Malaysian Journal of Civil Engineering 28(3):327-348 (2016)

ANALYTICAL STUDY OF SHELL THICKNESS VARIATION MODELS FOR NATURAL DRAUGHT COOLING TOWER ON VERTICAL PILE FOUNDATION

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Abstract: Natural Draught Cooling Tower (NDCT) is an important and essential structure in nuclear and thermal power stations as it contributes both to the energy efficient output and balance to an environment. From the structural point of view, high rise concrete structure is subject to various dynamic loads in an unfavorable way. Wind loading is important in NDCT design for structural safety, elastic stability, vibration properties and the initiation of concrete cracking in comparison to other structures. The behavior change of NDCT due to the variation of shell thickness when NDCT rested on a vertical pile foundation is very interesting. Therefore, the objective of the present paper is to briefly present the finite element modeling and analytical study of NDCT with twenty-seven different types of shell thickness models for the same height of NDCT. Each model is identified based on the separate case number from 1 to 27, and FEM analysis was carried out using *Staad Pro-V8i* software considering gravity loads, wind load. Further, design wind pressure at different levels along the height of NDCT was calculated as per IS 875 (part 3) 1987 code after applying Interference factor (IF) of 1.573. Due to the lack of wind study findings, the IF was considered as 1.573 while the maximum value of IF was 1.43 as per BS: 4485 (1975). Distribution of wind pressure at each level of NDCT in the circumferential direction was as per IS11504-1985. The overall study identified optimum shell thickness varying models to obtain the optimum foundation as well as super-stable structure. Further, the comparison was made between the guest and peak factor method and found that wind load due to gust factor method was critical and therefore recommended.

Keywords: *Gust factor method, meridional bending moment, circumferential shear stress, natural draught cooling tower, shell thickness.*

1.0 Introduction

NDCT's are essential and important for thermal and nuclear power stations as they provide both energy efficient output and balance in an environment. The major characteristics of NDCT are the cost of maintenance is low, and their performance is higher than cooling frames, but it is not appropriate for high dry bulb air temperatures.

Therefore, the disadvantages are inlet water temperature must be higher than the air dry bulb, seldom applied to air conditioning, close approach cooling not possible and capital cost may be higher owing to the great height necessary to produce the draught. Additionally, the control of exact outlet water temperature is typical and mainly used for large cooling duties, for instance, Power stations (Gaikwad *et al*., 2014). From the structural perspective the high rise concrete structure subjected to several dynamic behavior changes in an unfavorable way, such as wind effects and an earthquake motion. In the absence of earthquake loading, the wind comprises of the important loading for the design of NDCT. Therefore, it is important in Tower design for structural safety, elastic stability, vibration properties and the initiation of concrete cracking in comparison to smaller towers. In general, the shell structure is supported by inclined raker columns and studies have analyzed its behavior of NDCT (Rasikan & Rajendran, 2013). However, it is unclear about the behavior change of NDCT due to the variation of shell thickness when NDCT rested on a vertical pile foundation. This is important to address, as piles used in the cooling tower should withstand the self-weight of the structure along with the other loads acting on the structure. The present study aimed to analyse the behaviour of NDCT resting on a vertical pile foundation with different shell thickness profile's and attempted to identify the optimum shell thickness varying model. Finally, the findings obtained have been discussed in comparison with the previous papers and finally concludes the study findings.

2.0 Literature Review

Several studies have been conducted previously on the impact of wind loading on cooling tower (Murali *et al*., 2012; Mungan & Wittek, 2004; Orlando, 2001; Prashanth & Sulaiman, 2013; Murali, 2012). For instance, the study by Orlando (2001) examined the wind induced interference effect focused on pressure management on two adjacent cooling towers. The study conducted on cooling tower models and numerical linear analyses were performed to understand the structural responses of both grouped and isolated towers. Later, the study of Busch *et al*. (2002) based on the German codified safety concept, the authors had studied both design and structural analysis of the tower. The study also sheds light on the durability aspects of the tower. The author also identified 200m as the height of the cooling tower along with their base diameter of 152.54m. The top opening was observed at 88.41 m wide while the tower shell was 136.00. It has more than 60 000 m^2, equivalent that covered both outer and inner shell surface. However, the tower in this study was designed based on the Germany regulations VGB-BTR (VGB PowerTech, 2010). Further, Germany cooling tower technology accepted that they had suppression of initial imperfection especially during the designing stage; therefore, it possessed high surface area.

Similarly, wind loads acting on the NDCT were studied by the Mungan and Wittek (Mungan & Wittek, 2004). The author of this study specifically focused on the turbulent wind. The study compared the GRF, LRC, and optimized peak load-distributions methods with that of the quasi-static response of an isolated RC cooling tower shell under the turbulent wind. The findings showed that in comparison with the other methods, the quasi-static response was better and optimal. Later, Murali *et al*. (2012) studies the wind load analysis with the tower height of 200m and 122m above ground level. Further, both bending moments and meridional forces were calculated to identify the optimum height. The same author had conducted another similar kind of study, but this time, there were three different heights of the cooling tower of 122m, 177m and 200m height above ground level. This height varied regarding throat height to total height ratio, throat diameter to base diameter and diameter to thickness ratio. Murali (2012) did calculate the bending moments, hoop forces and meridional forces for identifying the optimum height.

Further Patil *et al*. (2013), described the concept of structural design of tall NDCT based on boundary layer with tunnel experiment studies on a group of towers. This study proposed two set NDCT numbers for each 700 MWe capacity NPP project, where the diameter is as large as 120m and to a height 165m. The paper dealt with the study of the hyperbolic cooling tower of varying dimensions and Reinforced Cement Concrete (RCC) shell thickness. The RCC shell thickness and the hyperbolic cooling tower of different dimensions were studied by Prashanth and Sulaiman (Prashanth & Sulaiman 2013). The comparison was made in an existing tower while, for other cooling tower models, the thickness and dimensions varied focusing on the specific type of cooling tower. Similarly, Kulkarni and Kulkarni (2014) focused on the two existing cooling towers of 143.50m and 175.50m high above ground level. Authors in this study studied both the wind and buckling analysis using eight nodes SHELL 93 elements with uniform SHELL thicknesses

It is well acknowledged that both large dimension and column slenderness of the NDCT make vulnerable to earthquake. Therefore, the study by Gaikwad *et al*. (2014) analyzed the effect of wind loads on NDCT structure. The authors of this study attempted to design and analyzed the cooling tower structure and presented with the V-shaped configuration of Raker column. Subsequently, the authors have applied finite element analysis (FEA) where the analysis was done by classifying shell into different plates and applied wind loading. Wind load was calculated based on the gust and peak method. *Staad* Pro V8i software was used to analyze these models and provided an overview of these models regarding constructability, design, and analysis. This methodology would shed light on the effective wind analysis model.

Although there are several studies, have been carried out to analyze the behavior of cooling systems, but to our knowledge, not many studies exist on a vertical pile foundation. Therefore, the study would be unique in that as the objective of the present paper analyzed the behavior of the structural design of NDCT with twenty-seven different types of shell thickness models for the same height of NDCT. The study also identified the optimum shell thickness profiles. Further, the comparison was made between gust and peak factor method and found that the wind load due to the gust factor method was critical and therefore recommended.

3.0 Methodology

In this study, 27 different shell thickness profiles (models) are considered to study the behavior of NDCT resting on vertical piles. Each model is identified based on the separate case number from 1 to 27.Dead loads & soil loads acting on NDCT are considered with standard unit weight. Further, NDCT was analysed for wind loads in meridional & circumferential directions as per the provisions of IS 875-Part 3 (IS 875, 1987), IS 11504 (1985) by an Interference Factor of 1.573.Finite Element Method (FEM) was used to analyse the behaviour NDCT by 3D modelling of NDCT and its foundation using *Staad Pro-V8i* software.

4.0 NDCT Geometry, STVM, Loading Analysis & Piling Layout

4.1 Geometry of the NDCT

General arrangement of the natural draught cooling tower considered in the study was shown in figure 1. The shell structure consists of a hyperbolic shell of revolution, which is supported on 56 pairs of raker columns. Raker columns are tangential to the meridian profile of the shell at its bottom and are also inclined in the plan. The open system of columns provides the air inlet opening. Ring beam is provided at the junction of shell and raker columns and is in the same meridional plane of the shell. The raker columns rest on the pedestal. At the bottom, pile cap is provided below the pedestal. The pile cap is horizontal. Vertical piles are provided to transfer of meridional forces in the founding system.

One hyperboloid of revolution starts from the top of ring bean and ends at throat level while the second starts with the throat and ends at the top of the cooling tower. The geometry of the hyperboloid of revolution shown in figure 1.0 is arrived as per Annexure B of IS 11504. Angle of shell to the vertical at the bottom of the shell is 16.699^{o}.Geometric features of natural draught cooling tower considered for the study are mentioned in figure 1 & table 1.

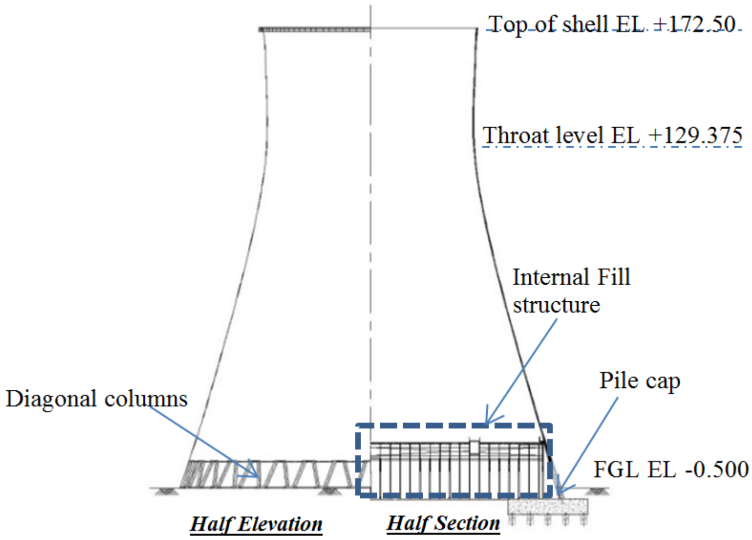


Figure 1: Natural draught cooling tower showing half elevation and half section

Table 1: Dimensions of NDCT considered for the present study

Item	Internal Diameter	Level
Finished ground level (FGL)		EL -0.5
Basin level	138 m	EL +0.0
Throat(Neck)	75.9 m	EL +129.375
Top of shell	77.42 m	EL +172.5
Bottom of Shell		EL +8.3

4.2 NDCT Shell Thickness Variation Models

Previous studies Gaikwad *et al*. (2014) showed that the period of vibration decreases approximately linearly varying with changes in thickness. In line with this, the present study also attempted to identify an appropriate shell thickness for the given height. 27 different types of Shell Thickness Variation Models (STVM) were considered (see figures 2 to 7). Each model identified with the separate case number from case 1 to case 27. Although minimum shell thickness is satisfying buckling check was 250 mm but in this study, minimum thickness was maintained at 280 mm to ensure sufficient factor of safety in buckling of shell and thickness was increased up to a maximum value of 330 mm.

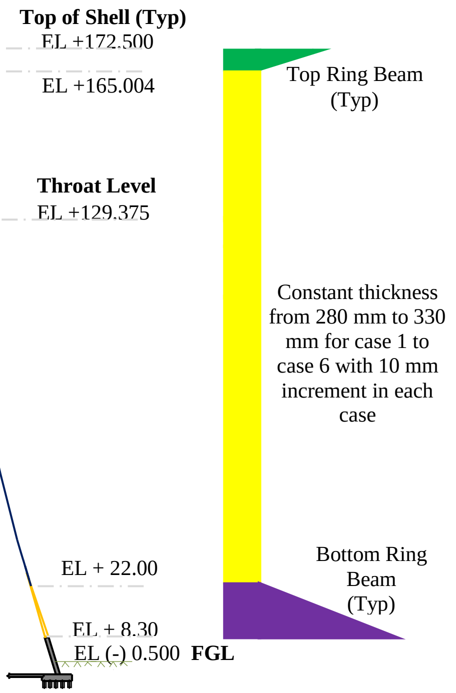


Figure 2: Shell thickness variation model for Case 1 to 6

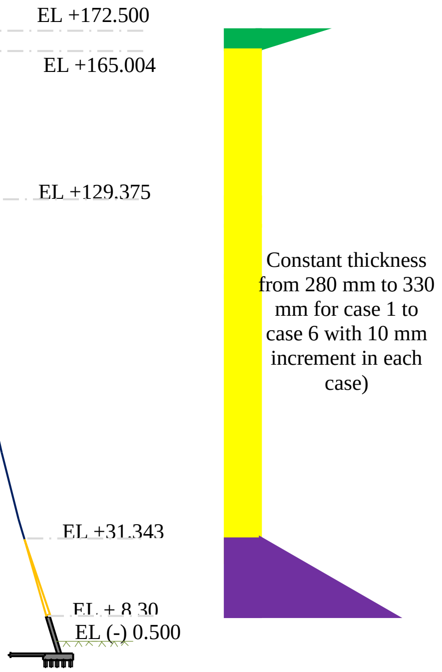


Figure 3: Shell thickness variation model for Case 7 to 12

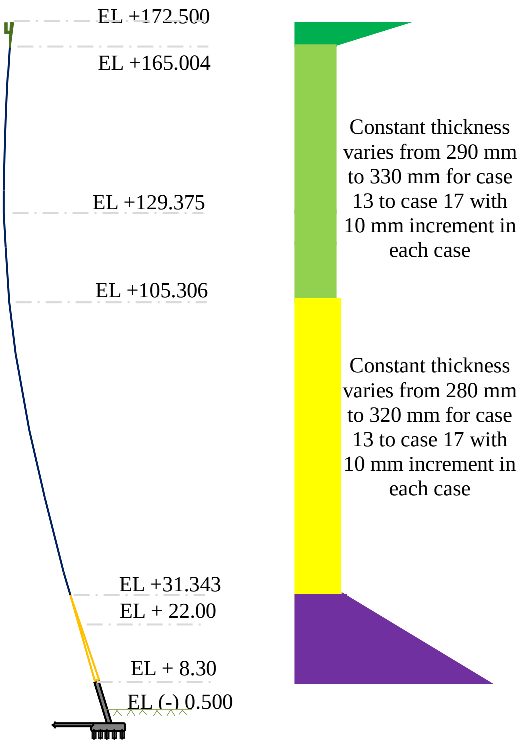


Figure 4: Shell thickness variation model for Case 13 to 17

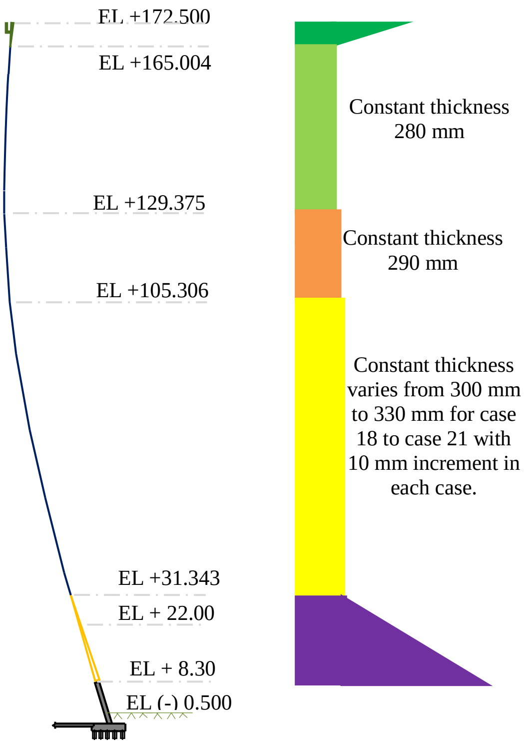


Figure 5: Shell thickness variation model for Case 18 to 21

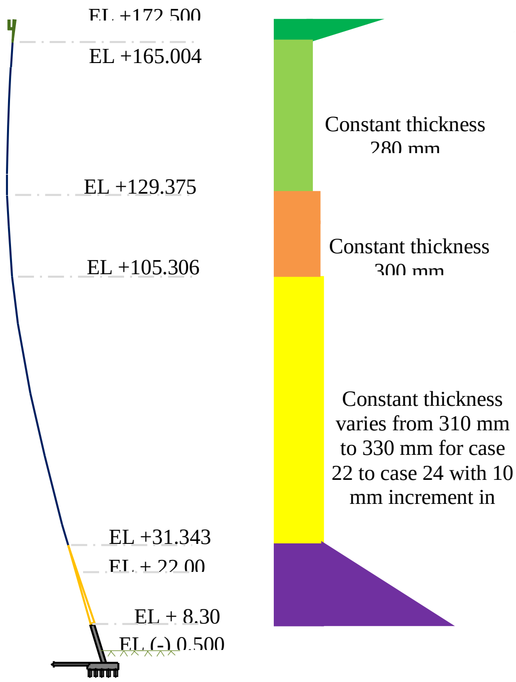


Figure 6: Shell thickness variation model for Case 22 to 24

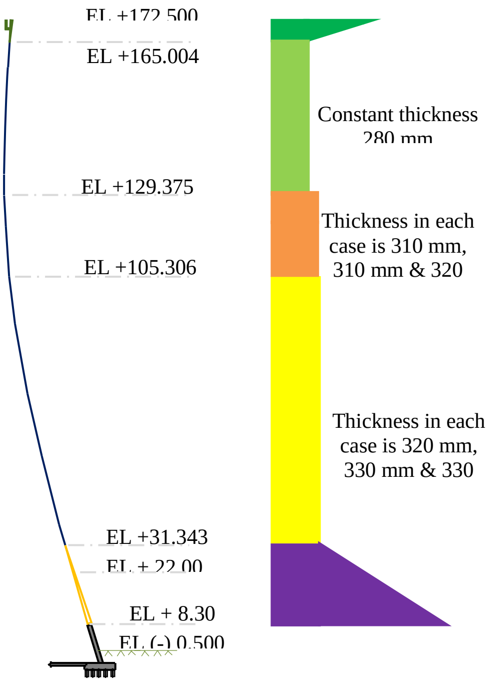


Figure 7: Shell thickness variation model for Case 25 to 27

4.3. Piling Layout

For NDCT foundation resting on vertical piles, not only the vertical load transfer, but also the horizontal load distribution shall be ensured. From the preliminary calculations, it was found that this tower requires 900 mm diameter pile of length 49 m. The spacing between the piles is maintained as three time's diameters. Piles are arranged in 5 rows with 168 no's and in each row, which gives 840 numbers of piles for the tower. Circumferentially three rows of piles are located on the inner side of the pedestal centreline, and two rows of piles are located outside the pedestal centre line. The outermost and innermost pile rows are located at 0.65m from the edge of pile cap. An annular pile cap of 12.1 m width, 2.3 m thickness is provided. Annular pile cap internal diameter is 125.586 m and outer diameter is 150.586 m. Safe carrying capacities of the pile are 4800 kN in compression, 280 kN in lateral direction and 800 kN in tension.

4.4 Material Properties for Cooling Tower Analysis

Various material properties of the cooling tower are as follows: Pedestal, pond wall, pile and pile cap are M30, while the tower shell and ring beam are M40, and Raker column was M50. Further, all reinforcing steel is corrosion resistant steel of marine grade with high yield strength deformed bars.

4.5 Gravity Loads

The gravity loads acting on NDCT such as self-weight & soil the loads calculated using below-mentioned unit weights:

Unit weight of concrete = 25 kN/m^3
Unit Weight of Soil = 18 kN/m^3

4.6 Wind Load Analysis

In this study, the wind pressure distribution in the circumferential direction is calculated and plotted as shown in figure 8, using the following equation (according to IS 11504):

$$p' = \sum_{n=0}^{7} F_n' Cos(n\theta) \tag{1}$$

Where

p' : Design wind pressure coefficient.
F_n : Fourier coefficient of nth term (Values are considered as per IS 11504)
θ : Angular position measured from the incident wind direction in degrees.

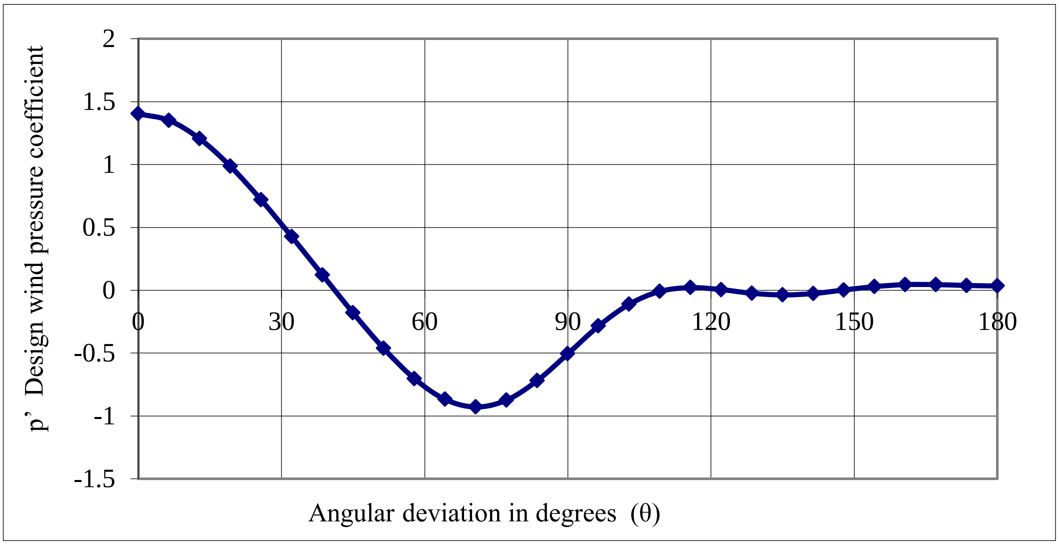


Figure 8: Circumferential Wind pressure

Pressure coefficients given above are based on the uniform pressure distribution in laboratory conditions (according to IS 11504). In a realistic situation, the NDCT is part of a dense arrangement of large surrounding power plant buildings. Hence, allowances should be made in assessing the wind loading for (a) Load intensification due to natural turbulence in the incident wind, and (b) Load intensification due to turbulence induced in the incident wind by adjacent cooling towers in a group or on the structures of significant dimension in the vicinity. It has become usual to term this influences (a) & (b) as interference effect.

Wind tunnel test on NDCT shall be conducted to investigate the effect of interference in four different angles of wind incidence ranging from 0^0 to 360^0. Based on the results of wind tunnel study, the Interference factor (IF) arrived shall be further considered in wind loading calculations. In this paper due to lack of wind study results, the IF was considered as per BS: 4485 (1975). As per BS: 4485 (1975) clause 3.1.1.5, the maximum value of Load intensification due to natural turbulence in the incident wind was 1.1 and load intensification due to turbulence induced in the incident wind by adjacent cooling towers in a group or on the structures of significant dimension in the vicinity was 1.3. Hence, the maximum Interference factor (IF) as per BS: 4485 (1975) was 1.1 x 1.3 = 1.43.

In the present study the maximum Interference factor (IF) as per BS: 4485 (1975) was increased by another 10 % (additional factor of safety), i.e. IF considered in the present study was 1.573 (1.1 x 1.43). This IF of 1.573 was considered while calculating the meridional wind pressure along the height of NDCT instead of changing the coefficients shown in figure 8. Wind Pressure for the design of a structure above the foundation is calculated with the help of peak wind method and gust factor method according to IS875- part 3.

4.6.1 Peak Factor Method

Design wind velocity (V_z) at any height z in m/s is calculated as per IS 875-3, using this following formula for a basic wind speed of 50 m/sec (coastal area):

$$V_z = V_b K_1 K_2 K_3 \quad (2)$$

Where, k_1 : Probability factor, (Terrain category = 1, Class of the structure = C),
k_2 : Terrain, height and structure size factor ,
k_3 : Topography factor.

Further, the design of wind pressure (P_{zs}) at any height z above the mean ground level was obtained as per IS 875-3, using the following relationship between wind pressure and wind velocity.

$P_{zs} = IF\ 0.6\ V_z^2$ (3)

4.6.2 Gust Factor Method

The method of calculating wind load through the application of gust factor method is available in IS 875-Part3. The design wind pressure (P_{zg}) at any height z above mean ground level shall be obtained by the following equation:

$P_{zg} = IF\ G.\ 0.6\ V_{zg}^2$ (4)

Where
V_{zg} : Hourly mean Wind Speed at height z
G : Gust Factor

All the parameters mentioned in eq.s (1), (2) & (3) are calculated as per relevant clauses of IS 875-3.

Design wind pressure values up to 200 m above ground level are calculated using both peak factor method and gust factor method and the variation of the same was presented in figure 9.

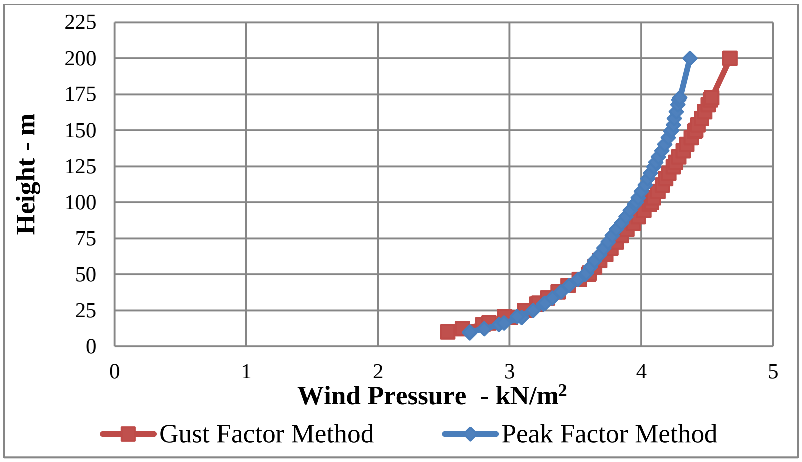


Figure 9: Meridional Wind Pressure variation

From figure 9, it is evident that wind pressures computed by the gust factor method increase with the height of the building and they are more critical than peak factor method. Gust factor method gives critical wind pressures to be considered in the design of NDCT compared to peak factor method. Hence, wind load due to gust factor method is only considered in this study.

4.7 Load Combinations

Following load combination was considered to study the variation bending moment & shear stress in the meridional & circumferential directions in the shell as per IS456 (2000):

1.0 DL + 1.0 WL (5)

Where, DL : Dead load
WL : Wind load due to gust factor method.

5.0 Results of the Analytical study on NDCT

Finite Element Model of NDCT & its foundation shown in figure 10.0 was generated using *Staad*. Pro V8i software. 3D finite element model of NDCT along with piles & pile cap consists of 6160 numbers of nodes, 112 numbers of beam elements for modeling raker columns, 5824 numbers of three noded and four noded plate elements for modeling tower shell, pond wall, pedestals and pile cap and 840 numbers of spring elements for modeling the piles. These elastic springs consists of stiffness's in vertical (600000 kN/m), lateral (56000 kN/m) & longitudinal (56000 kN/m) directions only to simulate the pinned connection between pile cap and piles. Material properties for all the elements of NDCT are considered in line with section 4.4. Boundary conditions for the model are: top edge of the shell structure was free to translate and rotate in all directions while the base was supported by elastic springs. The finite element model has been analysed for all load cases and load combinations with the aim of calibrating.

Findings limited to the present study i.e. Meridional & circumferential bending moment, meridional & circumferential shear stress at each level along the height of the NDCT was captured from the STAAD output results for all cases 1 to 27 in L/C 1.0 DL + 1.0 WL. At each level along the height of the NDCT for case 1 to case 27, Maximum meridional bending moment (MMBM), Maximum circumferential bending moment (MMBM), Maximum meridional shear stress and Maximum circumferential shear stress (MCSS) are calculated and plotted figures 11,13,15 & 17 respectively.

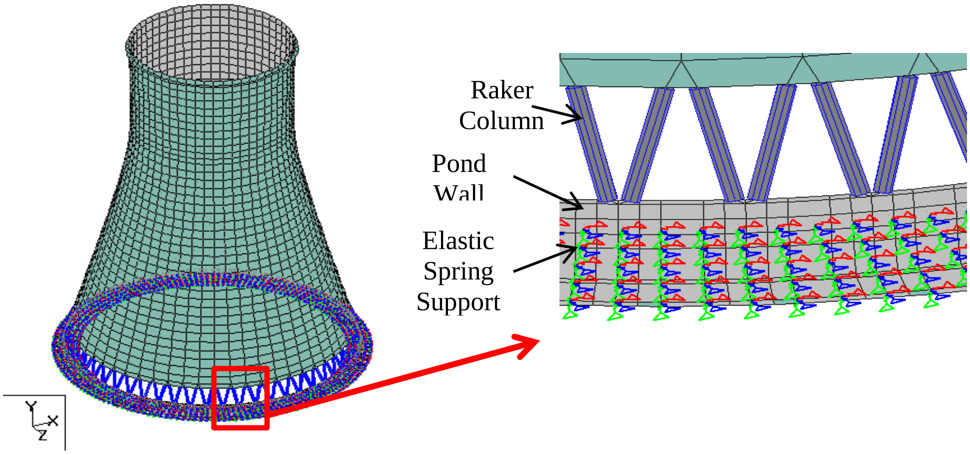


Figure 10: Finite Element Model of NDCT

5.1 Variation of MMBM

The findings from figure 11 are: MMBM is reduced with an increase of thickness in the bottom and ring beams for all cases 1 to 27 whilst MMBM is increasing with the increase in thickness of the shell (i.e. EL +35.659 to EL +162.754). Cases 1 to 6 are resulting higher values of MMBM in the bottom and ring beams. Cases 7, 13,18,22,26 are resulting fewer MMBM values at all levels along the height of NDCT. Hence MMBM profiles for cases 7, 13,18,24,26 along the height of NDCT are plotted as shown in figure 12.

From the figure 12, it is evident that cases 24 & 26 resulting higher values of MMBM up throat level. Whilst MMBM values are almost same for cases 7,13,18,24 & 26 above that level. Cases 7, 13& 18 resulting same values of MMBM throughout the height of NDCT with minor variation. Hence, cases 7, 13 & 18 are best STVM to get optimum MMBM in the NDCT shell.

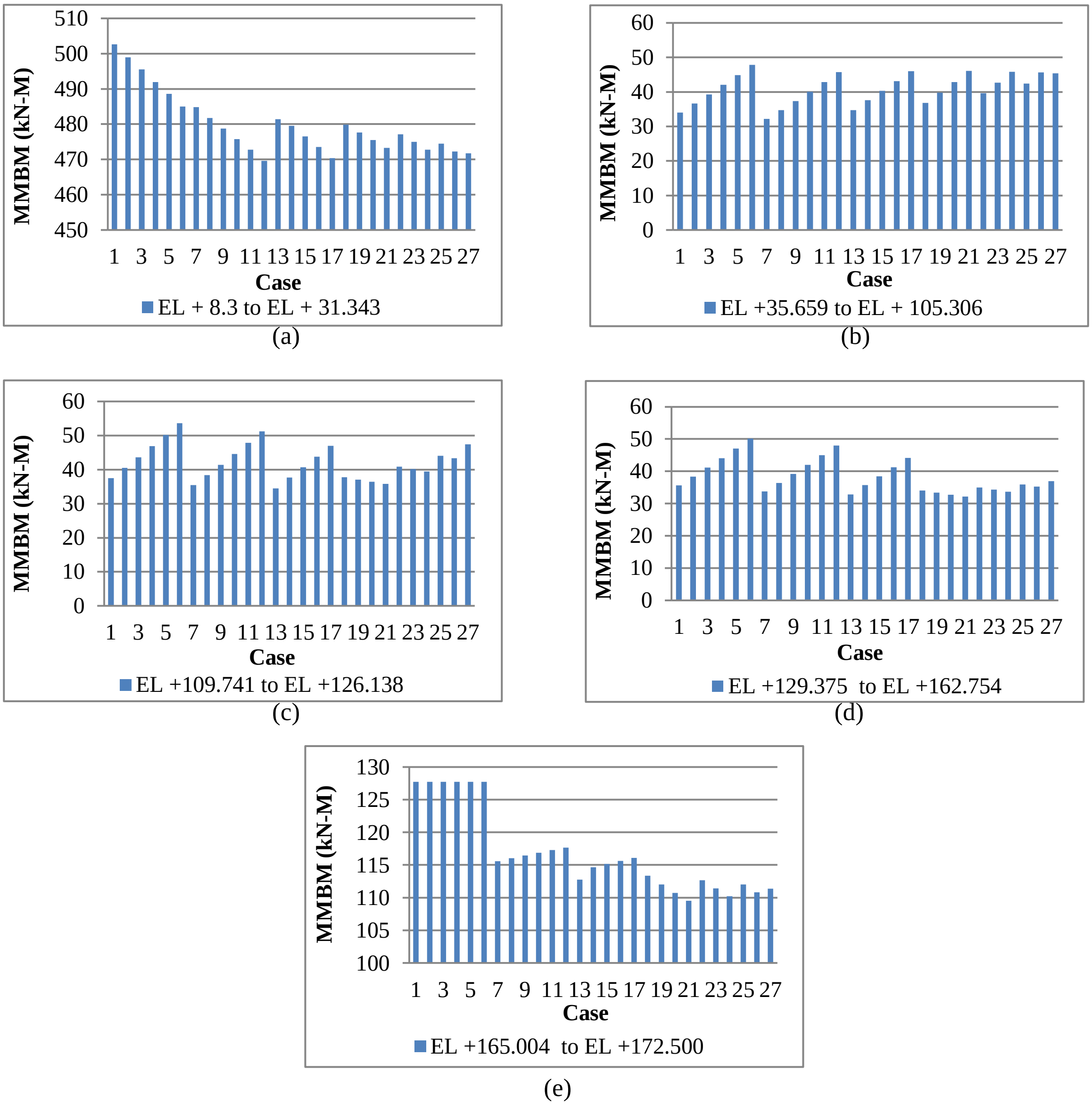


Figure 11: Comparison of MMBM for all cases 1-27

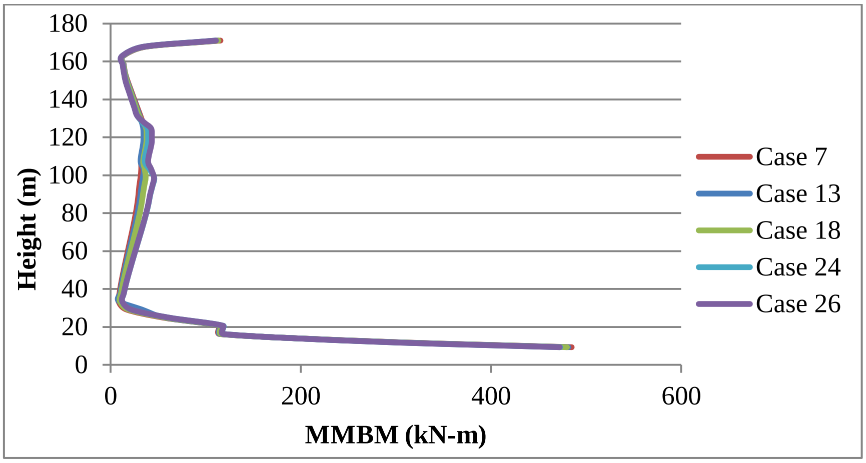


Figure 12 MMBM profiles for Cases 7, 13,18,24,26

5.2 Variation of Circumferential Bending Moment

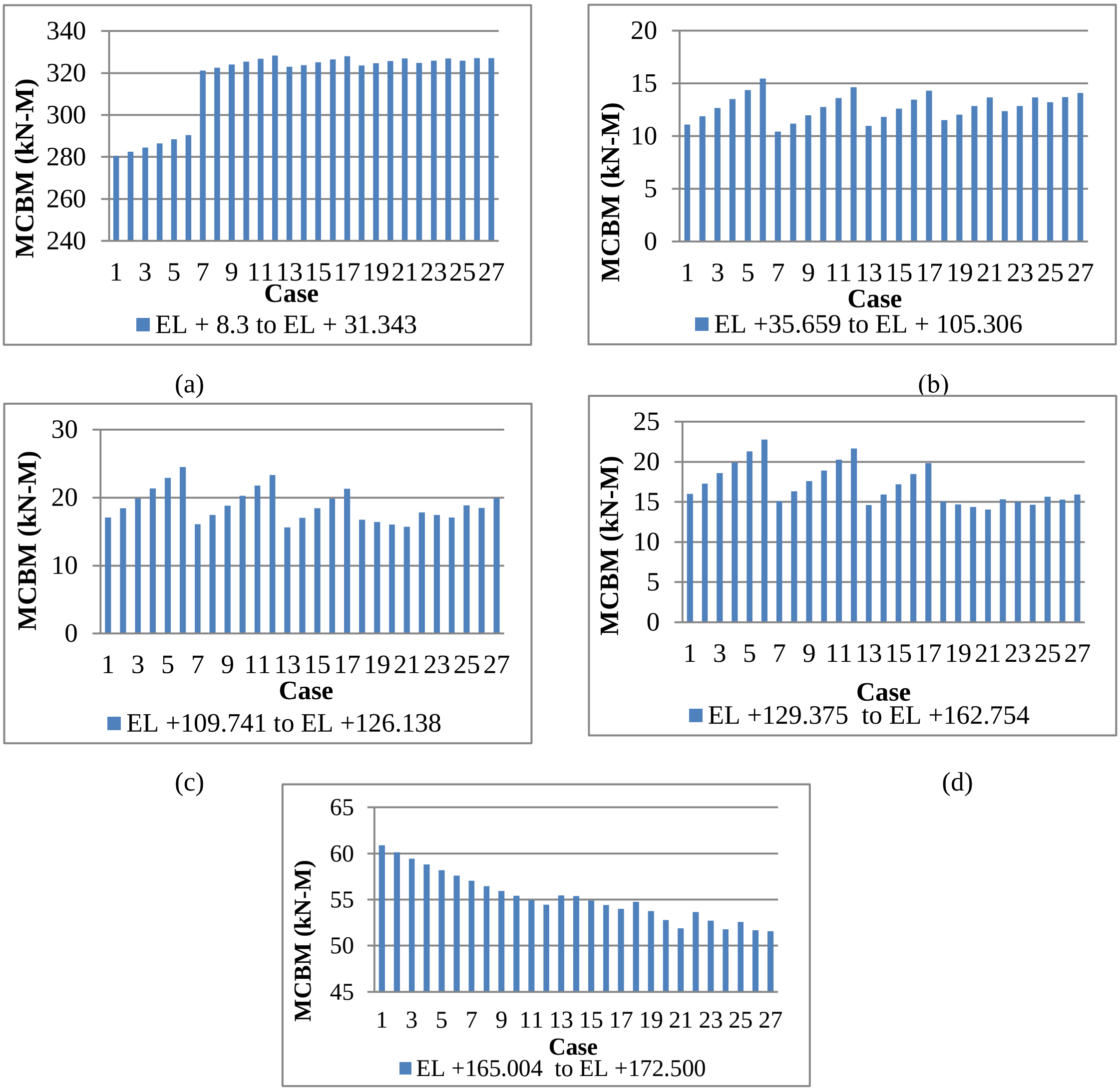
The findings from figure 13 are: Cases 1 to 6 are resulting lesser values of MCBM in bottom ring beam whilst cases 1 to 6 are resulting higher values of MCBM in the top ring beam. Between the ring beams, i.e., from EL 35.659 to EL +162.754, a variation of MCBM is very close to cases 7 to 27. Cases 7, 13,18,22,25, are resulting fewer MMBM values at all levels along the height of NDCT. Hence MCBM profiles for cases 7, 13,18,22,25 along the height of NDCT are plotted as shown in figure 14.

From the Figure 14, it is evident that MCBM profiles are representing the same profile (with minor variation in values) for cases 7,13,18,22 & 25. Hence, these are best STVM for arriving minimum values of MCBM in the NDCT shell.

5.3 Variation of Meridional Shear Stress

The findings from figure 15 are: Cases 1 to 6 are resulting higher values of MMSS throughout the height of NDCT. Variation of MCBM is very close in cases 7 to 27, however MMSS values are less in cases 7, 13,18,21,26 at all levels along the height of NDCT.

MMSS profiles for cases 7,13,18,21,26 along the height of NDCT are plotted in figure 16, from which it is evident that MMSS values are less and almost similar in cases 7,13,18,21 & 26 with a slight variation of values in case 26.



(e)

Figure 13: Comparison of MCBM for all cases 1-27

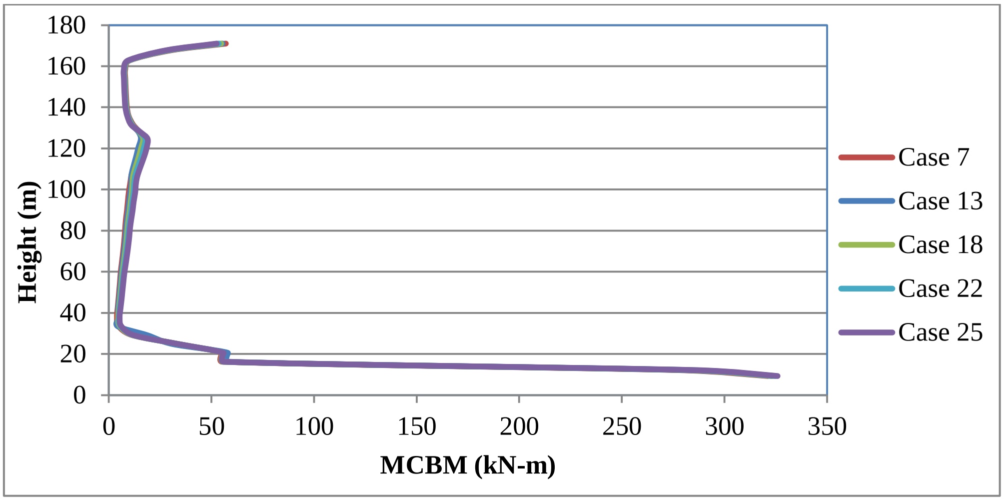


Figure 14 MCBM profiles for cases 7,13,18,22 & 25

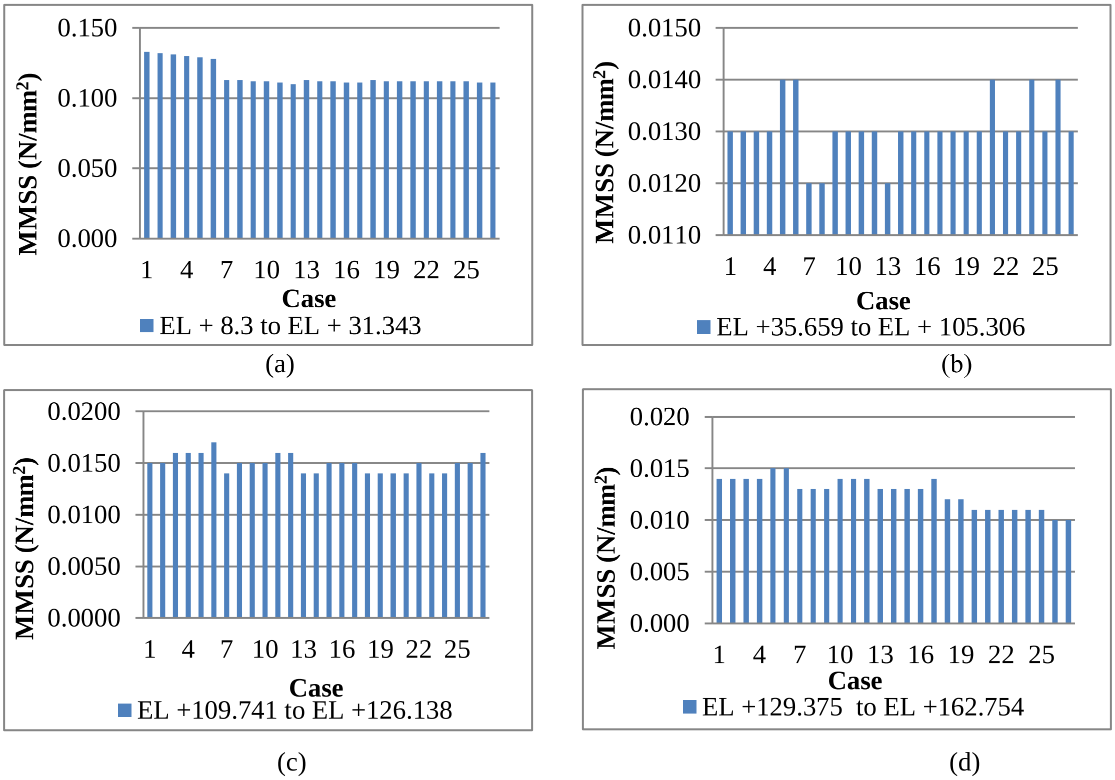
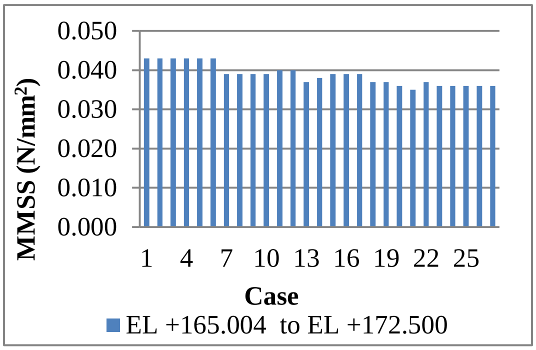


Figure 15: Comparison of MMSS for all cases 1-27



(e)

Figure 15(cont'): Comparison of MMSS for all cases 1-27

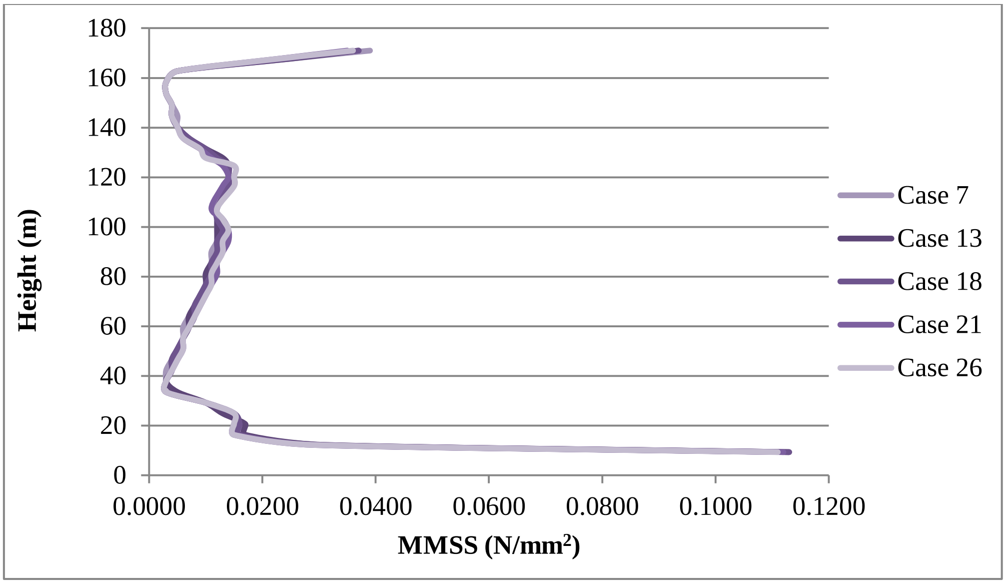


Figure 16: MMSS profiles

5.4 Variation of Circumferential Shear Stress

The findings from figure 17 are: Cases 1 to 6 is resulting higher values of MCSS throughout the height of NDCT. Variation of MCSS is very close across cases 7 to 27 and are resulting fewer MCSS values at all levels along the height of NDCT.

MCSS profiles along the height of the NDCT for cases 7 to 27 plotted as shown in figure 18, which shows that MCSS values are almost similar in cases 7 to 27 with a slight variation of values in cases 13 & 14 at bottom ring beam top level.

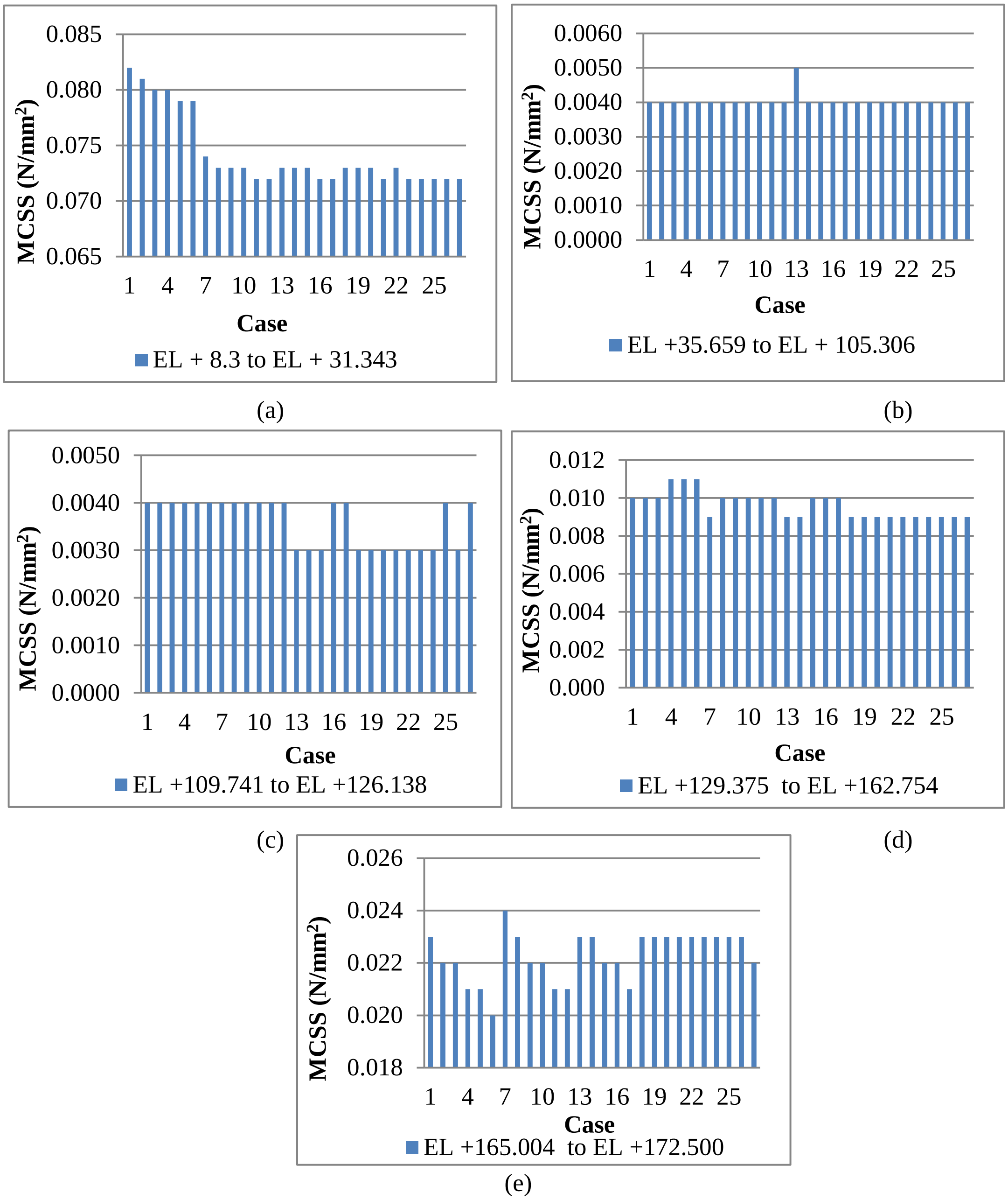


Figure17: Comparison of Circumferential Shear stress for all cases 1-27

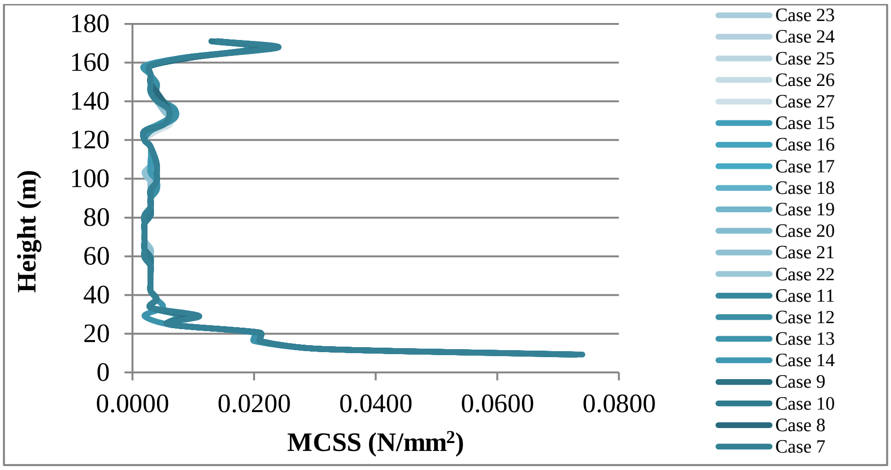


Figure 18: MCSS profiles

5.5 Discussions

Till now most of the NDCT‘s are supported on raker pile foundation which enables the axial transfer of forces from the shell to the piles through pile cap. Construction of raker piles for depth in the layered soils of the coastal area is always difficult due to the possibility of the collapse of pile bores. Hence, in the present case NDCT was supported on vertical piles with pile cap parallel to FGL, which generates additional forces at the junction of pile cap and superstructure. Redistribution of stress resulting from interaction effects between the subsoil and the shell structure has to be taken into account using composite model.

The behavior of NDCT supported on vertical piles was studied using the mathematical model: FEM analysis of NDCT and its foundation as a composite model (i.e. 3 D modeling of NDCT & its foundation as a composite model).Variation of the meridional bending moment, circumferential bending moment, meridional shear stress and circumferential shear stress in the shell are studied. Figure 19 shows the concrete quantity of NDCT shell alone for all cases 1-27.

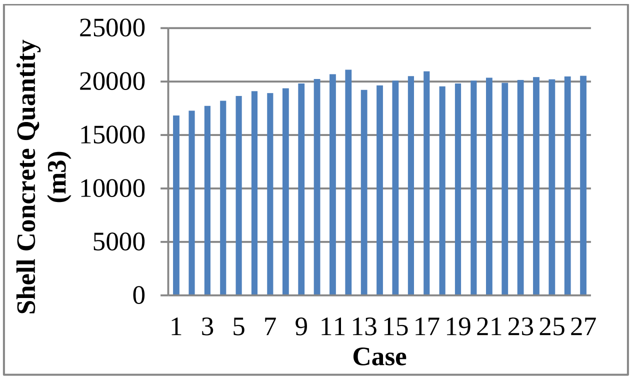


Figure 19: Comparison of Concrete quantity required for all cases 1-27

From the above results, it was identified that MMBM & MCBM values varied greatly across cases 1 to 27.Moderate variation was observed in MMSS values varied greatly across cases 1 to 27.Minor variation was observed in MCSS values across cases 1 to 27.Cases 7, 13 & 18 are best STVM to get optimum MMBM, Cases 7,13,18,22,25, are resulting fewer MMBM values at all levels along the height of NDCT, MMSS values are less for cases 7,13,18,21,26, and MCSS values are almost similar in cases 7 to 27 with slight variation of values in cases 13 & 14 at bottom ring beam top level. High concrete quantity was observed in cases 21, 22, 25 and 26 compare to case 7, 13, and 18. Hence for NDCT resting on vertical foundation cases 7, 13, 18 are best STVM for obtaining the super-stable structure.

6.0 Conclusions

The present study indicates analysis results of twenty-seven different types of shell thickness variation models for the same height of NDCT. The results showed that shell structure supported on 56 pairs of raker column which rested on pedestal with pile cap below resting on the vertical piles, the transfer of meridional forces to the founding system is found to vary linearly with changes in the shell thickness.

NDCT was analyzed using a FEM composite model of the superstructure and substructure elements. The study reveals consistent optimization of forces for the superstructure for a certain set of shell stiffness adopted. Meridional and circumferential bending moment is affected greatly due to change in shell thickness profile of NDCT. Meridional stresses are influenced moderately due to change in shell thickness profile of NDCT whilst hoop stresses are not much affected.

Increasing the shell thickness uniformly along the height of the shell as done in cases 1 to case 6, is not helping to reduce the forces in the shell and deflection of the shell.

Shifting of ring beam elevation and changing the thickness as done in cases 7 to case 26 are helping to reduce the forces in the shell and deflection of the shell. Hence Zone of transition for thickness variation will govern forces in the superstructure.

Further, the wind loading calculation based on the peak and gust factor revealed that wind load as calculated using gust factor is critical and hence the same is recommended for calculations. On the whole, the wind pressures computed by the gust factor method are not only safer for design but also they are more rational and realistic. This is an important and valid point to be considered for the design of NDCT.

In earlier studies the effect of wind pressure is taken into account by a static load in general. However, in this study, it was found that in comparison to peak, gust factor is critical for design. Moreover, gust factor findings are similar to the previous study findings by Gaikwad *et al.* (2014) where the study showed 1.601 during the present study 1.512 and thereby proves the validity of the methodology regarding meridional wind pressure due to gust factor applied in the study.

Overall, the analysis identified the shell thickness varying models shown in figures 3,4 & 5 (i.e. cases 7,13 & 18) to be adopted to obtain the super-stable structure for the an a NDCT structure.

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