Case Study: Numerical Analysis of Collapsed Steel Tower Silo to Quantify the Design Safety Factors

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Abstract. Design of strategic structures like tower wheat silos must be treated with cautious consideration, the design must be reliable to assure the structure will not fail even under rare incidents. for the current case study: a recently constructed single tower silo failed after a sudden wheat leakage that occurred from its mid-height, the collapse caused a progressive failure for an adjacent silo structure as well as serious damage for a third attached one, the site investigation clarified that many essential monitoring sensors have malfunctioned. The objective of this work is to quantify the design safety factors if satisfactory or not. In this paper, the leaked tower silo is numerically simulated using ANSYS FE package, the bolted steel rings of silo walls are modeled using shell elements, the vertical stiffeners used to hold the silo walls in place are simulated using solid elements, the design loading cases are applied, the structure is analyzed, and the design is rechecked based on the same used Euro code provisions. The margin of safety factors is normalized for every steel vertical ring. The results showed that leakage started to occur at the assembly point of minimum margin of safety. The work concluded that designers have to adjust an adequate margin of safety based on their expertise for local site conditions

Keywords: Tower Silo; Structure Collapse; Safety Factors; Numerical Simulation

I. Introduction

Silos and bins fail with a frequency which is much higher than almost any other industrial equipment. The major causes of silo failure are due to one or more of categories (Design; Construction; Usage & Maintenance Silo design require specialized knowledge. The designer must first establish the material's flow properties then consider (Flow & Static Pressure & Dynamic Pressure). Large concentrated load or non-Symmetric pressure on a silo wall leading to unacceptable bending moments. The load distribution can also be radically changed if alterations to the outlet geometry are made, and whether a flow controlling insert or construction is added. The designer or silo expert should be consulted regarding the effects of such changes before construction or use implemented. Maintenance mustn't be neglected to early discover the failure and try to prevent it, the maintenance is not for the structure health only but also for the other systems affecting health of structure such firefighting system, temperature and humidity sensors which leads to assurance of the health usage of silo according to standards. This maintenance, comes after periodic inspection for what was mentioned and repairing the damages early; So, we want to study that case of failure to stand on why it happened and to avoid such accidents in other silos and bins.

A 3D numerical model for the silo with similar geometry, material, loads is performed. 3D structural model is built in Inventor, hence imported to ANSYS FE package for analysis, the design loading cases are considered to obtain stress values in each case on each part of silo. The stress values are compared to the allowable stresses. Variance between the actual and allowable stresses are quantified. The obtained results are analyzed to predict if any residual stresses occurred and a potential for failure may exist as a result of temperature, humidity, or wrong usage. Silo scope is that first: static calculation covers the analysis of the silo bin (sheets; stiffeners& the anchorage); excluding the verification of the roof structure and the special construction elements of the silo. Second: The silo is designed for grain storage with density of 0.834

kg/m3(wheat). For the storage of other materials; their density shall be taken into account.

Third the silo is designed for central filling and emptying. The eccentrics or lateral filling and empting is not allowed.

II. Geometry

Materials:

- Stiffeners: -S350GD+1:2006-S355R
- Sheets: S350GD-S350GD
- Bolts: 1:2008-M10 (6.8and 8.8) and M12 (8.8)

types of silo			
Model	Diameter	Height (m)	No of rings
SBHE	11.5	19.52	17

Bottom [angle of incl.] (º)	0

Diameter (D in m)	11,459
Bin height (Z_{Bin} in m)	19,52
Roof height (R_{Roof} in m)	3,306
Total Silo height (H_{Total} in m)	22,826

Number of Rings	17
Number Of Stiffeners	45

Sheets:

i. Height of corrugation= 12 mm
ii. Separation of corrugate = 104 mm
iii. Length of sheet between holes = 2.40 mm
iv. Sheet height between holes = 1.144 mm
v. Total length of sheets = 2.50 mm
vi. Total sheet height = 1.20 mm
vii. Developed sheet height = 1.220 mm

Stiffeners:

Separation between stiffeners = 800 mm.
Min. height (2 sheets) = 2.288 mm

III. Construction :

The construction of the silo is according to UNE-EN 1993-1-3 (Euro code 3); design of steel structures. Supplementary rules for cold-formed members and sheeting.

Used Standard:

- Ansi Standad

IV. Loads:

- Load exerted by free flowing grain on bins.
- Load exerted by free flowing grain on shallow storage structures.
- Density, specific gravity and mass moisture relationships of grain for storage.

Density of steel 78.5 (kN/m3).

Sheets:

t (mm)	g (kN/m ring)
.8	0.082
1.0	0.102
1.2	0.123
1.5	0.153
1.8	0.184

Stiffeners:

t (mm)	type	B_{bst} (mm)	g (Kn/m ring)
1.5	Ω	246	0.029
2	Ω	246	0.039
3	Ω	246	0.058
3.5	Ω	246	0.068
4	Ω	246	0.079
5	Ω	246	0.099
5	Ω	246	0.138

Variable Loads:

Roof Loads Modelling of silo on Inventor software

Load on roof dome	F	30 KN
3rd temp. probes	On the beam roofs	10 KN

Wind load

Wind load are the forces that affects the building in direction perpendicular to the surface of the buildings and structure
This force is considered positive if it is in surface direction (pressure)
and negative if it is outside the surface; away from the surface direction (suction)
The external pressure or suction of wind force affecting the building surfaces is calculating using the following equation :

$$w.l = C_w * K * q$$

Where:
Cw : depend on case of loading as shown in figure (0.8, -0.8, -.05, -0.5).
K: depend on the height of building.

h = (0 – 10) m k=1

h = (10 – 20) m k=1.1

h = (20– 30) m k=1.3

q: depend on the location of building

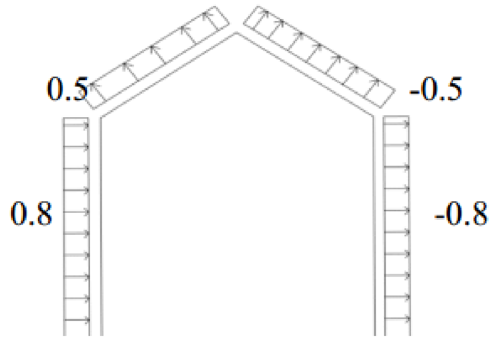

Fig. (1): Wind Coefficients

Product loads:

Material	Density (kN/m^3).	Coefficient of horizontal pressure	Coefficient of friction
Wheat	8.34	0.50	0.37

Sheet	Cyl. height	Z (m)	Pv. (kN/m2)	Ph. (kN/m2)	∑Pr. (kN/m2)
1	2.199	1.144	16.745	8.373	3.486
2	3.343	2.288	24.562	12.281	7.867
3	4.487	3.432	31.823	15.911	13.843
4	5.631	4.576	38.566	19.283	21.301
5	6.775	5.720	44.829	22.415	30.134
6	7.919	6.864	50.646	25.323	40.245
7	9.063	8.008	56.049	28.025	51.542
8	10.207	9.152	61.067	30.534	63.942
9	11.351	10.296	65.728	32.864	77.366
10	12.495	11.440	70.057	35.029	91.740
11	13.639	12.584	74.078	37.039	106.998
12	14.783	13.728	77.812	38.906	123.076
13	15.927	14.872	81.280	40.640	139.915
14	17.071	16.016	84.502	42.251	157.462
15	18.215	17.160	87.494	43.747	175.667
16	19.359	18.304	90.272	45.136	194.482
17	20.503	19.448	92.853	46.427	213.863

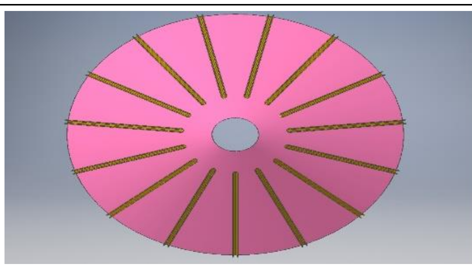
Fig. (2): Plan Cone of silo on inventor

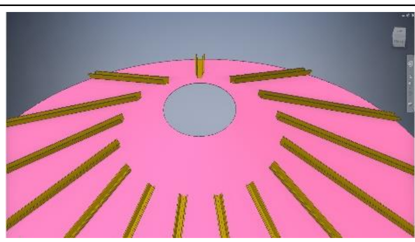
Fig. (3): 3D view for Cone of silo on inventor

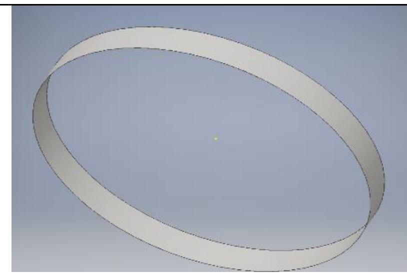
Fig. (4): 3D view for the ring

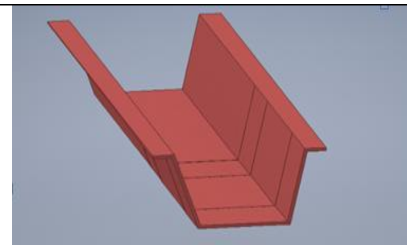
Fig. (5): 3D view for the ring

FULL MODEL

3D model of silo on Inventor software with equivalent stiffeners and geometry as shown in figure

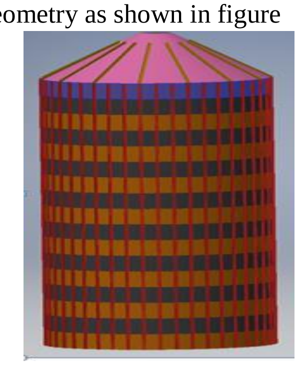
Fig. (6): 3D view for the ring

V. LOAD CASES

In this stage we put loads on model and make analysis on some cases of loading and getting actual forces and stresses on each ring and compare it with allowable forces and stresses for each ring

CASES OF LOADING :

1. Empty Silo
2. Empty Silo + Wind
3. Empty Silo + Wind +Temperature
4. Full Silo
5. Full Silo + Wind
6. Full Silo + Wind +Temperature
7. Loads Effect Only at the half of The Structure + Wind + Temperature

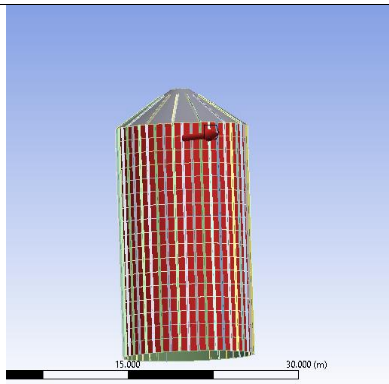

Fig. (7): Empty Silo

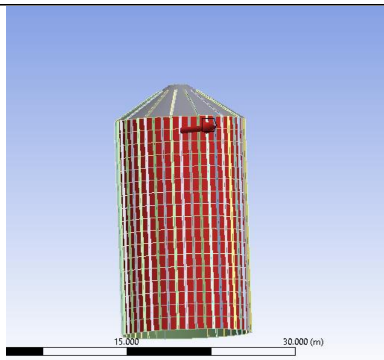

Fig. (8): Full Silo

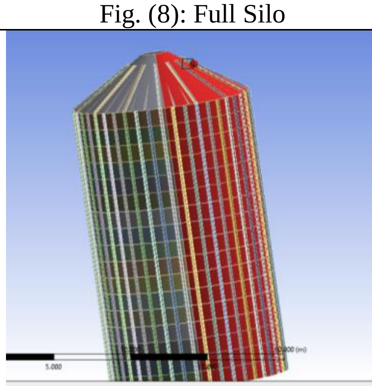

Fig. (9): Loads only at half of the structure

-Notes:

1. Normal Temperature = 28 ^{o}C
2. Temperature Inside the Silo = 45 ^{o}C

VI. FAILURE

Types of errors

1. Design.
2. Construction.
3. Utilizers.
4. Foundation settlement.
5. Corrosion and erosion.

Design errors:

material flow properties and flow patterns:

- The functional design requirements will dictate the flow pattern, either mass flow or funnel flow that is required. It is then the job of the design engineer to ensure, through the selection of geometry and materials of construction, not only that the selected flow pattern occurs, but also that the structure is capable of withstanding the loads induced by that flow pattern. Know your material's flow properties, and the type of flow pattern that is likely to develop in your silo.

If the flow properties are likely to vary (due, for example, to changes in moisture, particle size, temperature, suppliers), make sure that the silo is designed to handle this variation.

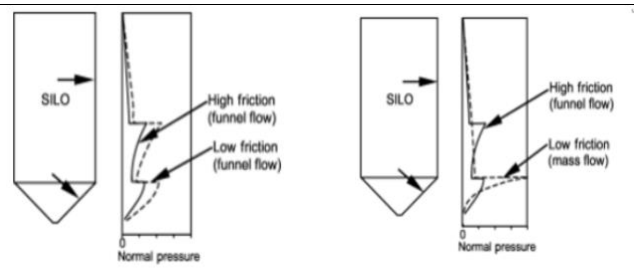

Fig. (10): Pressure normal to walls

Design errors:

out-of-round bending of circular walls:

- This is one of the most common cause of silo structure non-uniform pressure will develop around the circumference of the silo leading to H.L & V.L bending moments.

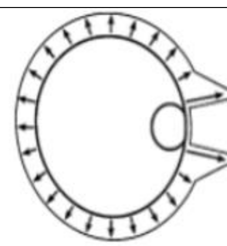

Fig. (11): non-Uniform pressure caused by eccentric withdrawal

Eccentric withdrawal with one of the most common cases of silo structural problems, because it is often overlooked. There are several situations which can result:

• Whenever possible, design your silo for centre fill and centre withdrawal.

• Consider non-uniform pressures in your design. Leaks due to wall erosion or abrasion or seemingly minor retrofits such as a bypass chute can cause non uniform load cases to develop after a silo has been in use for many years.

• If multiple outlets are required, consider splitting the discharge stream outside of the silo below the main central withdrawal point.

• Be aware of the potential effects of the feeder type and design.
In the case of silos that have an elongated hopper outlet, an improperly designed screw feeder or belt feeder interface, or a partially opened slide gate, will often result in an eccentric flow pattern with accompanying non-uniform loads. If a sweep arm unloader is used, be aware that operating it like a windshield wiper (back -and forth in one area) will create a preferential flow channel on one side of a silo. If a vibrating discharger is used but not cycled on-off on a regular basis, an eccentric flow channel may develop, particularly if a pantleg chute is below the outlet.
• Consider non-uniform pressures when designing silos with blend tubes

Design errors:

large and/or non-symmetric pressures caused by inserts:
- Support beams, inverted cones, blend tubes, and other types of internals can impose large concentrated loads and/or non-symmetric pressures on a silo wall. If an internal
is to be used, the design engineer must be aware of the high bending stresses that a reapplied to the silo walls at the support points.
-Don't ignore loads on inserts, since they can be extremely large
-Be aware that when internals are used, non-uniform pressures may develop if the resultant flow pattern is even slightly asymmetric.
- Open inserts can also have large loads acting on them. Consideration must be given to the consequences of the insert becoming plugged, thereby preventing material from flowing through it. In a case such as this, the vertical load greatly exceeds the dead weight of the material inside the insert and the surcharge of material above it.
- Be aware that inserts can be accompanied by a local pressure peak against the silo walls.
- The design engineer should carefully specify the desired construction method in
order to fully realize the design intent.

Design errors:

specific requirements for structure type:
- The structure type and construction materials and methods must be determined. When deciding on the structure type there are many factors to consider, such as cost, construction methods, and availability of materials.
-Specific requirements associated with the selected design must be considered.
-In the case of bolted steel design, consider all the various modes by which a bolted joint can fail, ensure that the design can withstand compressive buckling, and follow recognized design procedures.
Determine the likelihood of eccentric fill or discharge and design accordingly. In particular, do not use only a single layer of reinforcement in reinforced concrete silos if eccentric loading is possible.

Design errors:

temperature and moisture effects:
- Unusual loading conditions can also occur as a result of temperature and/or moisture effects. As was explained in the fly ash silo failure description above, temperature fluctuations, such as would occur from daytime to nighttime, can lead to much higher hoop stresses than would otherwise be expected. A similar phenomenon can occur if the bulk solid being stored is moist and has a tendency to expand with increased moisture content. Temperature fluctuations and other mechanisms may cause moisture to migrate between stagnant particles or masses of stagnant particles, causing some to expand. If this occurs while material is not being withdrawn, upward expansion is greatly restrained. Therefore, most of the expansion must occur in the horizontal direction, which will result in significantly increased lateral pressures on, and hoop stresses in, the silo walls. The authors are aware of a case in which the lateral pressures on a silo wall were increased by more than a factor of five. If it is possible for this phenomenon to occur, the larger pressures and stresses must be accounted for in the design.
- Include factors of safety in the design of outdoor metal silos to account for the
effects of thermal ratcheting.
- Assess the likelihood of significant moisture migration occurring while the bulk
solid is stationary, and design accordingly.

Construction errors:

- Mistakes that can lead to structural failure can also be introduced during the construction of the silo and its supporting structure.
- If design specifications, with respect to materials of construction, placement, and type of reinforcing steel, construction sequence, and other details are not followed, the full intent of the design will not be realized.

Construction errors:

poor quality workmanship:
• Use only qualified suppliers and contractors.
• Make sure that specifications are clear and tightly written.
• Use an experienced construction team that understands the specifications and
recognizes the potential consequences of poor-quality work.
• Carefully and frequently inspect the installation.

Construction errors:

unauthorized design changes:
- As with most structures, the construction of a silo requires careful planning and
scheduling. The availability, cost, and delivery times of the specified materials of
construction can often be such that design changes are warranted.
- Make sure that both the silo builder and design engineer carefully consider and
approve any changes in details, material specifications, or erection procedure.
- Closely inspect all construction.

Utilization errors:

- A properly designed and properly constructed silo should have a long life. Unfortunately, the incidence of silo failure is quite high. Even silos that have been well designed and constructed can fail.
- To ensure a silo's long and safe life, it is imperative that it be used only for the purpose for which it was designed and that appropriate inspection and maintenance programs be implemented and execute.

Utilization errors:

improper usage:

- Improper usage of a silo can result in failure. This can occur, for example, if a silo isnbeing used differently than the design engineer intended.

Fig. (12): End-result of mass flow developing in a silo design structurally for funnel flow

-Know the flow properties that were used to design your silo.
-Before putting bulk solids with different flow properties into your silo, determine the new material's flow properties and know how they will affect the silo loads.

Utilization Errors:

Improper Maintenance:

- As with any structure, a silo must be properly maintained if it is to have a long, useful, and safe life. Maintenance of a silo is the owner's or user's responsibility and must not be neglected.
- Two types of maintenance work are required. The first is the regular prevent- active work, such as the repair of the walls and/or liner used to promote flow, protect the structure, or both.
- Carefully inspect, both internally and externally, your silos on a regular basis. In the case of a reinforced concrete silo, look for any sig ns of corrosion, exposed rebar, unusual cracking, or spelling of concrete. In the case of a bolted metal silo, pay particular attention to the bolted joints near the top of the hopper and look for waviness along the edges of the sheets, elongation of bolt holes, or cracks between bolt holes. Buildup of material which could trap moisture on the exterior of outdoor silos should be removed.
- Determine the minimum wall thickness required for structural integrity and compare to the actual wall thickness.
- Perform a detailed structural inspection of your silo before designing modifications to it, and before using it after any unusual event, such as a storm with very high winds or an earthquake.
- At the first sign of silo distress, cease discharging immediately and assess the integrity of the structure. Limit access to the area surrounding the silo.

-Investigate the cause of the distress. Ensure that the staff who are dealing with the silo have the education and experience to safely deal with the situation.
-Retain experts with knowledge of silo structures to assist in the investigation

Foundation settlement:

- It's important to determine the rate of settlement of soil.
- we should be:
  - I-Use experience soils engineers and foundation designer.
  - II- Use reputable contractors.

Corrosion & Erosion:

- Using carbon steel construction to protect the structure from corrosion and erosion.

VII. Analysis of Silo on ANSYS Package:

Resultant stress distribution will be shown as follows:

1. Equivalent Stress
2. Maximum Shear Stress
3. Total Deformation

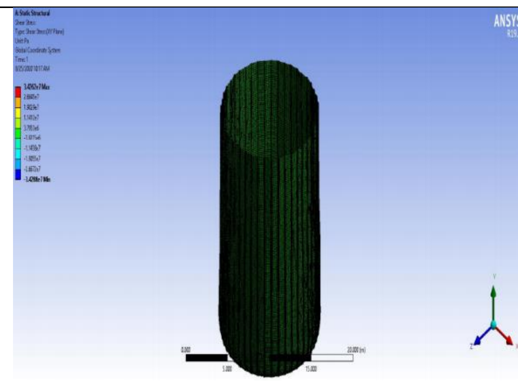

Fig. (13): Equivalent Stress (Empty Silo)

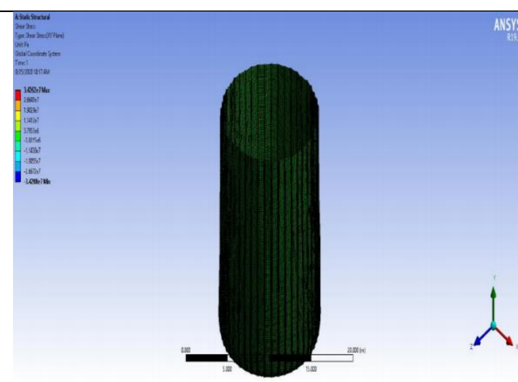

Fig. (14): Shear Stress (Empty Silo)

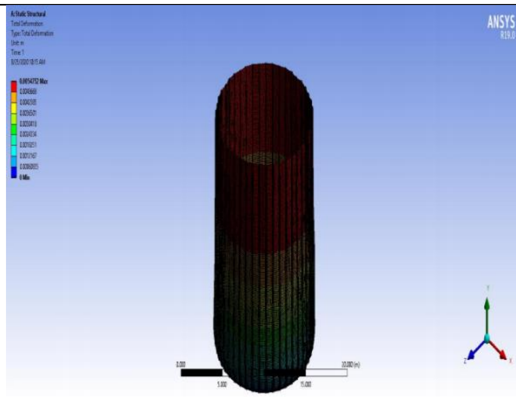

Fig. (15): Total Deformation (Empty Silo)

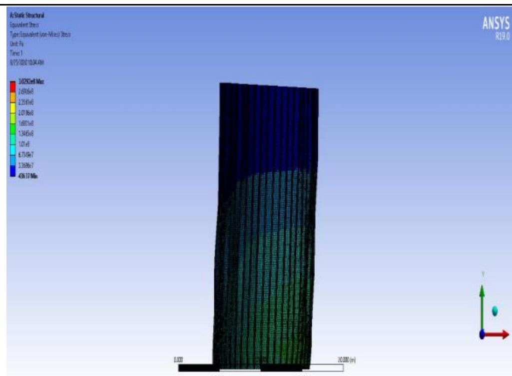

Fig. (16): Equivalent Stress (Empty Silo +Wind)

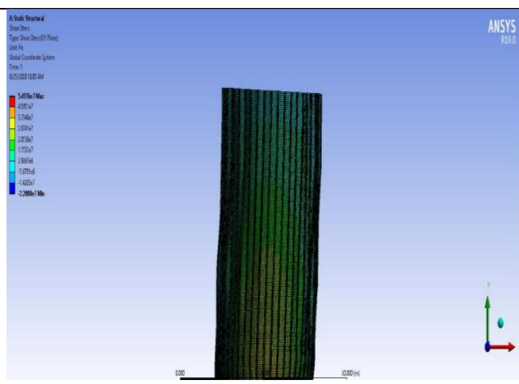

Fig. (17): Shear Stress (Empty Silo +Wind)

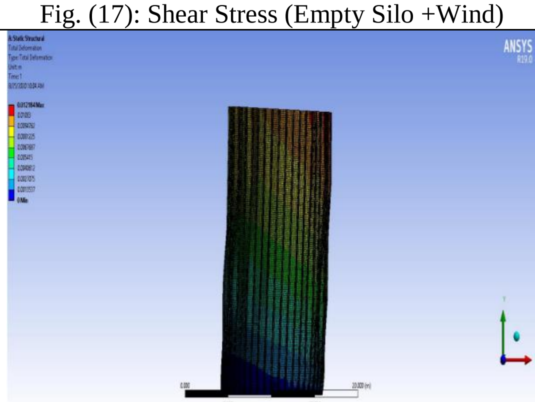

Fig. (18): Total Deformation (Empty Silo +Wind)

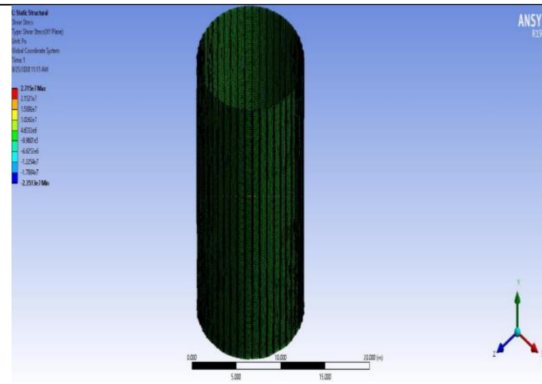

Fig. (19): Equivalent Stress (Empty Silo +Wind +Temperature)

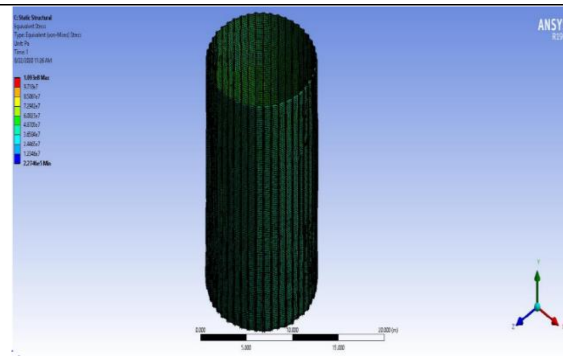

Fig. (20): Shear Stress (Empty Silo +Wind +Temperature)

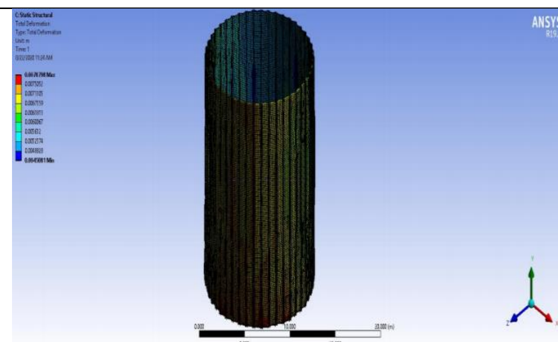

Fig. (21): Total Deformation (Empty Silo +Wind +Temperature)

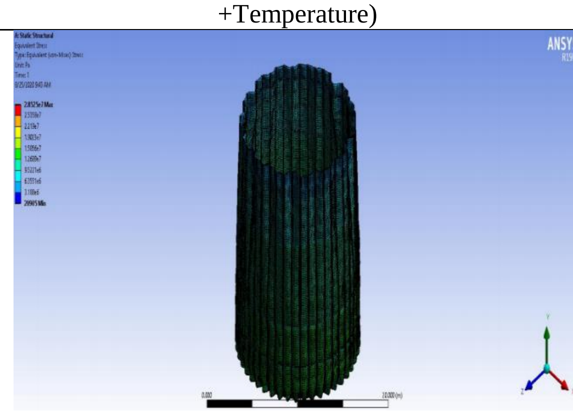

Fig. (22): Equivalent Stress (Full Silo)

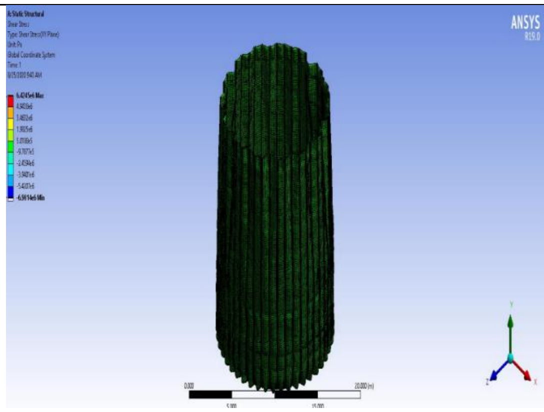

Fig. (23): Shear Stress (Full Silo)

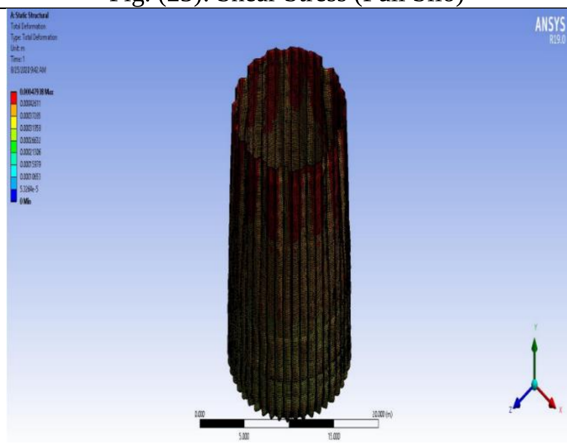

Fig. (24): Total Deformation (Full Silo)

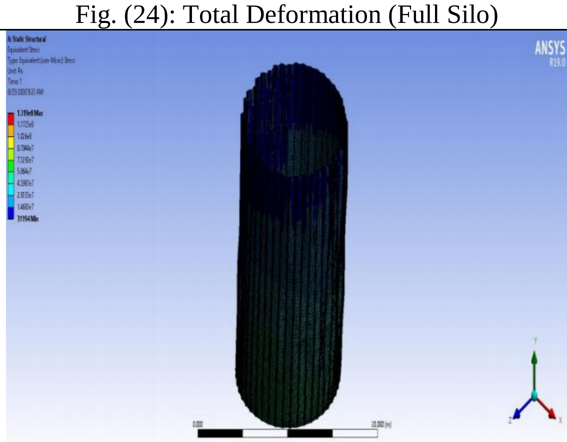

Fig. (25): Equivalent Stress (Full Silo + Wind)

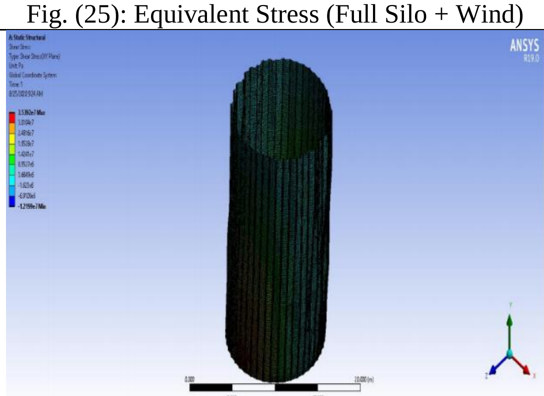

Fig. (26): Shear Stress (Full Silo + Wind)

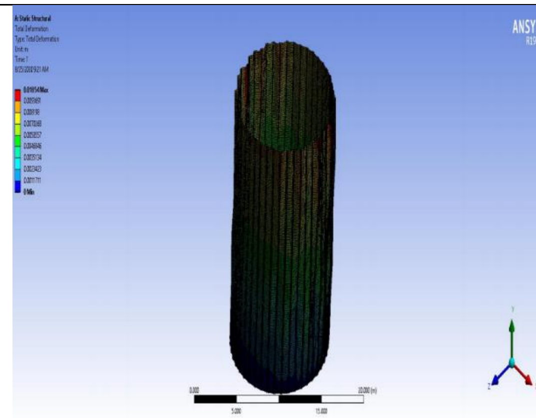

Fig. (27): Total Deformation (Full Silo + Wind)

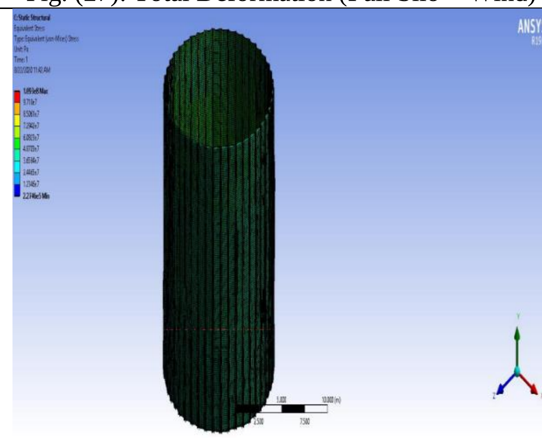

Fig. (28): Equivalent Stress (Full Silo + Wind + Temperature)

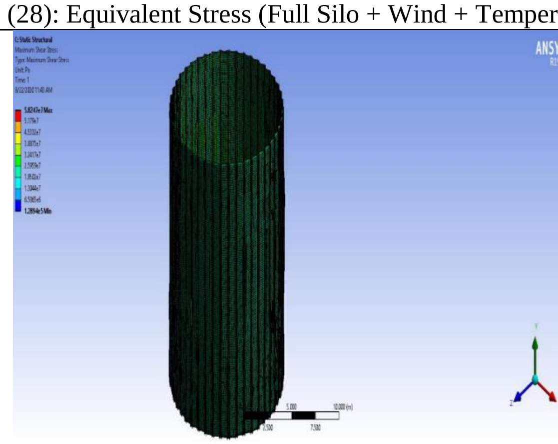

Fig. (29): Shear Stress (Full Silo + Wind + Temperature)

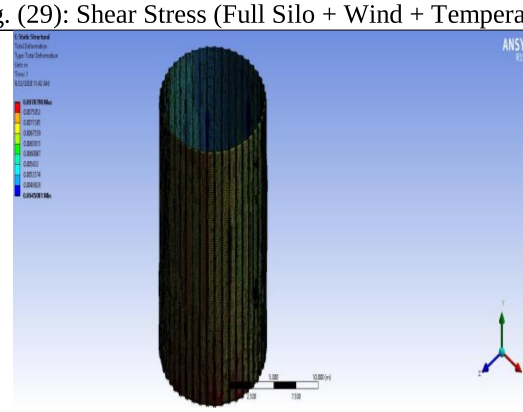

Fig. (30): Total Deformation (Full Silo + Wind +Temperature)

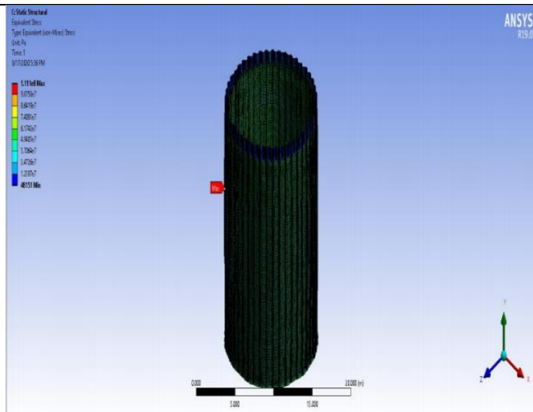

Fig. (31): Equivalent Stress (Half load + Wind + Temperature)

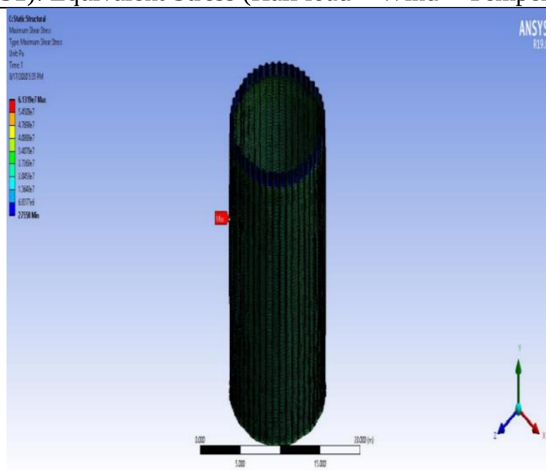

Fig. (32): Shear Stress (Half load + Wind + Temperature)

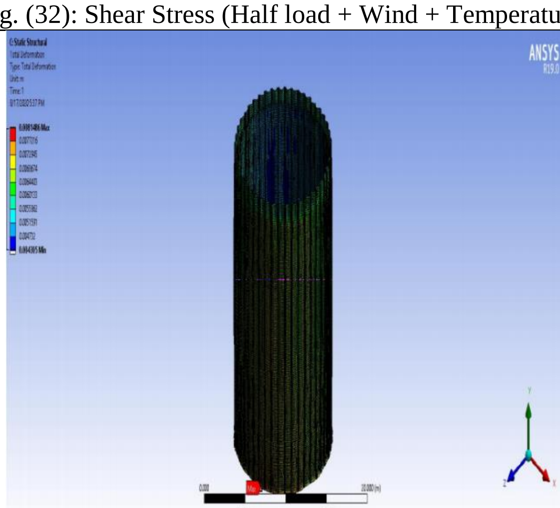

Fig. (33): Total Deformation (Half load + Wind+Temperature)

RESULTS

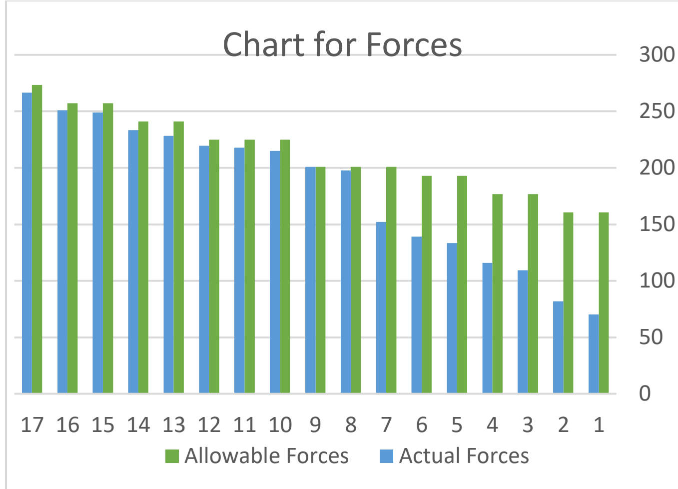

Fig. (34): Chart for forcing acting on rings

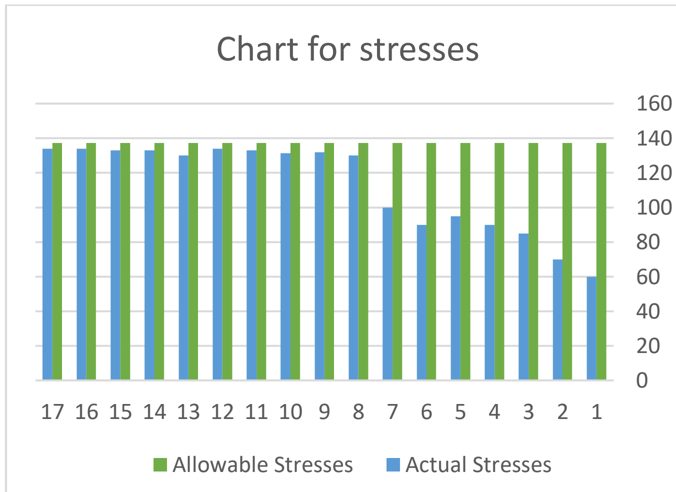

Fig. (35): Chart compare between actual stresses and allowable stresses

The results showed that all parts are safe but with variable safety factors and leakage started to occur at the assembly point of minimum margin of safety.

VIII. CONCLUSION

After checking all the evaluated results, Equivalent Stress, Maximum Shear Stress and Total Deformation, the work concluded that designers have to adjust an adequate margin of safety based on their expertise for local site conditions.and sensors should be calibrated and checked as some sensors may have malfunction. the design must be reliable to assure the structure will satisfy all load cases and will not fail even under rare incidents.

IX. REFERENCES