Evaluation of Effect of Angular Positioning of Legs on the Structural Stability of a Pressure Vessel Using Finite Element Analysis

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Abstract
Pressure Vessel design is primarily a process that is guided by the time tested principles of ASME code. The code has incorporated experience of past 100 years to create a rule based design approach. However this approach is applicable to only standard designs, and it is not feasible for ASME to give rules for nonstandard designs, hence ASME itself has recommended a design by analysis approach for such designs. Process requirements for the vessel under consideration of this paper, dictated that there should be an unsymmetrical distribution of leg supports. The vessel has six legs, with two of them having a gap of 80 degrees and the remaining maintaining a gap of 56 degrees. This variation from a normal 60 degree standard separation makes it a nonstandard design fit for design by analysis approach. In addition to this the supports are also titled with respected to the vertical. This angular inclination in combination with the unsymmetrical distribution of legs is the focus of this paper, wherein the effort is to evaluate the effect of this on the structural parameters of deformation and stress.
Keywords-Angular supports, Unsymmetrical legs, pressure vessel FEA

Nomenclature

θ	Leg inclination,degrees	Point A	Contact point bet. leg & vessel
OD	Outer diameter,mm	Point B	Reference Point at ground level
Thk	Thickness,mm	E	Young’s Modulus,MPa
h_S	Height of shell,mm	υ	Poisson;s ratio
F & D	Flanged & Dished head	σ_{YS}	Yield Tensile strength,MPa
SF	Straight flanged height ,mm	σ_{UT}	Ultimate Tensile strength,MPa

KR	Knuckle radius,mm	S	Allowable stress of material,MPa
h_L	Height of Leg,mm	ρ	Density,kg/mm^3
h_T	Overall height of vessel,mm	P_i	Internal Pressure,MPa
F_{wt}	Self weight,kg	F_w	Wind load,N
a,b	Vertical & horizontal distancs of Point A from CG	k_c	Combination factor
Point A	Contact Point bet. leg & vessel body	Point B	Reference Point at ground level
L_i	Height of inclined length,mm	Ø	Wind load angle (angle shift,degrees)
V_Z	Design wind speed at any height 'Z' , mm	V_b	Basic wind speed at sea coast , mm
k_1	Risk coefficient	K_a	Area averaging factor
k_3	Topography factor	k_4	Importance factor
P_d	Design wind pressure, N/m^2	P_z	Wind pressure at any height 'z', N/m^2
k_d	Wind directionally factor	k_2	Terrain roughness & height factor

Introduction

A pressure vessel is a closed container designed to hold gases or liquids at a pressure substantially different from the ambient pressure. The fluid being stored may undergo a change of state inside the pressure vessel as in case of steam boilers or it may combine with other reagents as in a chemical plant. When the pressure vessel is exposed to the internal pressure, the material comprising the vessel is subjected to pressure loading, and hence stresses, from all directions.

The mechanical design of most pressure vessels is done in accordance with the requirements contained in the ASME Boiler and Pressure Vessel Code, Section VIII A. Pressure vessel mounted on arbitrary leg-type supports forms a complicated support system with respect to lateral loadings such as wind loads and horizontal seismic motion which do not have a predefined direction of action.

A. *Cumene Process*

It is an industrial process of producing phenol (C6H5-OH) and acetone (CH3-COCH3) from benzene (C6H6) and propane (C3H6). This process illustrates the benefit of chemical engineering in merely converting two relatively cheap starting materials, benzene and propane into two more valuable ones, phenol and acetone. Other reactants required are oxygen from air and small amounts of a free radical initiator. Most of the worldwide production of phenol and acetone are now based on this method.

B. *System Requirement*

When pressure vessels are used to produce Phenol and Acetone by Cumene process, the vessel has to have a lot of controls & requires continuous monitoring of the process. The system requirement is to have more floor space and to have an 80 degree opening on one side of the vessel. It was hence decided to improvise on the design and introduce angular supports.

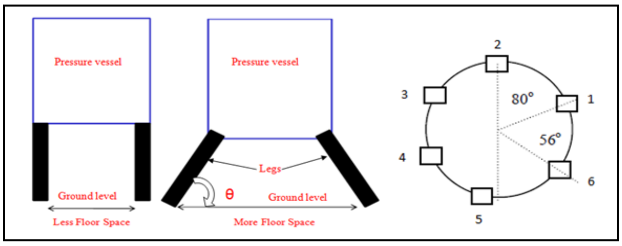

Figure.1 Block Diagram Of Conceptual Design

C. *Objectives*

Objectives of study are as follows:

i. A detailed study to understand the function and configuration of pressure vessel.
ii. Modeling of pressure vessel.
iii. Wind load calculation.
iv. Finite Element Analysis of model using Ansys for different leg inclination.
v. Stress analysis and optimizing the leg inclination & study the effect of optimum angle (θ) on the structural stability of the system Fig (1).

Finite Element Model Of Pressure Vessel

In order to proceed with the design by analysis, Finite element model of pressure vessel were designed for leg inclinations θ from 0^0 to 30^0 (total 31 cases). A model consists of boundary conditions, mesh of elements and nodes. Each model of pressure vessel was analyses for stress and deformation at the design conditions of 150 Psi at 120^0F for the entire considered cases. All finite element analyses were run using ANSYS WORKBENCH.

D. *3D Model of Pressure Vessel*

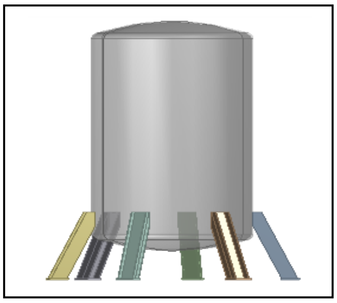

Figure.2 3D MODEL OF PRESSURE VESSEL

E. Design Inputs

Pressure Vessel is designed according to the principles specified in American Society of Mechanical Engineers (ASME) Sec VIII Division 1.

TABLE I. DESIGN PARAMETERS

Parameters	**Description**	**Material**
Cylindrical shell	O.D = 1524 mm Thk = 19.05 mm h_s = 3048 mm	SA 516 Gr.70
Head	Type = F & D OD = 1524 mm Thk = 19.05 mm SF = 38.1 mm KR = 91.44 mm	SA 516 Gr.70
Support	Type = Leg Section = I W6*15 h_L = 1079.5 mm	SA/CSA G40.21 44W
Vessel wt.when full liq.	8618 Kg	
Weight of liq. in vessel	5896.7 kg	
Vessel Orientation	Vertical	
Overall Height	h_T = 4127.5 mm	
Operating Pressure	150 Psi	
Operation Temperature	120 ^{0} F	

A typical pressure vessel is as shown in figure.2

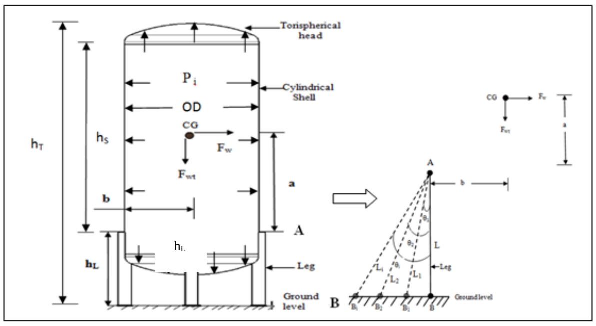

Figure.2 TYPICAL PRESSURE VESSEL WITH STRAIGHT LEG

Approach for Leg support design is to keep the contact point A constant for all inclination (θ_1, θ_2........., θ_i) from y axis and varying point B is as shown in Fig.2.1 (b). As leg inclination changes, height h_{Li} of leg and distance b from CG changes. These changes in dimensions will induce different axial and bending loads on leg. Using simple trigonometry relations inclined length of leg for each θ is calculated as,

$L_i = h_L * \cos(\theta_i)$ & $BB_i = L_i * \tan(\theta_i) + b$

A length calculated is required to model pressure vessel separately for the entire considered cases.

F. Material Specification

SA 516 Gr.70 has following specifications

TABLE II. MATERIAL PROPERTIES

Property	Value	Unit
E	2 e+9	MPa
Y	0.3	
б$_{YS}$	2.5	MPa
б$_{UT}$	4.6	MPa
S	137.89	MPa
P	7850	kg/mm^3

G. Meshing

The accuracy of the FE model is highly dependent on the mesh employed, especially if higher order (cubic, quadratic etc.) elements are not used. In general, a finer mesh will produce more accurate results than a coarser mesh. At some point, one reaches a point of diminishing returns, where the increased mesh density fails to produce a significant change in the results. At this point the mesh is said to be "converged." This process of refining the mesh and evaluating the results is normally referred to as a "mesh convergence "study or analysis. If higher order elements are used, good results can be obtained with fewer elements. Either mesh convergence analysis or a reliable error estimate is absolutely necessary to quantify the analysis results. Element used for meshing pressure vessel is solid 187 3D-10 node tetrahedron structural solid.

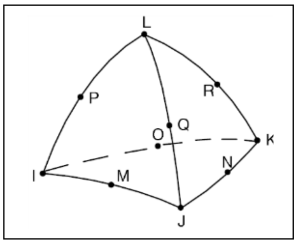

Figure.2 SOLID 187

The element is defined by 10 nodes having three degrees of freedom per node: translations in the nodal x, y, and z directions. The element supports plasticity, hyper elasticity, creep, stress stiffening, large deflection, and large strain capabilities.

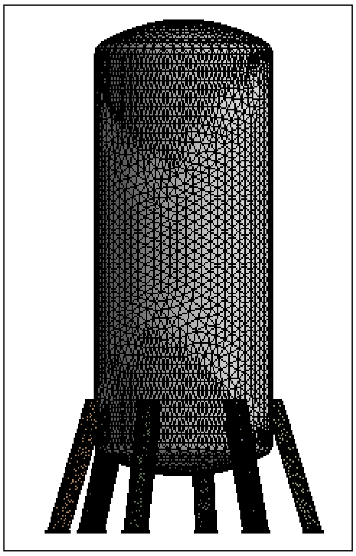

Figure.3 MESH MODEL

boundary conditions

Boundary conditions applied to Pressure vessel are internal pressure, wind load and self weight.

H. Internal Pressure (Pi)

The operating pressure in the vessel is 150 Psi during Cumene process. This pressure will cause radial expansion and exert radial outward acting force on legs where the legs are connected to vessel.

I. Wind Load(Fw)

With unsymmetrical distribution of supports, the wind direction will be significant factor in determining the bending. Since the distribution angles are not same, many more load cases need to be considered to account for the variation in bending. For analysis wind load is applied on vertical face of vessel in the form of uniformly distributed load. Loading perpendicular to the axis joining opposite legs will be the first case and subsequently the angle will be varied in increments of 15 degrees to cover 180 degrees so in all 12 load cases will be analyzed.

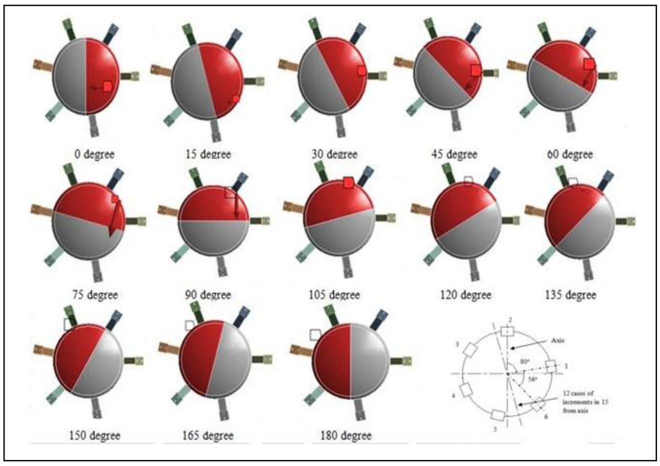

Figure.4 13-CASES OF WIND LOADINGS

1) *Wind load calculation:* Wind Load calculations are based on IS: 875 (Part 3) – 1987.Document No. IITK-GSDMA-Wind05-V1.0 Final Report: B - Wind Codes.

- Design wind speed:
  $V_z = V_b * k_1 * k_2 * k_3 * k_4$
  $V_z = 50*1.08*1.05*1*1.15$
  $V_z = 65.205$ m/s
- Design wind pressure
  $P_d = k_d * ka * k_c * P_z$; but, $P_z = 0.6*(V_z)^2$
  $P_d = k_d * ka * k_c * 0.6 * (V_z)^2$
  Hence, $P_d = 2040.812$ N/m^2
  The wind forces are obtained by multiplying the projected area of each element, within each height zone by the design wind pressure for that height.
  F_w = Projected area of vessel * design wind pressure
  $F_w = 11.037$ KN
  For analysis, $F_w \approx 11500$ KN.
  For all 12 cases of loading, wind load is resolved as F_w*cosØ & F_w*sinØ.

J. *Self Weight(F_{wt})*

Weight of fluid 5896.7 kg present inside vessel will act on CG as point mass & axially on the legs. Acceleration is applied to vessel model in upward direction.

K. *Fix Support*

One end of all legs at the ground level is fixed (point B in figure) and all six degrees freedoms are restricted.

L. *Non-Linearity*

Pressure vessel is subjected to geometric and contact non linearity. Geometric Nonlinearities occurs, if a structure experiences large deformations, its changing geometric configuration can cause the structure to respond nonlinearly.

Contact Nonlinearities i.e. weld contact is at the junction of legs & vessel body.

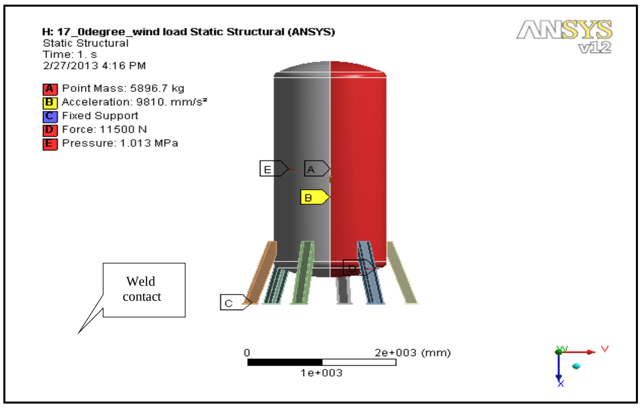

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Figure.5 BOUNDARY CONDITIONS (A, B, C, D, E)

Design Of Leg Support

Pressure vessel supported by legs generally has I-section. Let us consider above pressure vessel is supported by single leg just below the CG. The overall weight of vessel and wind load is applied on center of gravity as shown in Fig.6

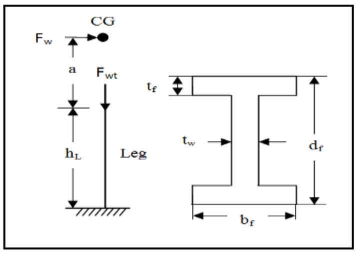

Figure.6 Typical I-section

Assumptions of I- section are as follows:

Depth & width of flange, $d_f = b_f = t$ and thickness of web & flange, $t_w = t_f = 0.1 \times t$

Cross-sectional area of section is given by

$A = 2 \times t_f \times b_f + [(d_f - 2\times t_f) \times t_w] = 0.016t^2$ mm^2.

Moment of inertia (I) is given as

$I = 1/12 \times \{2\times b_f \times (t_f)^3 + [t_w \times (d_f - 2t_f)^3] = 4.433\times e\text{-}3\times t^4$ mm^4

Section modulus $(Z) = I/Y = 8.867\times e\text{-}3\times t^3$ mm^3.

The leg is subjected to axial load and bending moment therefore the equation for calculating dimensions of leg is

We have, $F_{wt} = 85000$ N and $M = F_w\times (a + h_L)$

$\sigma_{all} = S = F_{wt} /A + M/Z$

$137.89 = (85000/0.016\times t^2) + (11500\times 2734)/ (8.867\times e\text{-}3\times t^{-3})$

Thus, t = 338.38 mm.

C/s area which has to sustain combined loading is

$A = 0.016\times (338.38)^2 = 1832.04$ mm^2.

This area is to be divided among the six legs therefore area of cross section for one leg will be,

A= 1832.04/6 = 305.34 mm^2.
Let t = t_1 therefore, $A_1 = 0.016 \times (t_1)^2$.
Thus, t_1 = 138.14 mm.
This dimension is very close to depth & width of W6 × 15 which comes under standard SA/CSA G40.21 44W.
Therefore, depth & width of flange, $d_f = b_f$ = 152 mm and thickness of web t_w = 5.8 mm & flange t_f = 6.6 mm.

Stress Analysis

The ASME and BS5500 pressure vessel codes do not provide comprehensive details for the design & stress analysis of inclined unsymmetrical distribution of legs support of pressure vessel, initial investigation is done for θ equals to 0^0 (straight leg);1^0;5^0;10^0 & 15^0 and its results are further studied to find optimum leg inclination.
Applying all the boundary conditions; assigning mesh size = 15 mm for leg and mesh size for vessel = 80 mm;
Sub-steps = 5, results obtained are as follows:

1) *$\theta = 0^0$ (Straight Leg)*

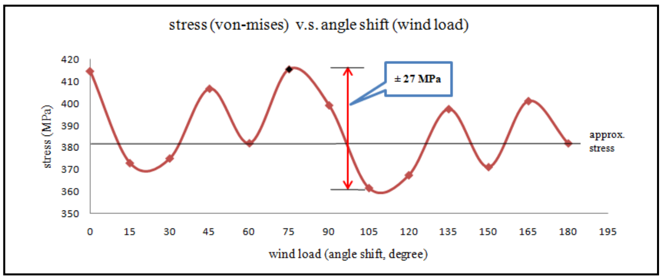

Figure.7 STRESS PATTERN FOR STRAIGHT LEG

The stress pattern obtain does not have specific trend it keeps on oscillating around approx. stress value. For straight leg the difference between max. & min. stress is 54.04 MPa which implies the error of ± 27.0 MPa occurs in exact stress.
Let us consider straight leg as a worst case and comparing the errors in exact stress for other cases.

2) *$\theta = 1^0$*

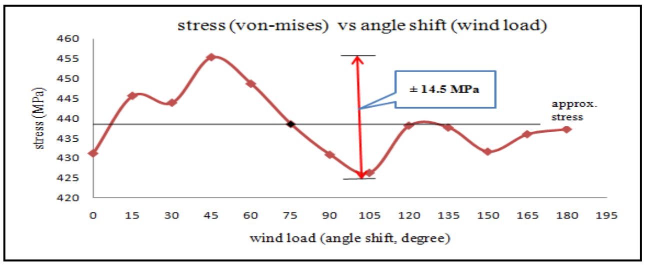

Figure.8 STRESS PATTERN FOR LEG INCLINATION OF 1^0

For inclination of 1^0, difference between max. & min. stress is 29.01 MPa which implies the error of ± 14.5 MPa occurs in exact stress.

3) $\theta = 5^0$

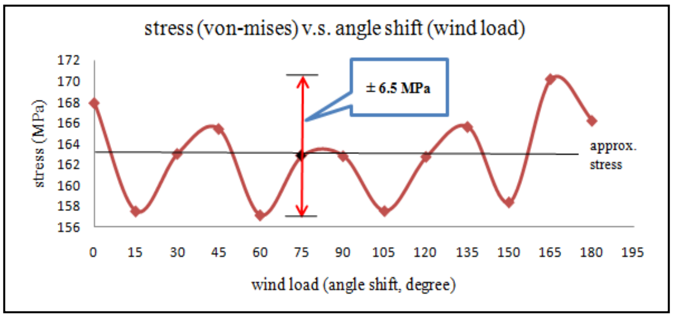

Figure.9 STRESS PATTERN FOR LEG INCLINATION OF 5^0

For inclination of 1^0, difference between max. & min. stress is 13.08 MPa which implies the error of ± 6.5 MPa occurs in For inclination of 5^0, difference between max. & min. stress is 13.0 MPa which implies the error of ± 6.5 MPa occurs in exact stress.

4) $\theta = 10^0$

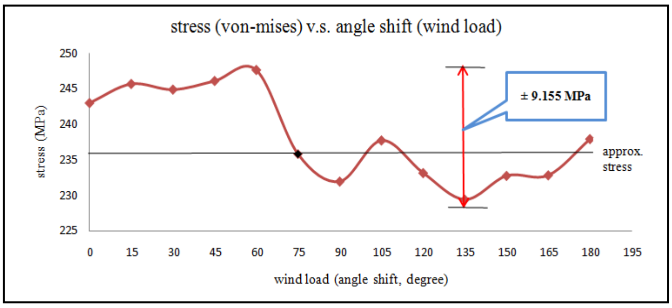

Figure.10 STRESS PATTERN FOR LEG INCLINATION OF 10^0

For inclination of 10^0, difference between max. & min. stress is 18.31 MPa which implies the error of ± 9.155 MPa occurs in exact stress.

5) $\theta = 15^0$

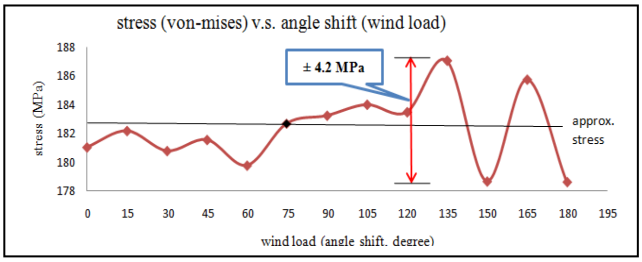

Figure.11 STRESS PATTERN FOR LEG INCLINATION OF 15^0

For inclination of 15^0, difference between max. & min. stress is 8.41 MPa which implies the error of ± 4.2 MPa occurs in exact stress.

Thus, as leg inclination increases the error value does not crosses the value obtained for straight leg. To obtain the optimum angle an analysis is done to all 31 cases ($\theta_i = 0^0$ to 30^0) for particular wind direction whose stress value lies on approx. stress line in above plots i.e. at 75 degree keeping all other boundary conditions same, so that stress obtained would be less than allowable stress (S =137.7 MPa) of material.

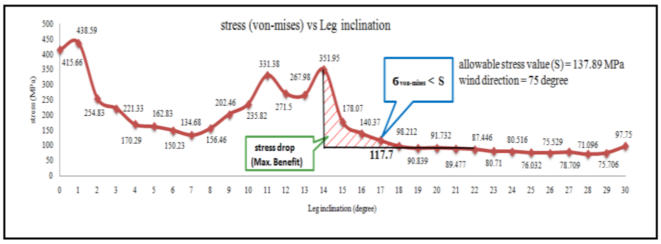

Figure.12 STRESS PATTERN FROM Θ 0^0 TO 30^0 LEG INCLINATION

From Figure.12stress drops down from 351.95 MPa to 177.7 MPa .These stresses corresponds to leg angle of
14^0; 15^0; 16^0; 17^0 which implies maximum benefit. The stress obtain for 14^0; 15^0 & 16^0 are greater than allowable stress value of material hence vessel cannot be inclined for these degrees. Hence, optimum angle is selected from 17^0; 18^0; 19^0; 20^0.
The stress obtain for 17 degree is as shown in figure.13

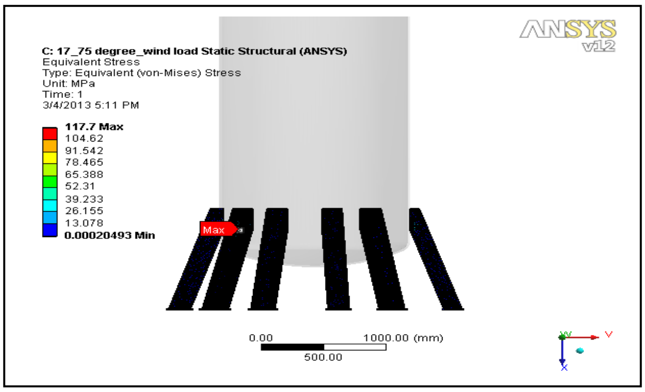

Figure.13 STRESS AT 75^0 OF WIND LOAD FOR LEG INCLINATION OF 17^0

Deformation pattern obtain for all leg inclination is as shown in Figure.14

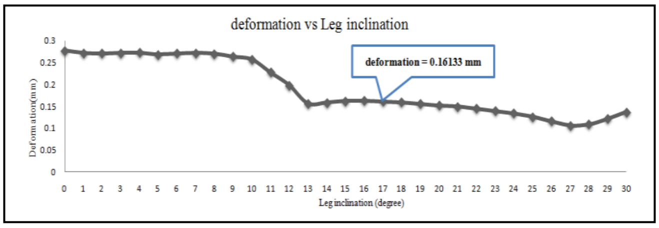

Figure.14 DEFORMATION PATTERN FOR LEG INCLINATION OF θ 0^0 TO 30^0

Deformation remains constant till 10^0 and gradually drops down from 10^0 again increases in small amount from 13^0. For 17^0 of leg, deformation is 0.16133mm which is acceptable.
The deformation obtain for 17 degree is as shown in figure.15

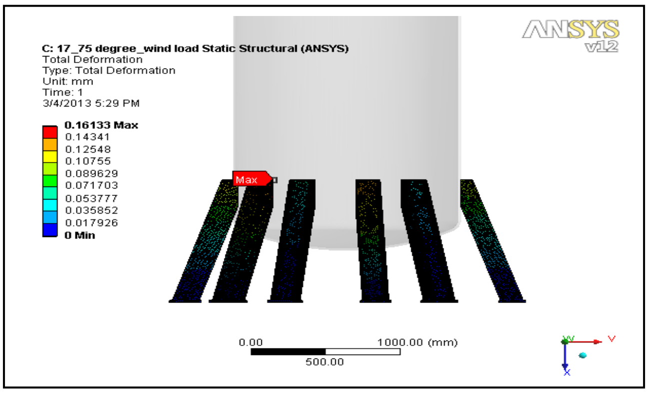

Figure.15 DEFORMATION AT 75^0 OF WIND LOAD FOR LEG INCLINATION OF 17^0

Detailed analysis is to be done on 17 degree inclined leg to study the effect on structural stability under the influence of all boundary conditions (A; B; C; D).
At 105^0 degree of wind load, stress concentration occurs at point A due to structural error and it increases as fine meshing is done, shown in fig. hence ignoring the elements associated with stress concentration and considering the stress 105.03 MPa in adjacent element.

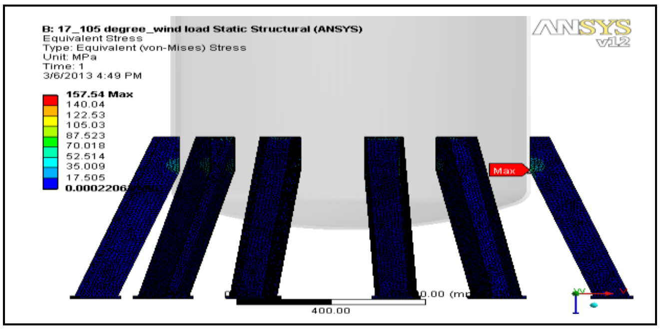

Figure.16 STRESS IN LEG INCLINATION OF 17^0 AT 105^0 ANGLE SHIFT

Structural error is amount of energy that is not conserved under the action of loading.

Figure.17 STRUCTURAL ERROR

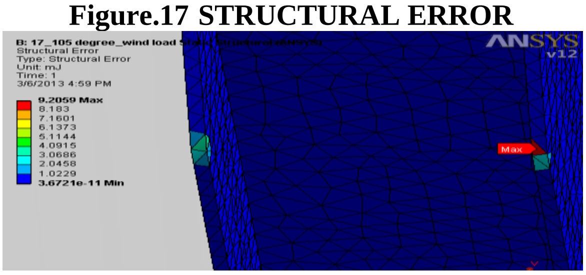

Figure.17 STRUCTURAL ERROR

Stress and deformation pattern for 17^0 is as shown in Figure.18 & 19

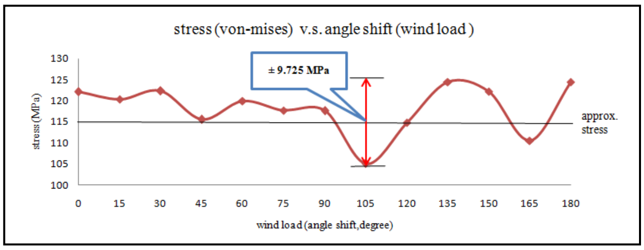

Figure.18 STRESS PATTERN FOR LEG INCLINATION OF 17^0

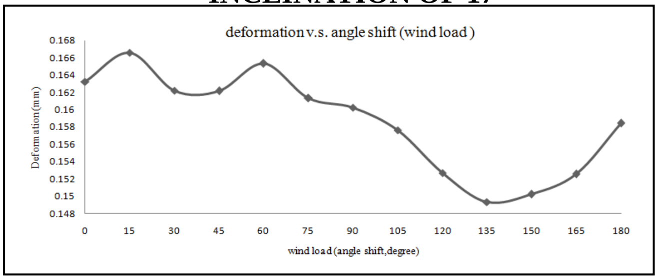

Figure.19 DEFORMATION PATTERN FOR LEG INCLINATION OF 17^0

For inclination of 17^0, difference between max. & min. stress is 19.45 MPa which implies the error of ± 9.725 MPa occurs in exact stress is comparatively much less than the worst case (Figure.5)

The difference between max. & min. stress is 19.45 MPa which shows the error of ± 9.725 MPa.
The von-mises stress obtained is less than stress considered in worst case i.e. ± 9.725 MPa < ± 27 MPa.
Thus, Stress obtained for all cases of wind loads are within the limit of allowable stress (S) of material, implies safety of pressure vessel.

Conclusion

The design by analysis approach has enabled us to do a fruitful analysis of the system using FEA.
As the angle of inclination increased there was significant variation in the deformation and stress values for the support system, however the effects were not linear and we saw a significant drop after 15 deg inclination.
This made this a prime case for optimization, with the objective of reduced stress and deformation implying greater stability.
Furthermore doing a check from various wind load angles has proved to be vital as there is a significant variation in stress as wind angle changes.

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