


Figure 4.3 Type of stiffener profiles

The linear static, free vibration and buckling analyses are carried out using ANSYS commercial software for the designed tank according to API 650 standard. The tanks are modelled and analyzed using fine meshes. The FE model of the tank is shown in Figure 4.4. The stress distribution and deformations in the tanks and weight, fundamental frequency and critical buckling loads of tanks are observed. The effect of the number of course, stiffener, location of stiffener, type of stiffener is investigated.

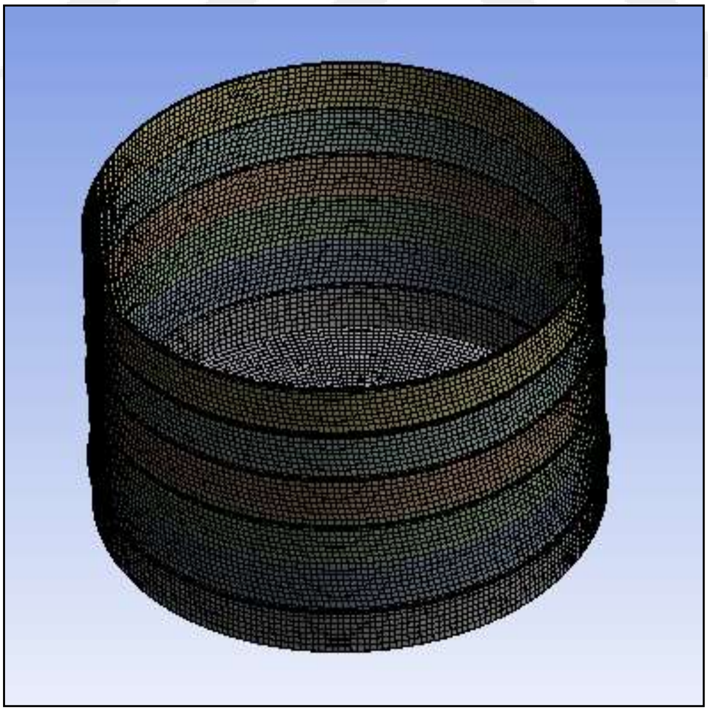


Figure 4.4 FE model of tank

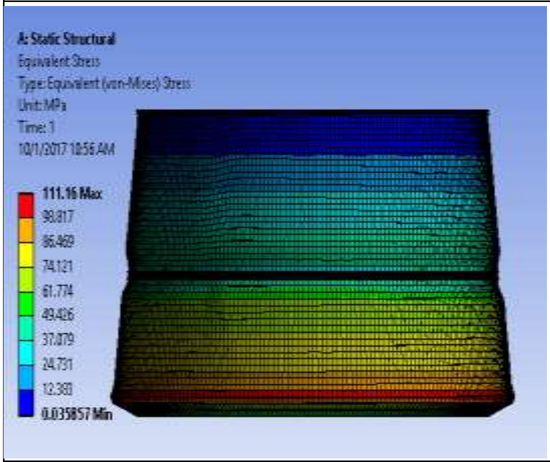
4.2.4 Result and discussion

The FE analyses for static, free vibration and buckling are carried out. The maximum equivalent stress values of each case and courses are summarized in Table 4.4. The maximum equivalent stresses are very close to each other for all cases considered. The smallest maximum equivalent stress is occurred at Case 3 with 2 courses and equal to 110.01 MPa which is less than minimum yield stress 250 MPa. The stress distribution for case 5 is shown in Figure.4.5.

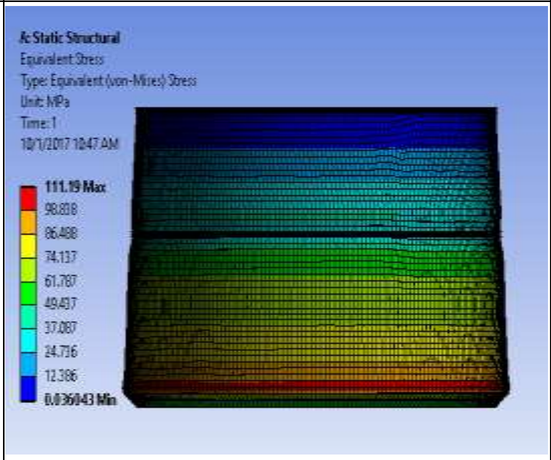
Table 4.4 The maximum equivalent stress values.

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Max, von Mises Stress (MPa)	2	110.36	110.37	110.01	110.88	111.16	111.25
	3	110.36	110.38	110.38	110.31	111.19	110.30
	4	110.20	110.22	110.23	110.24	110.21	110.22
	5	111.73	111.74	111.75	111.74	111.74	111.71
	6	110.77	110.08	110.76	110.96	112.75	111.42

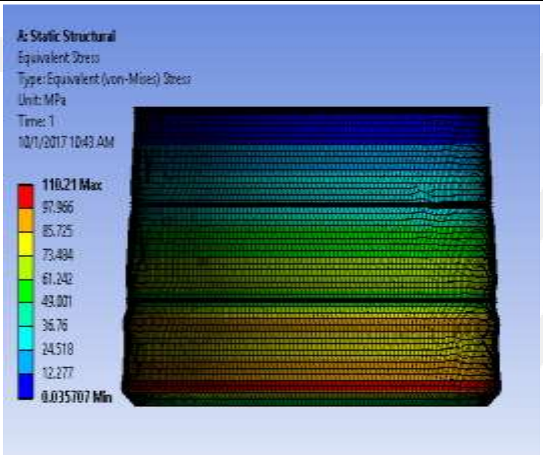
2 Courses



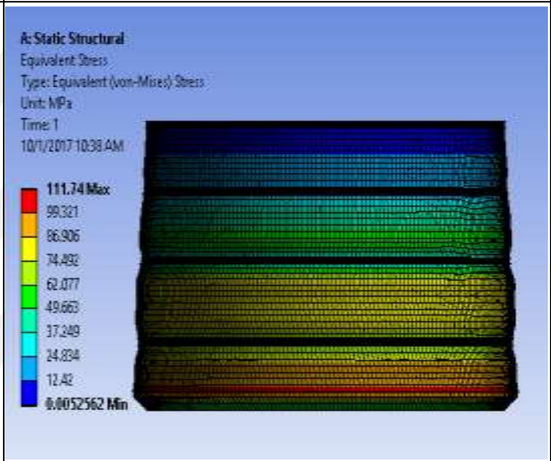
3 Courses



4 Courses



5 Courses



6 Courses

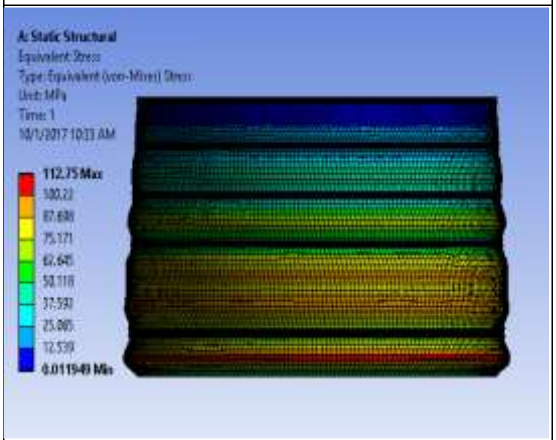


Figure 4.5 The maximum equivalent stresses for Case 5

The maximum deformation values of each tank is presented in Table 4.5. The smallest maximum deformations are again very close to each other for all cases considered. The maximum deformation is occurred at Case 1 and 2 with 2 courses and equal to 5.20 mm. The deformation of tanks for Case 1 and 2 is shown in Figure 4.6.

Table 4.5 The maximum deformation values.

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Max. Deformation (mm)	2	5.20	5.20	5.25	5.27	5.30	5.28
	3	5.22	5.22	5.22	5.22	5.28	5.22
	4	5.28	5.29	5.29	5.29	5.29	5.28
	5	5.32	5.32	5.32	5.32	5.31	5.32
	6	5.41	5.27	5.45	5.31	5.32	5.41

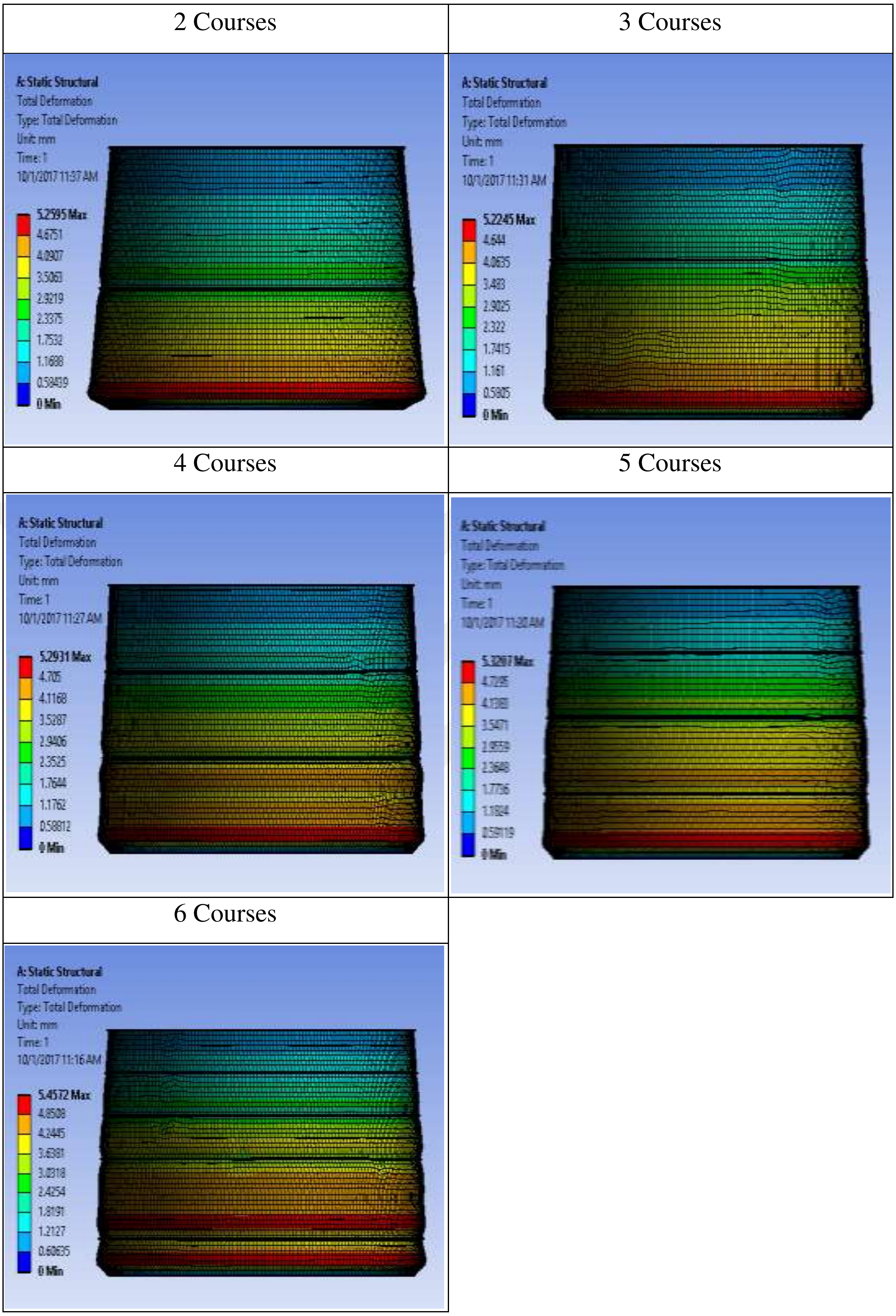


Figure 4.6 The maximum deformation shapes for Case 3

The seismic behavior of the tanks is investigated by studying fundamental frequency. The free vibration analysis is performed and fundamental frequencies are computed for tanks. The fundamental frequencies are presented in Table 4.6. The maximum fundamental frequency is occurred at Case 5 with 6 courses where C section stiffener is used and equal to 21.189 Hz. The corresponding mode shape is shown in Figure 4.7. The lowest fundamental frequencies are obtained in Case 1 as expected.

Table 4.6 The fundamental frequencies values.

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Fundamental Frequency (Hz)	2	6.4982	8.0534	8.1817	13.511	14.983	15.082
	3	6.7285	8.0357	8.3399	11.833	10.997	15.295
	4	6.9648	8.8812	8.8492	13.086	12.976	11.694
	5	7.2738	9.1952	9.1938	15.739	12.186	19.757
	6	7.6199	9.6296	9.5513	17.213	21.189	20.899

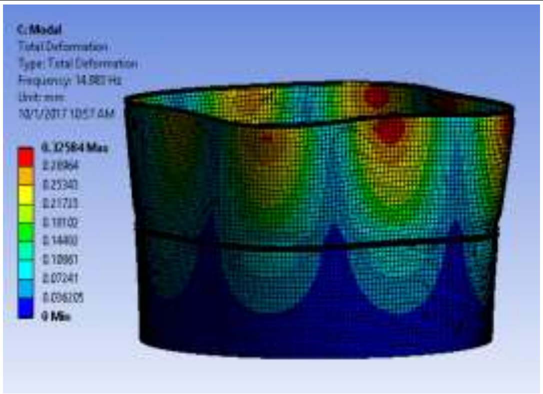
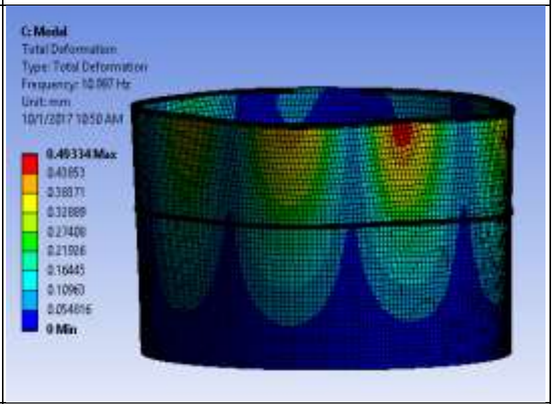
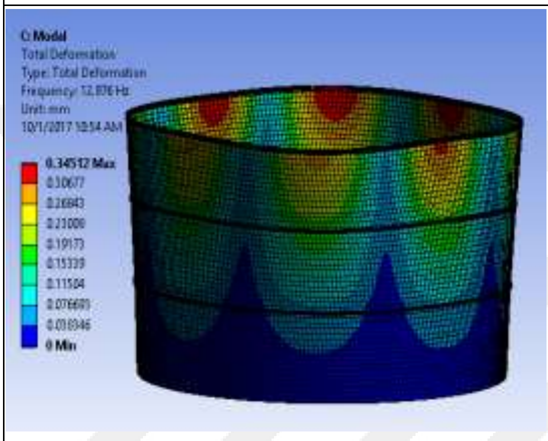
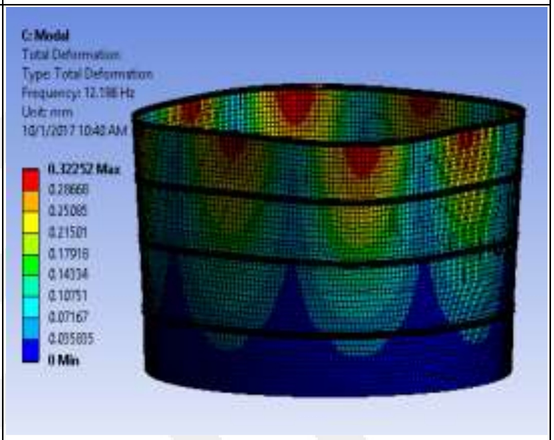
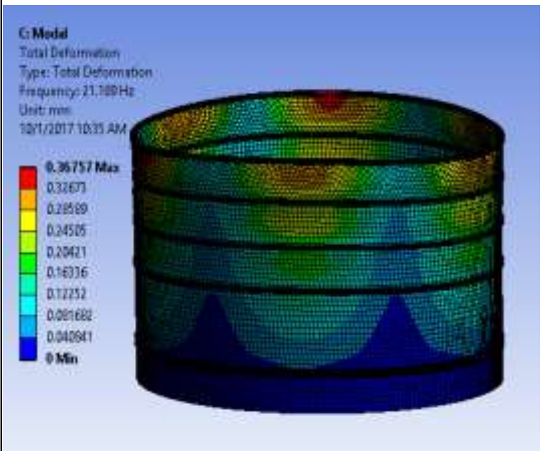
2 Courses	3 Courses
	
4 Courses	5 Courses
	
6 Courses	
	

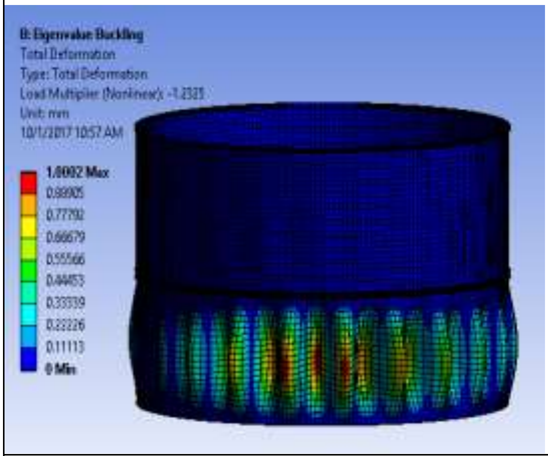
Figure 4.7 The fundamental frequencies values for Case 5

The one of the main reason of failure of tank is buckling. The buckling analyses of the tank are carried out and the buckling multiplier are computed and presented in Table 4.7. The worst case is the tank without stiffener. The best solution against buckling is obtained in Case 5 where C section stiffener is used. The maximum buckling multiplier is occurred at Case 5 with 5 courses and equal to -1.3107. The corresponding buckling mode shape is shown in Figure 4.8. It is observed that the buckling occurs near the bottom of the plate where this failure occurred in many constructed tanks.

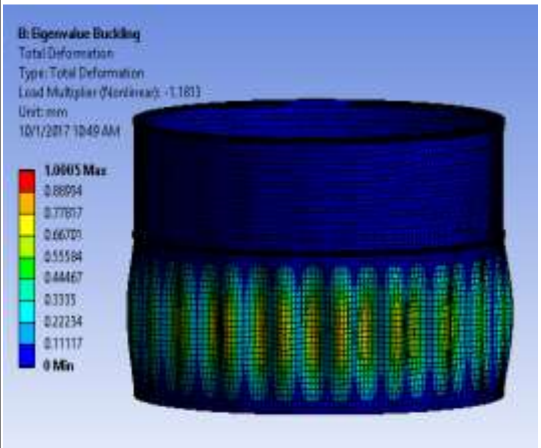
Table 4.7 The buckling multiplier value

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Buckling Multiplier	2	-1.1489	-1.2169	-1.2177	-1.2285	-1.2325	-1.2267
	3	-1.1244	-1.1738	-1.1748	-1.1793	-1.1813	-1.1813
	4	-1.0964	-1.2470	-1.2455	-1.2624	-1.2727	-1.2712
	5	-1.0772	-1.2434	-1.2443	-1.2823	-1.3107	-1.2832
	6	-1.0595	-1.1932	-1.1888	-1.2109	-1.2394	-1.2089

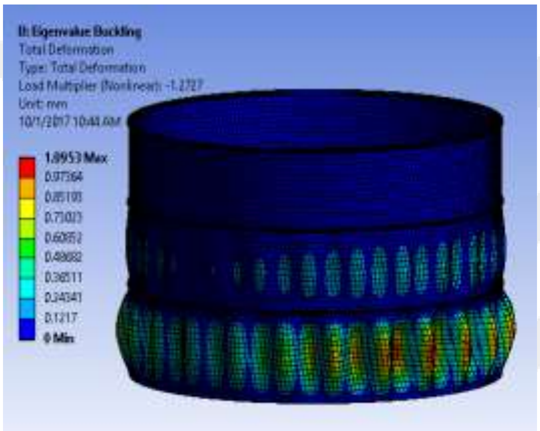
2 Courses



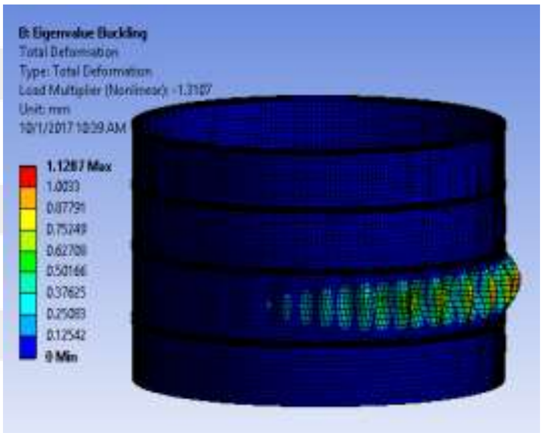
3 Courses



4 Courses



5 Courses



6 Courses

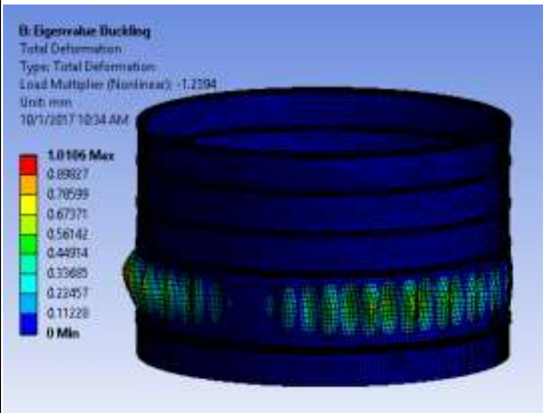


Figure 4.8 The maximum buckling multiplier for Case 5

The weight of the tanks is listed in Table 4.8. The weight of the tanks decrease with increasing number of courses. The lightest tank is obtained in case 1 with 6 course (without stiffener) in which these tanks do not satisfy the API 650 standards. The heaviest tanks are found in case of C section stiffeners.

Table 4.8 The total weight of tank

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Weight (kg)	2	87386.00	88722.28	89024.05	89024.05	91959.11	88966.52
	3	83440.00	85154.74	85212.55	85212.55	87293.65	84643.26
	4	78499.00	81876.13	81593.72	81593.72	83589.10	83491.31
	5	74352.40	77037.52	77254.83	77254.83	84170.40	76992.84
	6	70600.70	73697.67	74101.41	74101.41	82191.12	73702.55

4.3 Design Example: Tank with Dome Roof

4.3.1 Geometry, loading and material properties

The tank with dome roof considered in this section is shown in Figure 4.9 with inner diameter $D = 20$ m, roof height (above cylindrical shell) $h_r = 2.49$ m and high of the tank (liquid level) $H = 12$ m. The tank is designed for five different courses (2, 3, 4, 5 and 6 courses) and the results are compared for best solution. The courses have equal high.

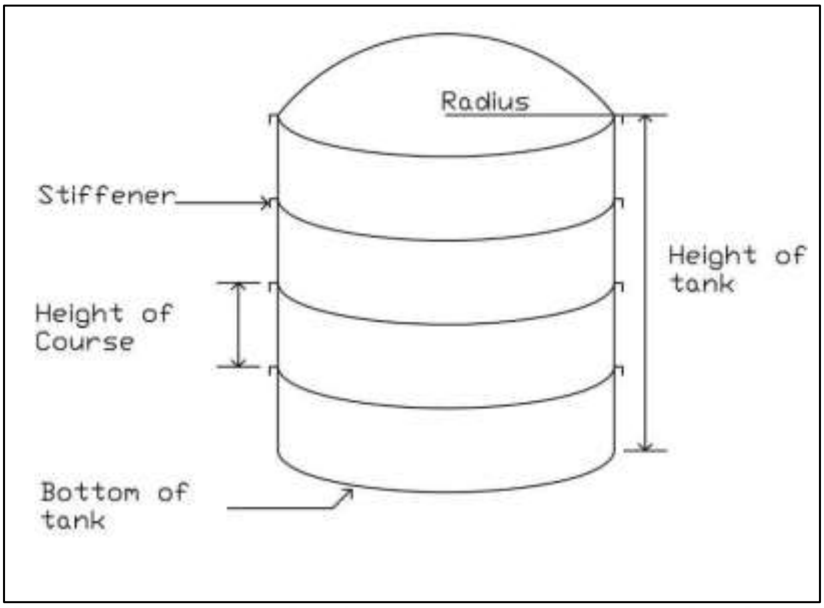


Figure 4.9 Geometry of tank

The design loading data same as previous example which is listed in Table 4.1 and shown in Figure 4.10. The tank is subjected to hydrostatic loading of a liquid of weight per unit volume and external pressure on the shell wall. The tank is only supported from bottom plate which is fixed support. The tank is made of A36 M Grade structural steel which has material properties listed in Table 4.2.

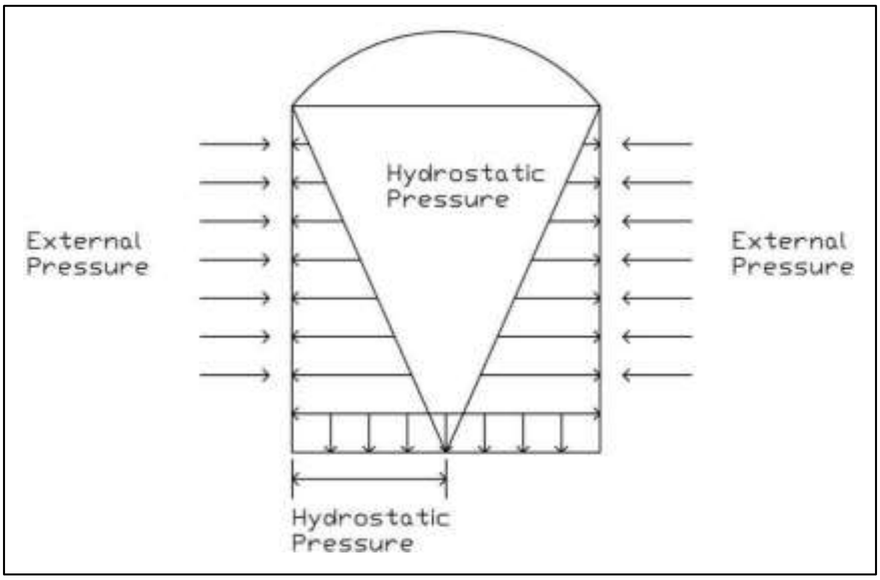


Figure 4.10 The schematic representation of tank loads.

4.3.2 Design of tank based on API 650 standard.

The 1-foot method is used to compute the thickness of each courses. Each courses are equal height. Lap welded bottom plates is used and thickness is computed according to API 650 Section 5.4. There is a stiffener at the top in order to restraint displacements in the above part of the tank. The number, locations and dimensions of intermediate stiffeners and dimensions of the top stiffener have been computed according to API 650 Section 5.9 [7]. The details of the designed tank (according to API 650) are given in Table 4.9. The thickness of the bottom plate for all courses cases is 9 mm. The thickness of the roof is 12 mm. the location and distance measurement of stiffeners from top to bottom just top stiffener from bottom to top.

Table 4.9 The summary of tank design according to API 650

<table>
<tr><th>Number of Course</th><th>Thickness of courses (mm)</th><th>Number of intermediate Stiffener</th><th>Inertia of stiffener (constant stiffener) (cm^4)</th><th>Inertia of stiffeners (cm^4)</th><th>Location of stiffener (mm)</th></tr>
<tr><td rowspan="2">2</td><td>11</td><td rowspan="2">1</td><td rowspan="2">$I_{1,top}$=224</td><td>I_{top}= 220.14</td><td>12000</td></tr>
<tr><td>11</td><td>I_1=468.84</td><td>6390</td></tr>
<tr><td rowspan="3">3</td><td>10</td><td rowspan="3">1</td><td rowspan="3">$I_{1,top}$=176</td><td rowspan="2">I_{top}= 173.36</td><td rowspan="2">12000</td></tr>
<tr><td>10</td></tr>
<tr><td>11</td><td>I_1= 468.84</td><td>5030</td></tr>
<tr><td rowspan="4">4</td><td>9</td><td rowspan="4">2</td><td rowspan="4">$I_{1,2,top}$=176</td><td rowspan="2">I_{top}= 173.36</td><td rowspan="2">12000</td></tr>
<tr><td>9</td></tr>
<tr><td>9</td><td>I_1= 223.56</td><td rowspan="2">3870</td></tr>
<tr><td>11</td><td>I_2= 223.56</td></tr>
<tr><td rowspan="5">5</td><td>8</td><td rowspan="5">3</td><td rowspan="5">$I_{1,2,3,top}$=142</td><td rowspan="2">I_{top}= 140.09</td><td rowspan="2">12000</td></tr>
<tr><td>8</td></tr>
<tr><td>8</td><td>I_1= 134.58</td><td>2880</td></tr>
<tr><td>9</td><td>I_2= 134.58</td><td>5760</td></tr>
<tr><td>11</td><td>I_3= 180.66</td><td>9130</td></tr>
<tr><td rowspan="6">6</td><td>7</td><td rowspan="6">4</td><td rowspan="6">$I_{1,2,3,4,top}$=97.20</td><td rowspan="2">I_{top}= 140.09</td><td rowspan="2">12000</td></tr>
<tr><td>7</td></tr>
<tr><td>7</td><td>I_1= 96.38</td><td>2060</td></tr>
<tr><td>8</td><td>I_2= 96.38</td><td>4210</td></tr>
<tr><td>9</td><td>I_3= 134.58</td><td>6250</td></tr>
<tr><td>11</td><td>I_4= 298.35</td><td>10120</td></tr>
</table>

4.3.3 FE analysis of the liquid storage tank

The FE package ANSYS is employed to carry out the analyses. The 8-node, connectivity, first-order interpolation, stress/displacement continuum solid shell 190 element with reduced integration is chosen to discretize the cylindrical wall. And (CONTA174) has been utilized to represent contact and sliding between 3-D "target" surfaces (TARGE170) and a deformable surface, defined by this element.

For stiffener, three type of profiles (see Figure 4.3) which have section details satisfying the inertia requirement stated in Table 4.2 are investigated. The tank is analyzed for same cases as previous example:

Case 1 which is tank without stiffener is considered in order to investigate the effect of stiffener. Case 1 does not satisfy the API 650 standards. In the case of constant stiffener, the minimum inertia value which is computed according to API 650 is used in all stiffener. In case of variable stiffener, the inertia of each stiffener is computed individually according to API 650. In this case, C, Unequal L angle with two different orientations and WT profile sections are investigated. In order to get meaningful comparison, the inertial values of different types of profiles are selected from catalogue in a way that they approximately equal to each other.

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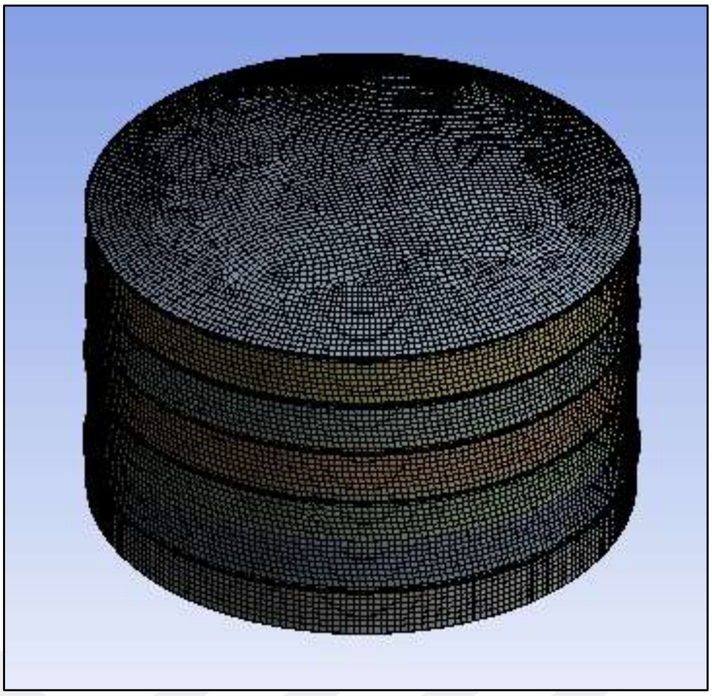


Figure 4.11 FE model of tank

4.3.4 Result and discussion

The results of FE analyses for static, free vibration and buckling is summarized in Table 4.10. The maximum equivalent stresses are very close to each other for all cases considered. The smallest maximum equivalent stress is occurred at Case 3 with 2 courses and equal to 110.01 MPa which is less than minimum yield stress 250 MPa. The stress distribution for case 5 is shown in Figure.4.12.

Table 4.10 The maximum equivalent stress values.

	Courses	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Max. von Mises Stress (MPa)	2	110.37	110.37	110.01	110.88	111.17	111.26
	3	110.37	110.82	110.39	110.31	111.19	110.3
	4	110.20	110.21	110.22	110.23	110.21	110.21
	5	111.72	111.74	111.75	111.74	111.73	111.71
	6	110.18	110.08	110.75	111.72	112.75	111.42

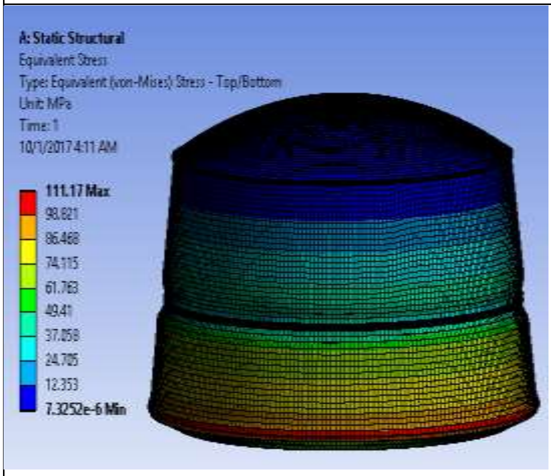
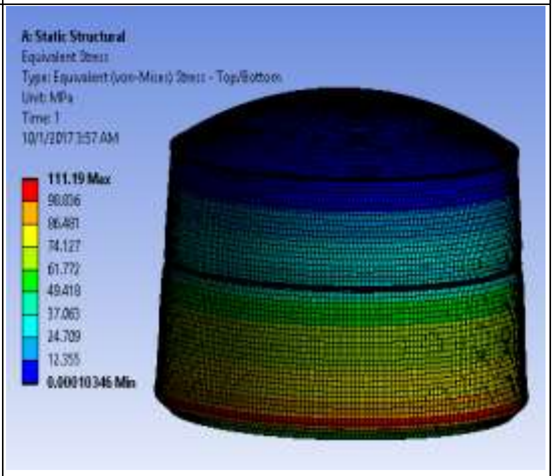
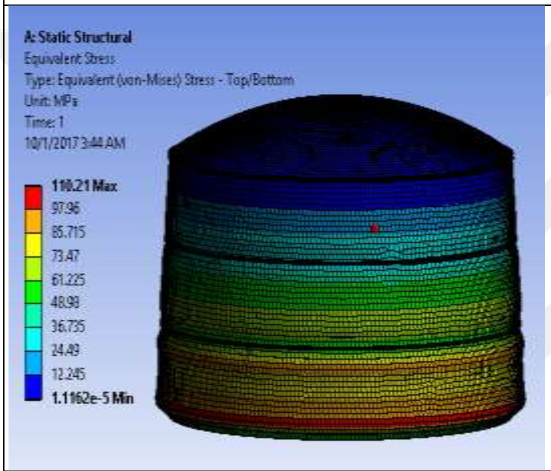
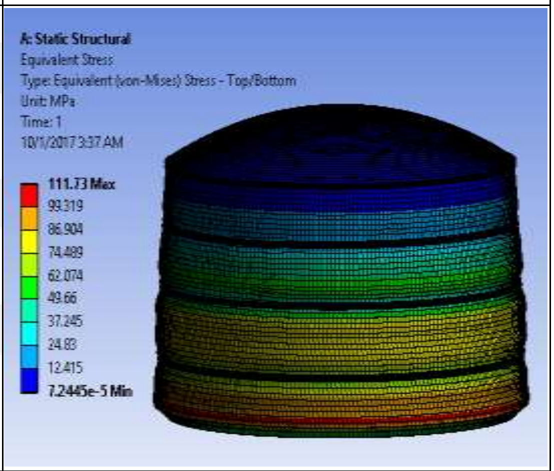
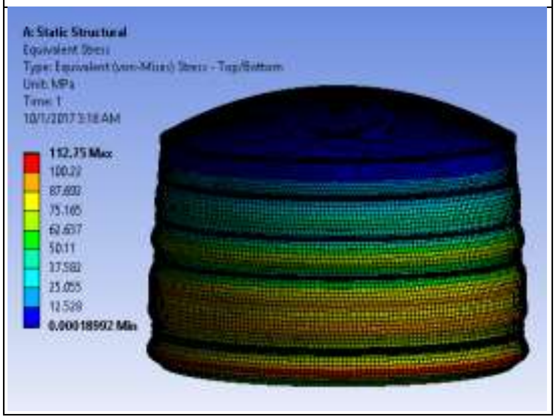
2 Courses	3 Courses
	
4 Courses	5 Courses
	
6 Courses	
	

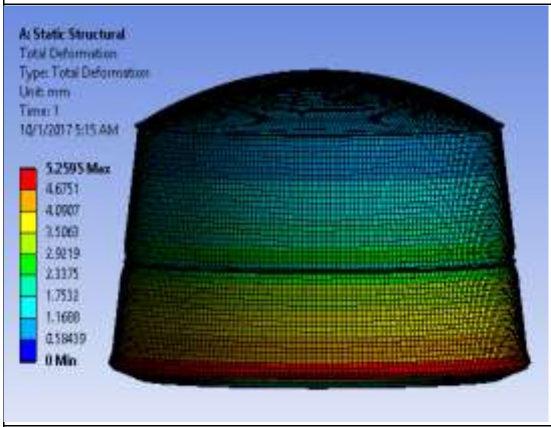
Figure 4.12 The maximum equivalent stresses for Case 5

The maximum deformations are again very close to each other for all cases considered. The smallest maximum deformation is occurred at Case 1 with 2 courses and equal to 5.20 mm. The deformation for Case 3 is shown in Figure 4.13.

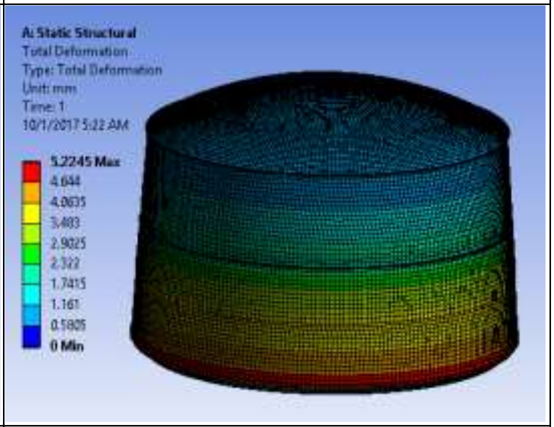
Table 4.11 The maximum deformation values.

	Course	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Max. Deformation (mm)	2	5.20	5.20	5.25	5.27	5.30	5.28
	3	5.22	5.33	5.22	5.22	5.28	5.22
	4	5.28	5.29	5.29	5.29	5.29	5.28
	5	5.31	5.32	5.32	5.32	5.31	5.32
	6	5.30	5.27	5.45	5.34	5.32	5.41

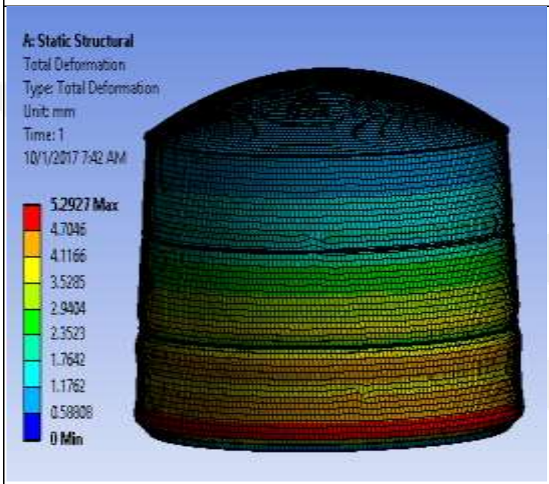
2 Courses



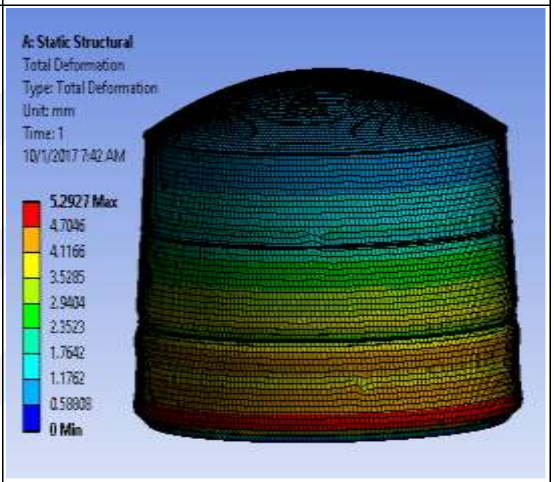
3 Courses



4 Courses



5 Courses



6 Courses

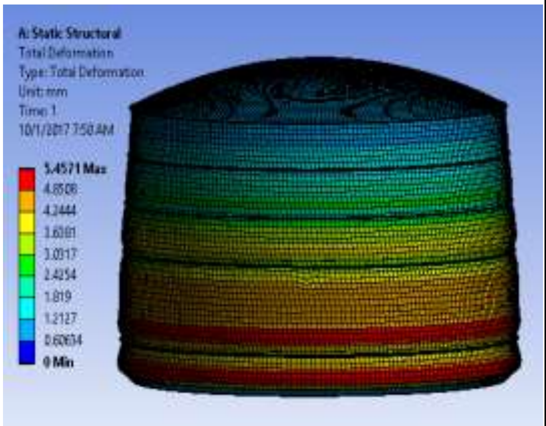


Figure 4.13 The maximum deformation shapes for Case 3

The seismic behavior of the tanks is investigated by studying fundamental frequency. The maximum fundamental frequency is occurred at Case 5 with 2 courses where C section stiffener is used and equal to 18.010 Hz. The corresponding mode shape is shown in Figure 4.14. The lowest fundamental frequencies are obtained in Case 1 as expected.

Table 4.12 The fundamental frequencies values

	Course	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Fundamental Frequency (Hz)	2	13.675	15.046	15.687	17.342	18.010	16.952
	3	14.027	14.879	15.868	16.974	17.229	16.702
	4	14.496	15.979	15.631	16.725	16.840	16.513
	5	14.215	14.794	14.888	15.739	17.226	15.604
	6	13.567	14.164	11.416	14.930	17.008	12.308

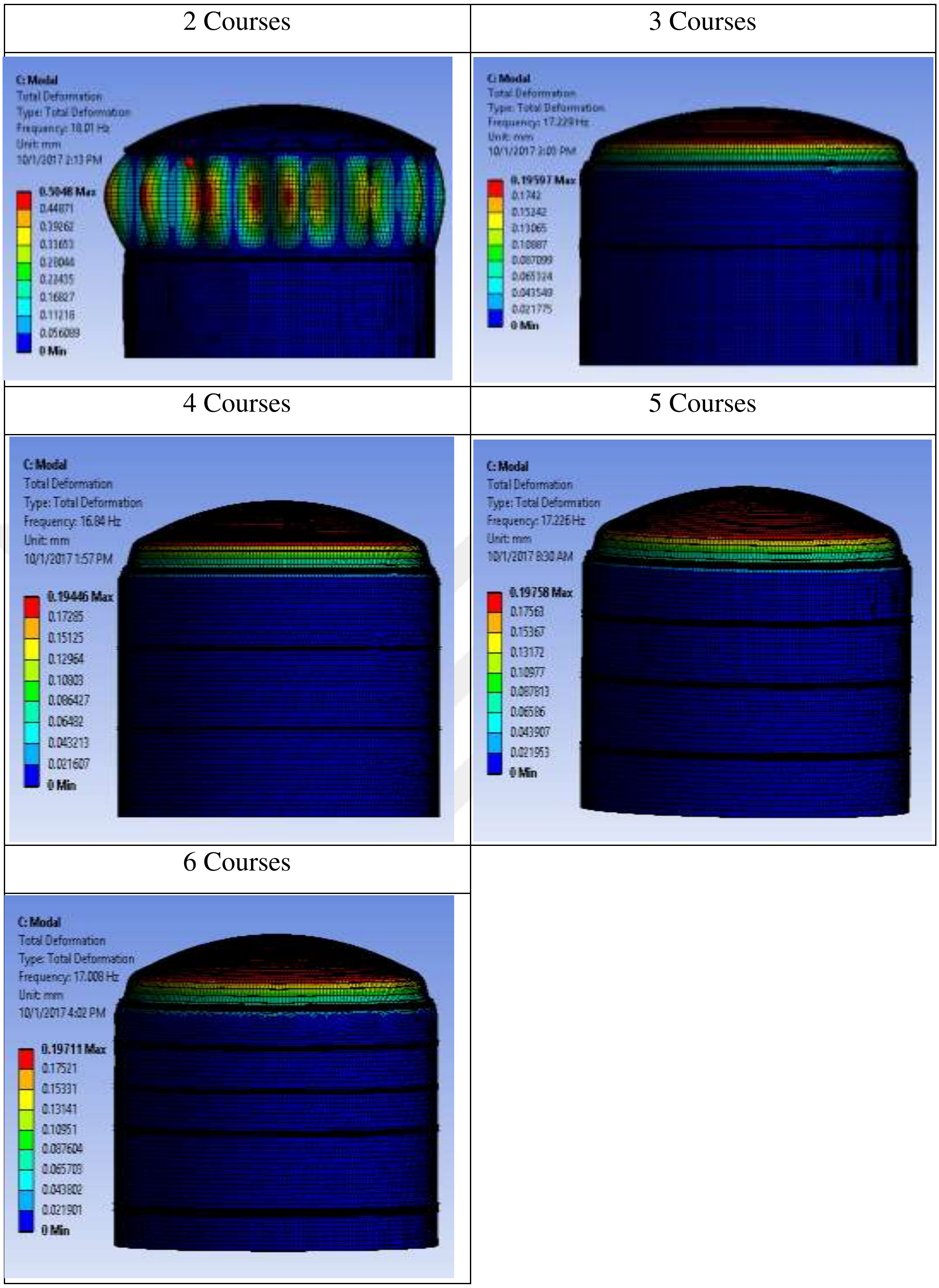


Figure 4.14 The fundamental frequencies.

The one of the main reason of failure of tank is buckling. The buckling analyses of the tank are carried out and the buckling multiplier have been computed and given in Table 4.13. The worst case is the tank shell wall without stiffener. The best solution against buckling is obtained in Case 5 where C section stiffener is used. The maximum buckling multiplier is occurred at Case 5 with 5 courses and equal to -1.3107. The corresponding buckling mode shape is shown in Figure 4.15.

Table 4.13 Maximum buckling multiplier values

	Course	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Buckling Multiplier	2	-1.1495	-1.2169	-1.2177	-1.2285	-1.2325	-1.2267
	3	-1.1280	-1.2548	-1.1749	-1.1793	-1.1813	-1.1813
	4	-1.0978	-1.2470	-1.2455	-1.2624	-1.2727	-1.2712
	5	-1.0789	-1.2434	-1.2443	-1.2823	-1.3107	-1.2832
	6	-1.0647	-1.1932	-1.1888	-1.2109	-1.2394	-1.2089

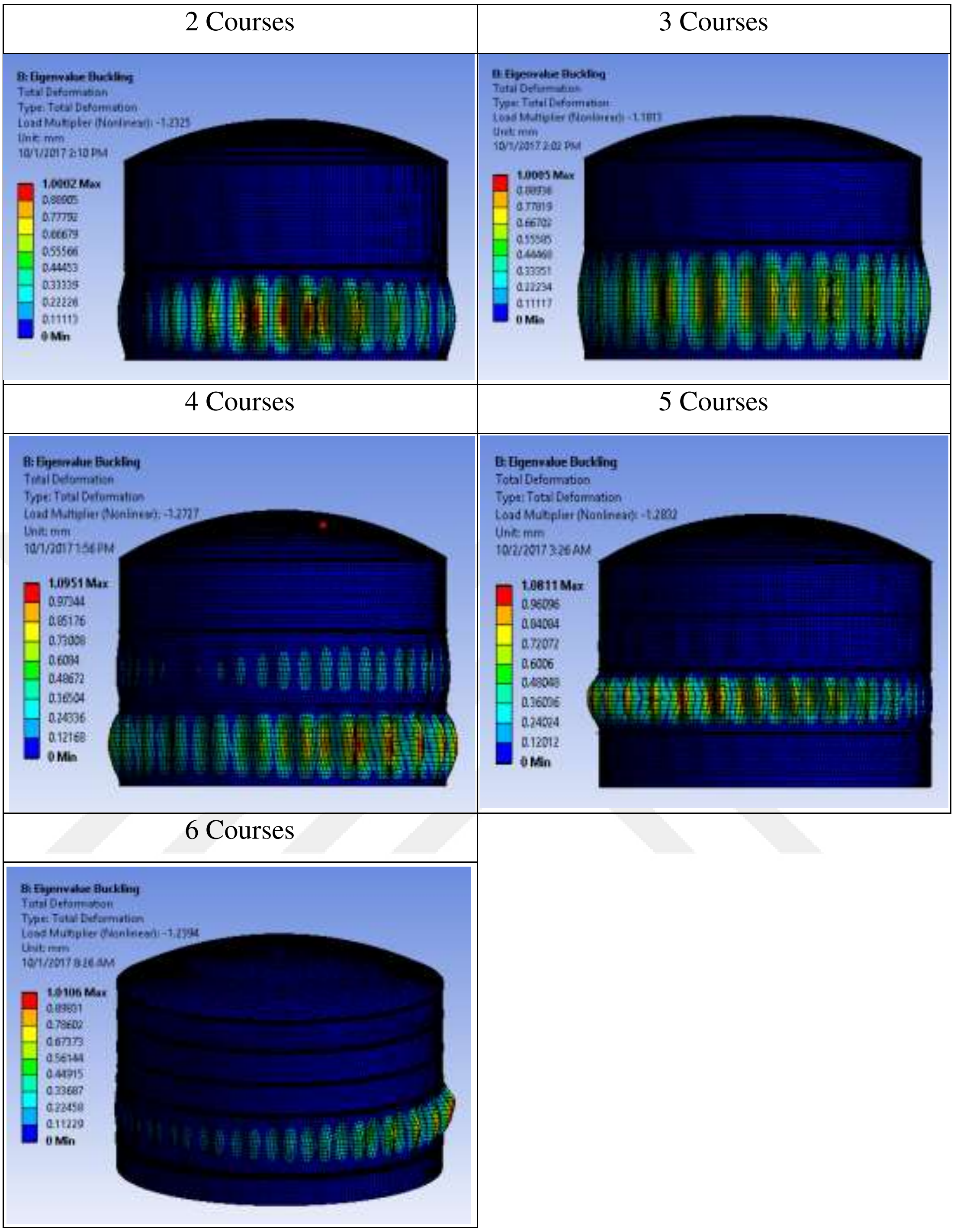


Figure 4.15 Maximum buckling multiplier

The weight of the tanks decrease with increasing number of courses. The lightest tank is obtained in case of without stiffener. The heaviest tanks are found in case of C section stiffeners

Table 4.14 The total weight of tank

	Course	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
Weight (kg)	2	118760.00	120096.28	120398.05	120398.05	123333.11	120340.52
	3	114808.00	116510.74	116580.55	116580.55	118661.65	116011.26
	4	109861.00	113238.13	112955.72	112955.72	114951.10	114853.31
	5	105708.40	108393.52	108610.83	108610.83	115526.40	108348.84
	6	101950.70	105047.67	105451.41	105451.41	113541.12	104389.55

CHAPTER 5

CONCLUSION

5.1 General

The two types of cylindrical steel liquid tank constructed from sheets with the circular cross are investigated. These are self-supporting roof and umbrella roof tanks The investigation consisted of two step. In the first step, tanks are designed according to API 650 standard. In the second step, static, free vibration and buckling analyses are carried out in order to observe the effect of various parameters on the performance of tanks using FE method. The examined parameters are: number of stiffener, number of course, type of stiffener profile and orientation of profile. The loads were evaluated according to API 650 standards. The FE method were effectively used for the computation of von Mises stress distribution, deformations, fundamental frequency and buckling load multiplier of the shells.

5.2 Conclusions

In this thesis preliminary design of elements of a circular liquid tank was performed according to the API 650 standard. With obtained dimensions of tank elements (such as thickness of course, number of stiffener, location of stiffeners, required moment of inertia of stiffener), tank was modeled in the software package ANSYS. Static analysis is done to evaluate the von Mises stress distribution and deformations. Free vibration analysis is performed for evaluation fundamental frequency and corresponding mode shape. The bifurcation linear buckling analysis are carried out to investigate the buckling load multiplier and mode shapes. The main conclusions drawn from this thesis may be listed as follow:

- The maximum von Mises stress is very close to design stress in self-supporting and umbrella roof tan.

- The maximum von Mises stress is generally occurred at the bottom of shell wall and gradually decrease from bottom to top.
- Average maximum deformation for all cases and roof types is 5.30 mm.
- The maximum deformation is generally occurred at the bottom of tank wall and gradually decrease from bottom to top.
- The stiffeners limit the excessive deformations in all case and type of roof.
- For open tank, the smallest (worst situation) fundamental frequency which is equal to 6.4982 Hz, is occurred at two course shell without stiffener. The highest fundamental frequency is equal to 21.189 Hz and is found at six course shell with C type stiffeners.
- For dome roof tank, the smallest (worst situation) fundamental frequency which is equal to 11.416 Hz, is occurred at six course shell with L type stiffener. The highest fundamental frequency is equal to 18.010 Hz and is found at two course shell with C type stiffener.
- For open tank, the smallest (worst situation) buckling multiplier factor which is equal to -1.0595, is occurred at six course shell without stiffener. The highest buckling multiplier factor is equal to -1.3107 and is found at five course shell with C type stiffeners.
- For dome roof tank, the smallest (worst situation) buckling multiplier factor which is equal to -1.0647, is occurred at six course shell without stiffener. The highest buckling multiplier factor is equal to -1.3107 and is found at five course shell with C type stiffeners
- For open tank, the lightest weight of tank which is equal to 70600.70 kg, is occurred at six course shell without stiffener. The heaviest weight of tank is equal to 91959.11 kg and is found at two course shell with C type stiffeners.
- For dome roof tank, the lightest weight of tank which is equal to 101950.70 kg, is occurred at six course shell without stiffener. The heaviest weight of tank is equal to 123333.11 kg and is found at two course shell with C type stiffeners.

- The stiffeners improve the static, buckling and dynamic behavior of the tank. For high seismic region, the C type stiffener profile with large number of courses can be recommended.

- WT and C section stiffener show better performance. When the number of the courses increase the weight of the tank is reduced meanwhile the structural behavior of the tank does not change so much.

- FE analyses show that the liquid tanks designed according to API 650 standards are efficient, robust, reliable and safe.

5.3 Recommendation for Future Work

Previous experience with natural disasters and environmental risks provides a basis for investigating and developing safe liquid tank design in risky places and situations Huge progress has been made in analysis and design of liquid storage tanks by many researcher and many design standards are developed, but many important research and technical questions needs remain. Some of the research subjects need to be studied are:

- Nonlinear seismic analysis of liquid tank subject to various load combinations.
- The optimization of the liquid storage tanks.
- The research work on the structural health monitoring of tank is necessary for hazard prevention.

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