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Finite Element Analysis of Plain and Corrugated Walled Steel Silo subjected to Patch Load

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Abstract: Silo is a structure used for storing variety of materials in large quantities. The silo is considered as the special structure as it is designed for the material induced loads. The study focuses on the analysis of the stresses and deformations of the silo wall with and without corrugations and subjected to the patch load. Finite element analysis is carried out by using Abaqus software to investigate the structural behavior of the silo wall under the effect of non-uniform pressure. The silo with plain wall, vertical corrugation and horizontal corrugation are considered in the present investigation and the behavior is discussed. The results reveal that the horizontal corrugated wall silo is less prone to buckling failure and plastic collapse.

***Index Terms**: Corrugated wall silo, Finite element analysis, Patch load, Plain wall silo*

I. INTRODUCTION

Special structures like silo become essential for storing raw materials and products for factories and industries in bulk quantities. The silo is classified as tall structure and bunker is a shallow structure. In general, the materials like ores, cement and food grains are stored in the silos. To fulfill the demand of storing and discharging the different range of materials, the various forms of silos can be constructed in the industries [1]. It may be ground supported or elevated and made of either reinforced concrete or steel.

The research made by Andrew W.Jenike provides the base for the bin design [2]. As the design of silo is based on the properties of stored materials, it is considered as the special structures. The silo is particularly designed for the material induced loads other than the loads that are acting on the normal structures. The theoretical and empirical methods form the basis for the formulation of standards and rules for the silo design.

Janssen's theory states that the effect of the stored material depends on the radius of silo, bulk density of material, angle of friction and the pressure ratio [2]. The Janssen's theory is used in almost every standards and rules for the design of silo. The horizontal and vertical pressures during the discharge of silo can exceed the static pressure results as calculated by Janssen's theory. The variation of theoretical and actual static pressure resulted in the modification of Janssen's theory [2]. As the modification of Janssen's theory is highly complex, the researchers move on to the application of finite element analysis. Today, the availability of computers with increased capacity and speed makes it easy to manipulate, analyze and visualize the results for the silo problems by the finite element techniques [3-6].

Finite element technique is used to determine the stresses and displacements on the walls and the solids during filling and discharging conditions of the silo. Due to the unpredictable behavior with respect to the geometry and support conditions, the analysis of shell structures become challengeable. The European standards provide the design rules for the strength and stability of shell structures, especially for the design of silos, the load cases are given in the European standards EN 1991-4.

The safety of the structure and the different possible mechanisms of failure taken into account are considered as the main advantage in the European standard. The calculation of load due to stored material which induced pressures on the silo wall is important for the analysis of the stress developed in the silo. As per the European standard, the design loads during filling operation is composed of fixed load and patch load [7]. The Janssen's theory is used for the calculation of fixed load after filling operation. The symmetric load from the stored material is only considered in the traditional method of silo design.

The asymmetric components of loads are taken into account in the German DIN standards by introducing the concept of patch load. The DIN and Euro codes provide the guidelines for the design of silo under patch load, which results in the unsymmetrical pressures due to the stored material. C.Y.Song [8] investigated the structural behavior of circular silo subjected to patch loads. The discussion was made on the buckling failure of the silo under the effects of patch loads by considering both material and geometrical non linearity. From the linear elastic analysis, the patch loads have more effect on the state of stress in the silo.

M.Gillie, J.M Rotter [9] studied the effect of patch load on the stresses in the thin walled circular steel silos. The study revealed that the stresses lead to failure of the silo either by elastic buckling or plastic collapse. The magnitude of stresses was found to be varying linearly with the vertical extent of patch load.

The objective of this paper is to analyze the behavior and the state of stress under the effect of patch load on the plain walled steel silo and the corrugated walled steel silo like horizontal and vertical corrugations.

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II. FINITE ELEMENT MODEL

The finite element analysis was performed by the finite element package Abaqus CAE 6.14. The effect of axisymmetric patch load is examined for the different wall profiles. Using finite element techniques, the axisymmetrical model is developed to simplify the calculations. The German DIN standards were used to calculate the patch load developed on the silo wall due to the material stored. The study is performed on the cylindrical steel silo containing cement as the stored material. The model is analyzed under static condition as the principal parameter (i.e) the material at rest.

A. Reference geometry of the silo

The steel silo considered for the present study was Height of 9m, Diameter of 4m, Radius to thickness ratio (r/t) of 500 and Thickness of 4mm. The thickness of the wall is constant over the whole height of the silo. According to the European standards, the silo under consideration was slender silo with aspect ratio (H/D) greater than 2 [10]. The bottom end of the silo was pinned so that all translational degrees of freedom were restrained and the top end was left free.

The location and amplitude of the patch load were calculated for the steel silo as per the recommendations of the European standards. According to DIN and Eurocode, the patch load should be acting at the mid height of the silo wall, S=0.2D [10, 11]. Here the patch load due to cement on steel silo was found to be 0.005 N/mm^2 and the properties of steel silo with Young's modulus E= $2x10^5$ N/mm^2, Poisson's ratio υ= 0.3 and yield stress f_y = 250 Mpa are considered for the study. In Abaqus, the four node general shell element was used to discretize the silo wall [8]. In the analysis, the pressure is considered to act in the outward direction.

The corrugated wall silo was made of two types of corrugations namely horizontal and vertical corrugations. For the corrugated wall silo, the width and depth of corrugations was taken as 100 mm and 15mm respectively.

The study investigated the structural behavior of the silo wall along with the stresses and deformations caused by the non-uniform pressures.

The results of the plain wall silo, horizontal corrugated wall silo and vertical corrugated wall silo under the effect of patch load are compared and discussed.

B. Material Parameters

The Young's modulus of the material has a greater contribution on the development of wall pressures. The pressure induced by grains can be found by taking Poisson's ratio as a key parameter in a static position. When the Poisson's ratio is high, the material will unable to reach the yield state of stress. The behavior of the material stored inside the silo is considered to be elastic in the finite element analysis. So the elastic – plastic behavior of the silo wall can't be achieved during high Poisson's ratio. Hence, the low value of Poisson's ratio should be used for the elastic-plastic behavior model [2]. The angle of internal friction is high (25º) with low Poisson's ratio (0.3) required for the plastic behavior of the material. The bulk density of the material is in proportion to the static pressures. Good results will obtained with the larger mesh size compared to the finer meshes [2]. The mesh size of 800 mm and 80 mm were used in the finite element model. Due to the effect of radial deflection, the pressures of low magnitude are exerted by the stored on the silo wall with less thickness.

The bilinear stress strain curve is used for the prediction of von mises stress model. The slope of the stress strain curve in the elastic region is considered to determine the value of the modulus of elasticity. The strain hardening modulus is the value of the slope of the stress strain curve in the plastic region, beyond the yield point of the material. The strain hardening modulus is based on the initial point (origin), yield point and elongation point which results in the bilinear stress strain curve. Generally, the stiffness of the material depends on the properties of the material and the way in which the load was applied. The elastic section modulus is used upto the yield point and for the elastic yielding as well as for the plastic behavior, the plastic section modulus is used. The combination of high load and low elastic section modulus is taken into account to contribute for the safe design.

III. RESULTS AND DISCUSSION

The two major failure mechanisms of the silo are buckling and plastic collapse. The buckling failure is caused by the combination of tensile and compressive stresses and it is mainly governed by membrane stresses. The European standards namely EN 1991 -4, EN 1993-1 and EN 1993-4 defined the loading calculations and conditions of the resistance of the structure along with the failure mechanisms, particularly deal with the buckling failure of the structure [12]. The buckling behavior caused by the non uniform stress distributions on the shells is reported to be complex [13 - 15]. When the structural behavior is elastic, then the buckling is also elastic with no effects of bending stress. If the von mises stress equivalent exceeds the value of yield stress of the steel, the plastic collapse of the structure will occur.

The circumferential tensile stresses and circumferential compressive stresses are observed at the zones of application of patch loads. In general, the circumferential tensile stress values are greater than the circumferential compressive stress values. The mises stress and the meridional compressive stress are the two important resulting stress components for the silos under the effect of patch load against failures. Based on the modeling and analysis of silo wall using Abaqus, the variation of stresses and deformations observed are discussed for all the three types of silo walls.

A. Plain wall silo

The plain wall silo subjected to patch load resulted with uneven buckling of the wall. The von mises stresses was observed to be the most significant stress and it was high at the region where the load was applied. The stress profile of the plain wall silo is shown in Figure 1.

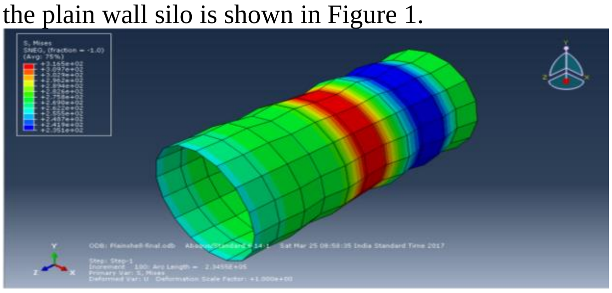

Figure 1 : Stress profile for the plain wall silo

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When subjected to the patch load, the silo wall developed with high positive bending over a small region of the load. The silo wall is found to be bent and buckle around the loading zone. The mises stresses in the silo wall are increased in proportion to the vertical extent of the patch load [9]. Silo walls, when subjected to pressure, the cross sectional distortion (ovalisation) occurred in the circular cylindrical silo structures [16 -23]. Due to the effect of patch load, the ovalisation was critical only at the region of loading of the silo wall. As the result of this ovalisation, the silo wall was failed at the centre region.

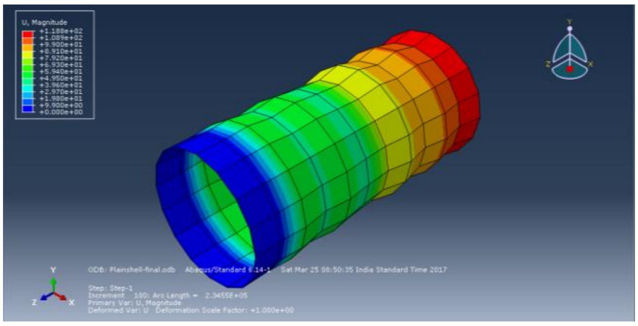

Figure 2 : Deformation profile for the plain wall silo

Figure 2 shows the deformation profile of the plain wall silo. In the plain wall silo, the deflection tends to be more at the surface above the region of application of the patch load. The bottom of the wall was pinned to provide good rigidity as well as to arrest lateral sway of the wall. Based on the boundary conditions, the silo wall is rigid at the bottom. As a result, there is no deflection on the silo wall below the patch load. But the deflection tends to increase gradually above the surface of loading and reaches the peak at the top end which was left free.

The graph is plotted for the stresses and displacements with respect to true distance along the path. True distance along path is the distance measured along the profile of the path which is created from the nodes or elements of the model. The path was created through the nodes in the plain wall silo. The stress and displacement values are taken on the vertical axis and the true distance along the path is the horizontal axis in the graph. The values are incorporated in excel to explore the XY plot. The most significant von mises stress values and displacement U values are taken for plotting the graph. The XY plot for the true distance along path against stress and displacement of the plain wall silo are shown in Figure 3 and 4 respectively.

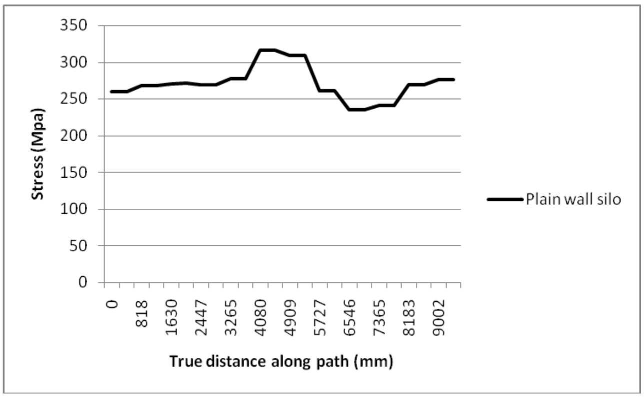

Figure 3 : XY plot for stress of the plain wall silo

The maximum stress is obtained at the surface near the application of the patch load. There is no abrupt changes in the value of stress along the meridional direction.The stresses at the remaining surfaces are almost at the same magnitude but observed to be more than the yield stress of the material. The maximum stress is found to be about 25% of the yield stress of the steel. C.Y.Song [8] reported that the maximum compressive stress value exceeds the yield stress of the material for the silo subjected to patch load. The maximum compressive stress is one of the important stress component for the design of steel silo against wall buckling and material strength failure [8].

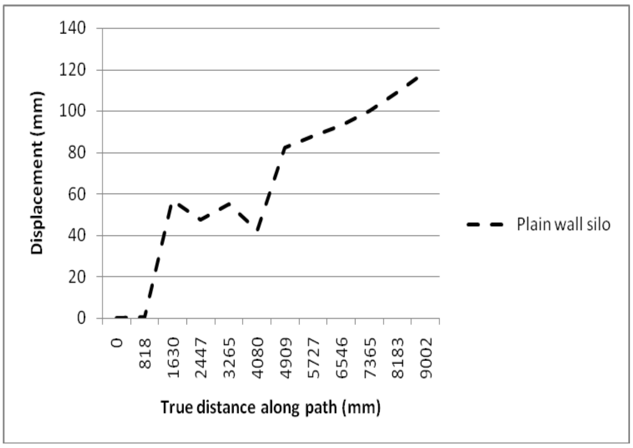

Figure 4 : XY plot for displacement of the plain wall silo

The graph clearly shows that the deformation is gradually increased from zero value at the pinned end and reaches the peak deformation at the free end. Minimal deformation is observed below the region of loading and abrupt changes occurred above the loading surface.

B. Corrugated wall silo

When the corrugated sheet is used for the construction of silo walls, then the analysis will be made by considering the sheet as an equivalent uniform orthotropic wall [24]. The properties of the corrugated sheeting is treated as one dimensional with no Poisson's effect along different directions.The shearing properties like shear modulus G should be independent of the corrugation orientation [24]. Using the value of E and υ, the value of G was calculated from the relation as 80800 Mpa. The above conditions are assumed for the present investigation related to the analysis of corrugated silo wall.

C. Silo wall with Vertical corrugation

In the vertical corrugated wall silo, the corrugations are made to run in the meridional direction. For the corrugated wall, the corrugations running vertically should be assumed to carry no circumferential forces. The corrugations are made with the effective length of 100 mm and the height of 15 mm each as illustrated in Figure 5a. The view of the vertical corrugated wall silo is given in Figure 5b.

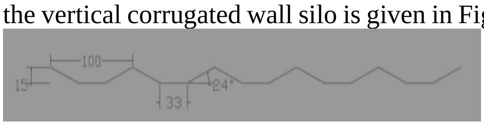

Figure 5 a: Corrugation profile

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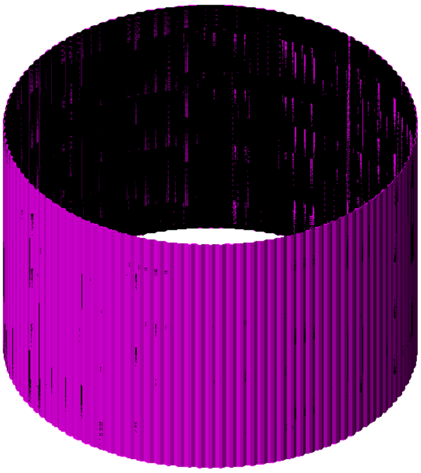

Figure 5 b: View of the vertical corrugated wall silo

The von mises equivalent design stress is calculated based on the elastic bending theory analysis (Linear Analysis - LA). The sign of buckling failure is not observed in the vertical corrugated wall silo. The stress profile of the vertical corrugated wall silo is shown in Figure 6.

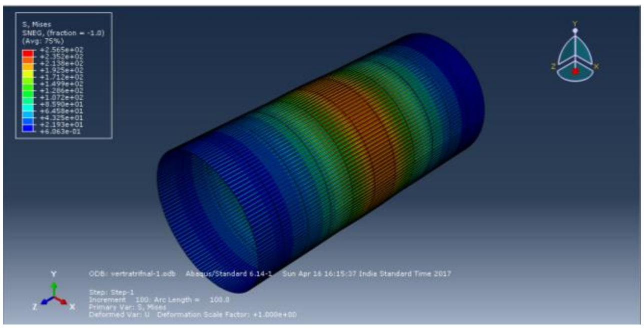

Figure 6 : Stress profile for the vertical corrugated wall silo

The vertical stresses are large when compared to the horizontal stresses in the vertical part of the silo. Normally, the stress increases linearly with depth in the vertical part of the silo. As the corrugations are oriented towards the vertical direction, the stress gradually decreases in the lower regions after attaining the maximum stress at the loading zone. The stress is observed to be low at the top and bottom surface of the silo. The region of application of patch load experiences the maximum stress and then the stress gradually reduces in the upper and lower regions of loading. With respect to the shape of the corrugation, there is variation in the stress between flat surface and sloping sides.The stress experienced by the flat surface of the corrugation is found to be more than the sloping sides of the corrugation. Figure 7 shows the XY plot for the true distance along path versus stress of the vertical corrugated wall silo.

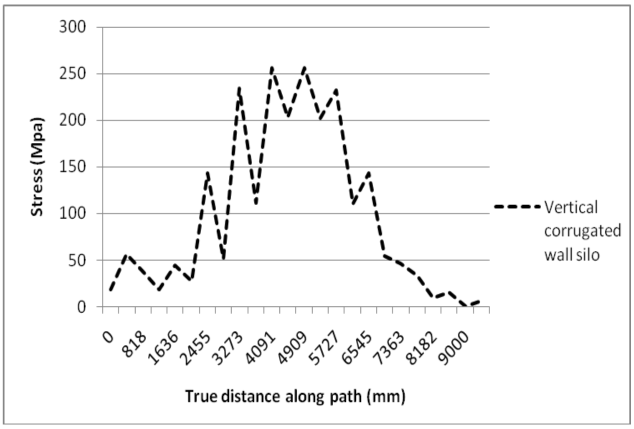

Figure 7 : XY plot for stress of the vertical corrugated wall silo

The path was created on the vertical corrugated wall silo along the nodes.The maximum observed stress is found to be about 2.5% of the yield stress of the steel and is greatly less than the maximum stress value generated for the plain wall silo. The maximum mises stress exceeds the yield stress of the matereial. Hence, the silo with vertical corrugation fails by plastic collpase.From Figure 7, steep decline in the value of stress is evident at all the boundaries of the mesh. The deformation profile of the vertical corrugated wall silo and the XY plot for the true distance along path versus displacement are shown in Figure 8 and 9 respectively.

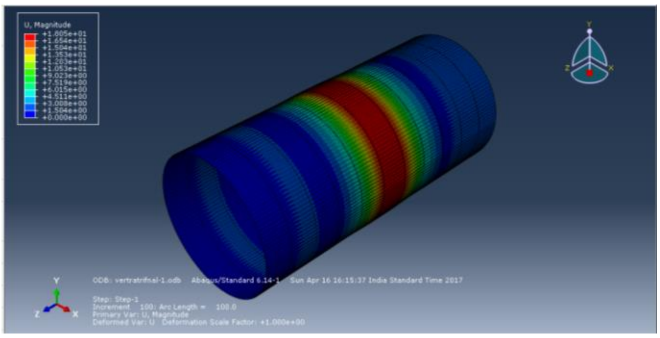

Figure 8 : Deformation profile for the vertical corrugated wall silo

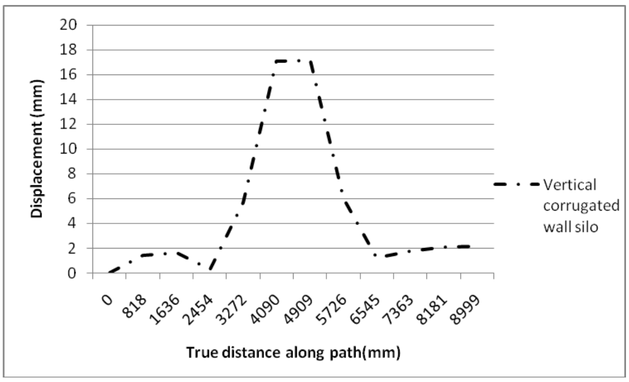

Figure 9 : XY plot for displacement of the vertical corrugated wall silo

The vertical displacements are resisted at the lower edge of the cylindrical shell as it is effectively anchored.The deformation is found to be maximum in the region of loading.

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The similar pattern of deformation is observed in the upper and lower regions of loading. As there is no failure occured due to buckling of the wall, the deformation is less compared to the plain wall silo.

D. Silo wall with Horizontal corrugation

The horizontally corrugated wall silo is fabricated using corrugated sheeting with the corrugations running in the circumferencial direction.The assumptions made for the horizontal corrugated wall silo is that the wall do not carry any vertical forces unless it is treated as an orthotropic wall. The length and depth of the corrugations is considered as in the vertical corrugated wall silo. The corrugation profile is given in Figure 10a and the view of the horizontal corrugated wall silo is given in Figure 10b.

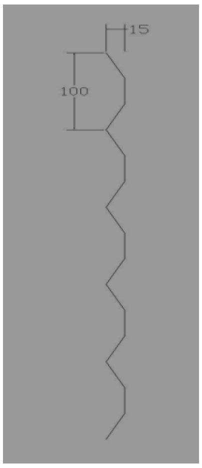

Figure 10 a: Corrugation profile

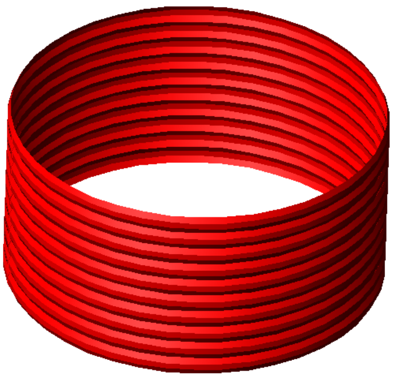

Figure 10 b: View of the horizontal corrugated wall silo

The horizontal corrugated wall silo subjected to patch load is observed with the maximum stress developed only at the loading zone. The remaining zone other than loading region is noticed with very minimal von mises stress. Eventhough the maximum mises stress is noticed in the center zone, the value of the mises stress is less when compared with the vertical corrugated wall silo. In the case of corrugated portion, the flat portion and the sloping portion of corrugation experiences equal amount of stress such that no variation of stress can be reported based on corrugation.The stress profile of the horizontal corrugated wall silo is shown in Figure 11 and the XY plot for the true distance along path against stress is shown in Figure 12.

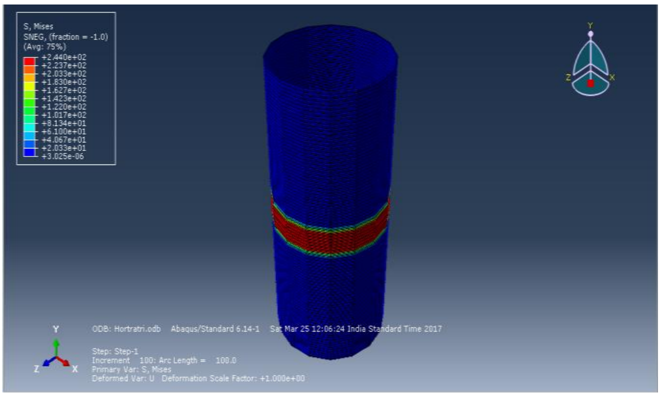

Figure 11 : Stress profile for the horizontal corrugated wall silo

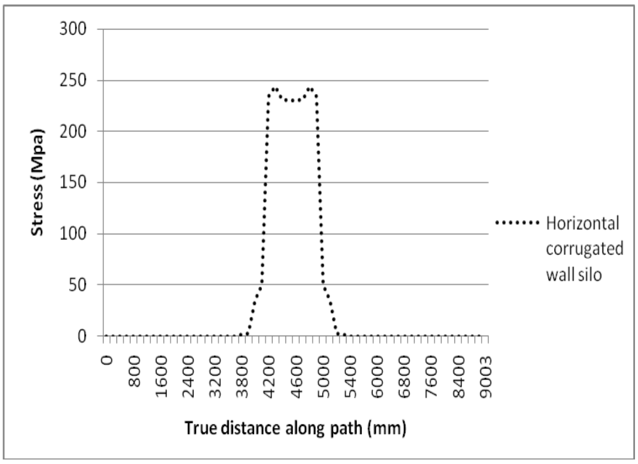

Figure 12 : XY plot for stress of the horizontal corrugated wall silo

The nodes are used to create the path for plotting the graph in the horizontal corrugated wall silo.From the Figure 12, it can be concluded that the stress tends to be maximum at the loading zone. The maximum stress is about 2.5% less than the yield stress of the steel. Due to the minimum value of maximum mises stress , the plastic collpase is not expected to occur. From the strength point of view, the horizontal corrugated wall silo is considered to be safe as the maximum stress value is lower than the yield value of the material. The deformation profile of the horizontal corrugated wall silo and the XY plot for the true distance along path against displacement are shown in Figure 13 and 14 respectively.

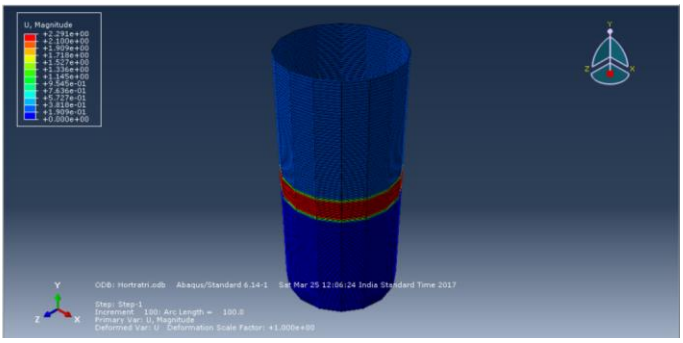

Figure 13 : Deformation profile for the horizontal corrugated wall silo

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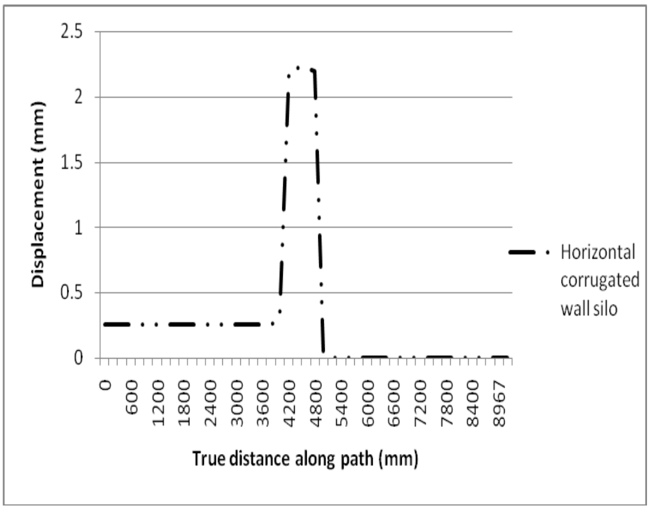

Figure 14 : XY plot for displacement of the horizontal corrugated wall silo

The deformation observed is very less in the lower region of the horizontal corrugated wall silo. The loading region experiences high deformation and the zero deformation are noticed in the top regions of the silo. The value of deformation is very low when compared to the plain wall silo and the vertical corrugated wall silo.

The stiffness of the corrugated profile is inversely proportional to the stress as well as the bending of the corrugation [24]. In the walls of horizontally corrugated silo, the bending is less and parallel to the orientation of corrugation. The stiffness of the silo wall is greatly achieved by the low magnitude of stress and hence, the silo wall with horizontal corrugation is not observed with buckling failure. This is the main advantage of sheets with horizontal corrugation and hence more preferable for the construction of silo.

IV. CONCLUDING REMARKS

The silo was analyzed using Abaqus software and their structural behavior was studied under the application of patch loads. The three different silo walls namely Plain wall, Vertical corrugated wall and Horizontal corrugated wall silo were considered for this study. The study reveals that the plain wall silo fails by buckling under the effect of patch load. Eventhough, the stress is more for silo walls with the vertical corrugation and the horizontal corrugation wall silo are not observed with sign of failures. The minimum values of stress and displacements are resulted in the horizontal corrugated wall silo. Based on the results, the horizontal corrugated wall silo is less prone to buckling failure and plastic collapse. The study concludes that the silo walls made with corrugations run in the circumferential direction and is found to be beneficial in the practical applications and safe for the construction.

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