Finite Element Analysis for Displacements and Stresses Developed over Horizontally Corrugated Steel Silo Wall Panels

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In this study, finite element analysis approach was used to investigate the displacements and bending stresses exerted by shelled corn on a wall configuration made of folded steel plates. Silo walls panels with trapezoidal corrugations were considered. Entire bin geometry was created with finite element approach; loads calculated by using Jansen's equations for pressures in deep bins were applied over the bin geometry. Resultant displacements and bending stresses were evaluated by using the plots generated by finite element analysis software. The highest bending stresses occurred at the corner of each wall panel with greater bending stresses occurring around the tie bars. The highest displacements were observed at mid-points of wall span. Corrugations with tie bars had significantly lower bending stresses than the corrugations without tie bars. Using the results of this theoretical work, further studies can be performed for a complete silo model with a roof structure and a hopper bottom and wind forces and the shear stresses can be added to the model. This may give a better interpretation of the theoretical results on real models.

Key Words: Storage bins, silo design, wall pressures, steel silos, finite element analysis

Sonlu Elemanlar Yöntemi ile Trapez Kesitli Çelik Silo Duvarlarında Eğilme Gerilmesi ve Yer değiştirme Analizi

Bu çalışmada sonlu elemenlar yöntemi kullanılarak oluklu çelik silo duvarlarında mısır tarafından oluşturulan eğilme gerilmeleri ve duvar yer değiştirmeleri incelenmiştir. Silo duvarları trapez kesitli oluklara sahip duvar panellerinden oluşmaktadır. Silo geometrisi sonlu elemanlar yöntemi kullanılarak oluşturulmuş ve derin silolar için geliştirilmiş Jansen eşitlikleri kullanılarak hesaplanan yükler uygulanmıştır. Sonlu elemanlar paket programı kullanılarak elde edilen grafikler yardımıyla eğilme gerilmeleri ve yer değiştirmeler değerlendirilmiştir. En yüksek eğilme gerilmesi değerleri duvar köşelerinde gözlenirken en büyük yer değiştirmeler ise duvar açıklığının orta kesimlerinde gözlenmiştir. Karşılıklı duvarları birbirine bağlayan bağlantı demirlerinin olduğu oluklar diğerlerine nazaran oldukça daha düşük eğilme gerilmesine maruz kalmaktadır. Bu teorik çalışmanın sonuçları kullanılarak çatı ve taban kısmı ile birlikte tam bir silo modeli dikkate alınarak rüzgar ve kesme kuvvetleri de eklenip daha ileri bir model çalışması yürütülebilir. Bu tür bir model, sonuçların daha iyi bir şekilde yorumlanabilmesine olanak sağlayacaktır.

Anahtar Kelimeler: Depolama yapıları, silo tasarımı, duvar basınçları, çelik silolar, sonlu elemanlar analizi

Introduction

Silos are storage structures built to store mostly the granular materials. They are often made of concrete and steel and usually constructed in circular, square or rectangular plan-view configurations with vertical walls. The first bins and silos with large dimensions were built as early as the 1880s for storing large quantities of grain. Early silo designs were based on the assumption that the bulk solids behave like liquids. A granular material or powder, unlike a liquid material, can resist static shear stresses. Furthermore, a cohesive material is capable of forming a pattern that obstructs the steady flow of the bulk solids. Unlike other structures, storage structures have an unusually high rate of structural failures (Molenda *et al*. 2009). This brings a need for more studies on silo design. Most of the failures occur primarily because the pressures on the walls of the structure cannot be exactly predicted when the grain is in motion. In recent years, several attempts to apply the finite element method to predict these pressures have shown a distinct promise for handling the general silo problems. There are many reasons for silo failures and most occurrences were due to foundation failures, discharge over pressures, friction forces, pressure on silo bottom and abnormal outlets.

The non-homogenous make up of grain makes the determination of the pressures exerted on bin walls difficult. Roberts (1882) studied the pressures exerted by wheat on the floor of square and hexagonal wood bins and concluded that in any silo cell which has parallel sides, the pressure of wheat on floor ceased when the grain was filled up to twice the diameter of the inscribed circle. Janssen (1895) made a significant contribution on the estimation of lateral and vertical pressures on silo walls and bottoms. Janssen studied deep bins made of wood. His study along with the corresponding pressure theories for lateral and vertical pressures on silo walls became the basis for calculating loads on silo walls for the next sixty years.

Wall friction is an important factor in determining the pressure exerted by grain on walls. Airy (1897) made some investigations to determine the coefficients of friction between the grain and the material of the bin. With the new materials used for bins in the beginning of 20th century Jamieson (1904) conducted a series of grain pressure tests. Jamieson conducted his tests on round, square and rectangular model silos constructed with wood and steel. Results of these initial studies have been used for almost a century. Reimberts (1976) carried out tests on bins with sizes varying from small-scale models up to actual silos. He also developed his own formulas for lateral and vertical pressures exerted by the ensiled material on bin walls and floors.

The proper design of bulk storage structures requires knowledge of individual and bulk properties of the particulate material under static and dynamic loading conditions. Several researchers studied the bulk properties of various grains like bulk density, angle of repose, internal and external angles of friction and flow properties (Janike (1964); Carr (1965); MWPS (1983); Gaylord and Gaylord (1984); Ravenet (1984); Reimberts (1987); Thompson *et al*. (1998); Öztürk *et al*. (2008); Ünal (2009)).

During the recent years, finite element analysis (FEA) methods are started to be used to investigate silo wall loads. In its most general sense, the FEA is a numerical procedure to solve the differential equations. As with any other numerical procedure, the finite element method transforms a problem defined in a continuum with an infinite number of unknowns into a problem with a finite number of unknowns at certain points called nodes. The accuracy of the results depends on the discritization procedure and number of elements used in FEA.

Clough (1960) was one of the first to describe the procedure as a finite element method. Champion (1992) defined the information required for a typical analysis made by using the finite element methods as: nodal points spatial locations (geometry), elements connecting the nodal points, mass properties, restrains or boundary conditions, loading or forcing function details and analysis options.

In this study, finite element analysis approach was used to analyze bending stresses and displacements over the folded steel plates of silo walls. Especially the difference in wall pressures over the different sections of corrugations and effects of tie bars on bending stresses were investigated.

Material and Methods

The bin analyzed in this study has 500 x 500 cm square cross-section with a height of 725 cm. Bin walls were made of pre-fabricated folded steel plate wall panels. Corrugations were trapezoidal and height of each corrugation was 100 cm. There are seven corrugations along the height of the bin. Four tie bar sets were placed between opposite walls. A prefabricated wall panel made of folded steel plates with trapezoidal corrugations was shown in Figure 1.

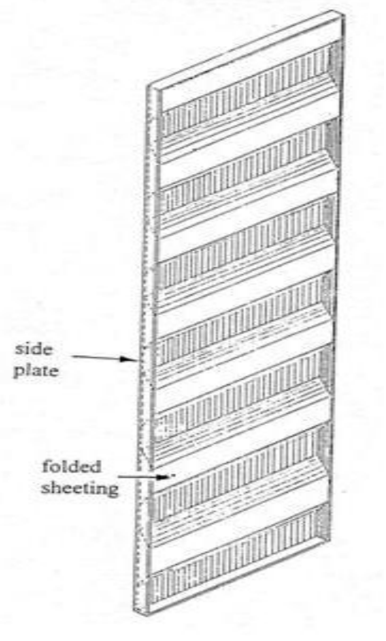


Figure 1. Pre-fabricated wall panel

The structure is composed of four walls made of horizontally corrugated steel wall panels. The

wall panels are prefabricated and assembled at job site. The vertical sides of wall panels have side plates. The panels are welded to each other at corners and steel plate is used to form a triangular hollow core at corners. The bottom of structure is fixed to a flat bottom to prevent lateral movement and rotation. Because of the square cross-section of the bin, no corner rotations were considered. The top of the structure is open. There are no loads coming from the bottom and the top and the only loads considered are the design pressures and frictional forces due to ensiled grain inside the wall segments.
Shelled corn was considered as the ensiled grain to calculate the wall pressures and frictional forces exerted by the ensiled grain. Following grain properties were used in calculations (Anonymous, 1983):

- Bulk density of the shelled corn, w = 768,89 kg/cm^3
- Coefficient of friction between ensiled corn and steel, μ'= 0.20
- Internal angle of friction, $\phi = 27^o$
- Filling angle of repose, $\alpha = 16^o$
- External angle of friction, ϕ', equal to $\tan^{-1}$ μ'= 11.3 º

The entire structure was modeled by using finite element method. To perform the finite element analysis, a software called IMAGES-3D (Interactive Microcomputer Analysis of General Elastic Structures) version 3.0 developed by Celestial Software Division of Robert L. Cloud & Associates, Inc. was used (Anonymous, 1993). Images-3D performs three types of analysis: static, model and dynamic. The displacements and stresses resulting from ensiled grain loads were solved. The analysis was performed in two steps as geometry definition and analysis.

Definition of Plate Elements

Plate elements were defined by connecting four nodes in a counter-clockwise direction. There were 1 856 plate elements used in modeling the corrugations with each one having 25 x 30 cm dimensions in vertical parts and 35 x 30 cm dimensions in inclined parts of the corrugations. A total of 232 plate elements were used for attaching end plates to the ends of wall panels and 116 plate elements were defined to form triangular shape at the corners. First, the plate elements of bottom corrugation were defined (Figure 3 (a)) and then element generation option was used to establish the other six corrugations (Figure 3 (b)).

Geometry definition

Mathematical Modeling

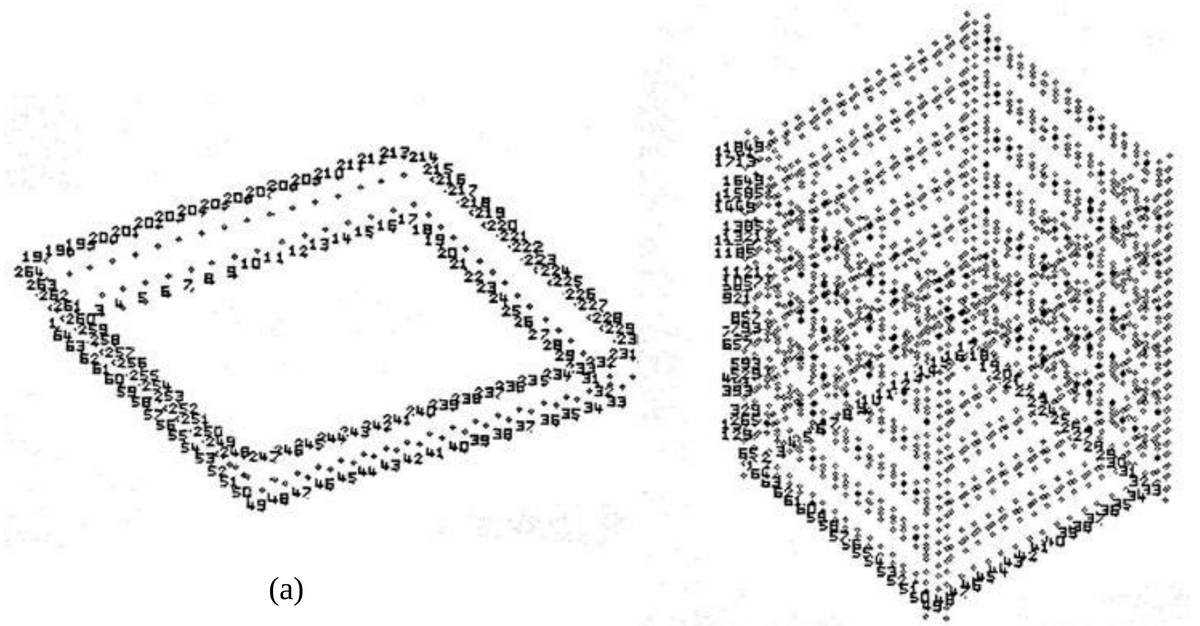
The aim of mathematical modeling is to provide observation of actual behavior of a structure, or a specific part of the structure or its structural members under various loads or physical conditions. Actual behavior of a structure is generally very sophisticated. Thus, many simplifications are necessary while modeling the structure. In order to obtain a simple model, the mechanical properties of the structural materials should clearly be defined.

The basic steps that are given below should be followed to form the mathematical model of a structure:

- The assumptions about material behavior are determined according to that of a very small part, which is also known as the differential element, of the material. The differential element forms the material model. In material model, stress-deformation stressstrain relationship is taken into consideration.
- The differential elements are assembled in order to provide the behavior of the elements, which define a specific part of the model and are known as finite elements.
- The next step is to assemble finite elements to make them reflect the behavior of the entire structure.

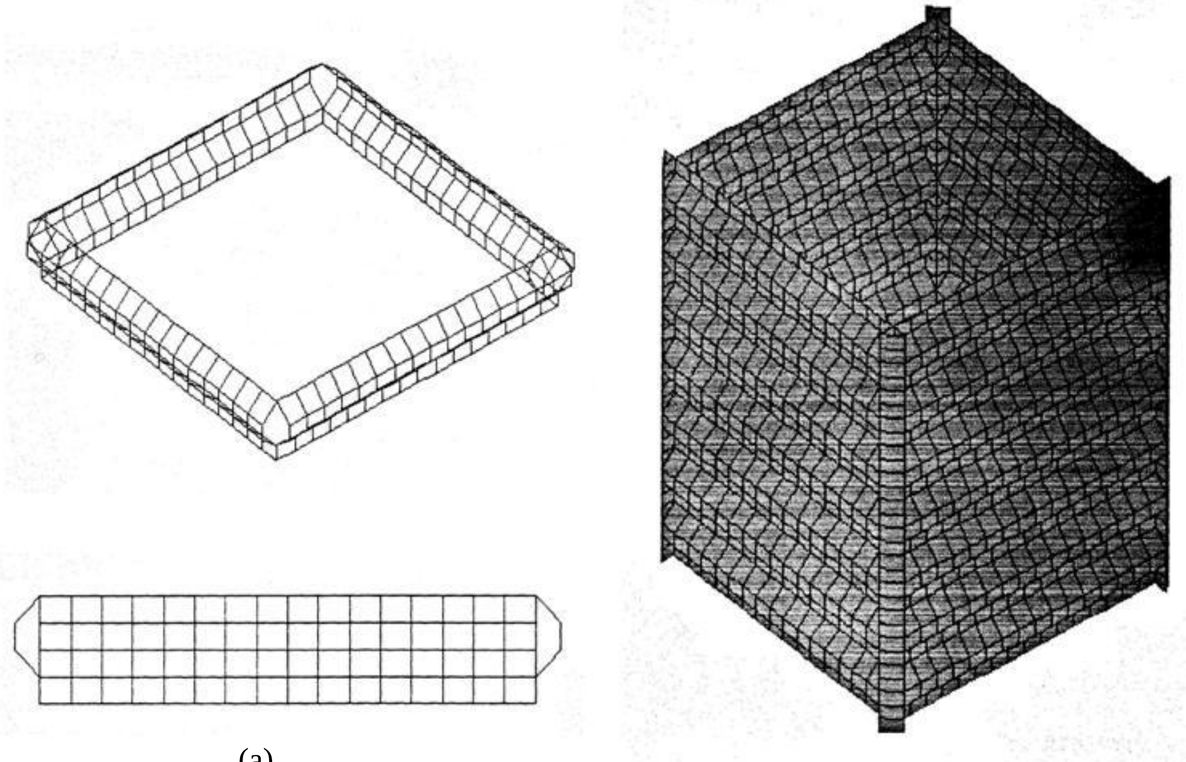
Definition of node points

In this model, a total of 2160 node points were used to define four sides of the bin. Nodes were entered by inputting X,Y, and Z coordinates of each point. First, a set of nodes were defined as shown in Figure 2(a), then additional nodes above these initial nodes were generated at a spacing of 25 cm in Y-axis coordinate direction to complete the model to a height 725 cm. Completed node points can be seen in Figure 2(b).



(a) (b)

Figure 2. (a) First set of node points (b) Completed node points



(a) (b)

Figure 3. (a) First set of plate elements (b) Completed plate elements

Definition of truss elements

Truss elements were defined by connecting two node points at opposite walls. To reduce the deflections and stresses of the wall panels under lateral design pressures, a total of 8 truss elements were defined. Steel tie bars were defined as truss elements connecting two nodes at center of walls on opposite sides of the bin. Four sets of tie bars were located 200 cm apart from each other starting at an elevation of 125 cm from the bottom of the bin.

Definition of boundary conditions

Structural FEA displacement boundary conditions are the limitations on movement of the structure at places such as restrains or anchor locations. The boundary conditions in a finite element model must limit translation or rotation in a manner appropriate to the case at hand. Boundary conditions can be used to imply symmetric behavior in a structure that has symmetry, so that the model size can be halved, quartered, or similarly reduced, if the loading of the structure is also symmetrical. The structure should be properly restrained at certain node points so that no rigid body movement of complete structure is possible. Each node has six global degrees of freedom. For the bin structure, the bottom node points were all restrained against translation and rotation about global X, Y, and Z directions. The restrained conditions of the model can be seen in Figure 4. Completed geometry was presented in Figure 5.

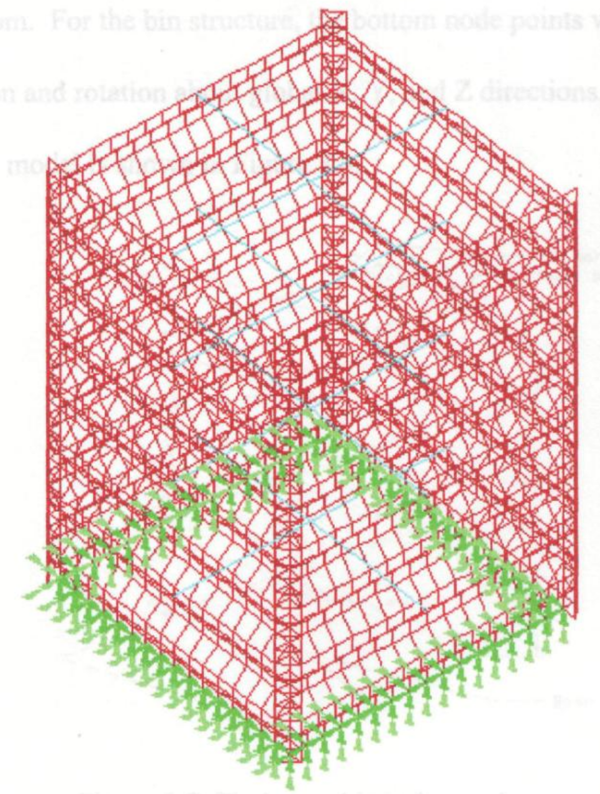


Figure 4. Restrain conditions

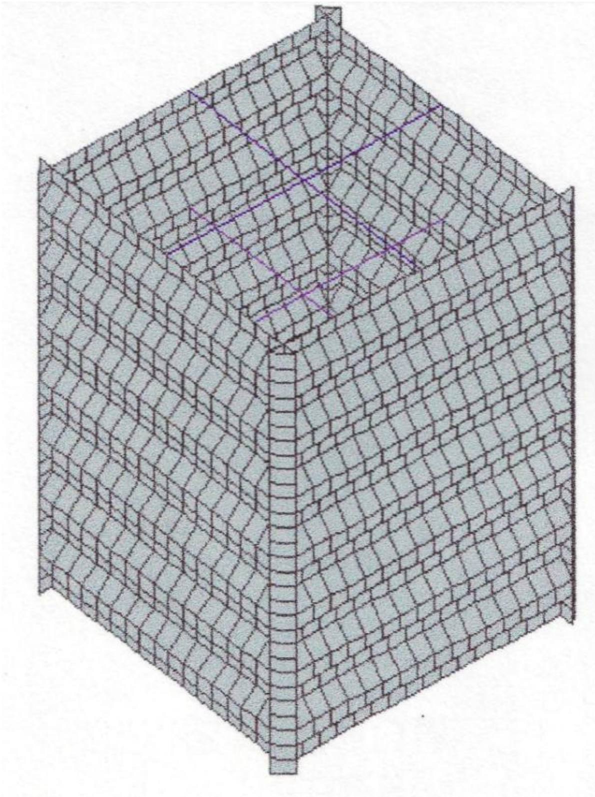


Figure 5. Completed geometry

Definition of material properties

The material properties of structural steel were:

- Modules elasticity : E = 2 038 902 kg/cm^2
- Poisson's ratio v = 0.3
- Density q= 7.85 g/cm^3

Definition of loading conditions

Lateral design pressures and vertical frictional forces were applied over the plate elements. The loads were determined by using Jansen's equations for deep bins. Loads applied over the bin geometry were given in Table 1.

Following the definition of geometry and applying the loads, the stiffness matrix for the structure was assembled by computer program and the stress and displacement resultants for the elements were determined. Bending stresses were also calculated by the software for two geometries; one with tie bars and the other without tie bars.

Table 1. Lateral design pressures and vertical friction forces

Y(cm)	F(kg/cm^2)	L_d(kg/cm^2)	V_w(kg/cm^2)
0	0	0	0
25	0.019686	0,011853	0.002371
50	0.038669	0.00569	0.001138
75	0.056949	0.034289	0.006858
100	0.066089	0.179242	0.035848
125	0.093508	0.056301	0.01126
150	0.115303	0.016967	0.003393
175	0.127959	0.077044	0.015409
200	0.113897	0,308906	0,061781
225	0.161706	0,097363	0,019473
250	0.191235	0,030225	0,006045
275	0.194047	0,12549	0,025098
300	0.147645	0,430096	0,086019
325	0.225685	0,145951	0,02919
350	0.265057	0,041892	0,008378
375	0,255917	0,176916	0,035383
400	0,172252	0,536384	0,107277
425	0,284743	0,196843	0,039369
450	0,337473	0,057016	0,011403
475	0.312866	0.216284	0.043257
500	0.189829	0.629254	0.125851
525	0.339583	0.249899	0.04998
550	0.409186	0.073592	0.014718
575	0.365596	0.269042	0.053808
600	0.201781	0.668874	0.133775
625	0.390907	0.287668	0.057534
650	0.47879	0.08611	0.017222
675	0.414811	0.305259	0.061052
700	0.210921	0.699171	0.139834
725	0.438012	0.322333	0.064467

Results and Discussions

The plot of stress intensity (membrane & bending) on wall corrugations predicted by finite element analysis was presented in Figure 6. The plot shows that the highest bending stresses occurred at the corner of each wall panel with greater bending stresses occurring around the tie bars. There was only a small bending stress occurred at top of the bin due to very small lateral design pressures. Lower stresses were obtained for the center of wall panels than the corners.

The displacements in global X direction were given in Figure 7. The largest displacements occurred close to the bottom of bin due to the highest lateral design pressures at the bottom sections. The largest displacements were also occurred at mid points of wall span. The smallest displacements were observed in the areas around the location of tie bars and areas close to the corners of wall panels. Similar results were observed in displacements at global Z direction. The highest displacements occured again at bottom sections of the bin and mid points of wall panels and the lowest were observed around tie bars and corner sections of wall panels (Figure 8). A symmetric displacement pattern can be seen when comparing displacement figures. This indicates that elements and loads were defined in the same way for each wall panel.

The software yielded the maximum bending stresses over the wall panels for two models; one with tie bars and the other without tie bars. Maximum bending stresses for two cases were given in Table 2 and change in bending stresses was presented in Figure 9.

Table 2. Maximum bending stresses for two cases

Corrugation	Maximum Bending Stresses (kg/cm^2)	
	With Tie Bars	Without Tie Bars
1	181.25	346.47
2	231.17	590.93
3	683.66	814.86
4	312.73	1008.91
5	976.56	1167.80
6	450.18	1235.29
7	985.00	1138.27

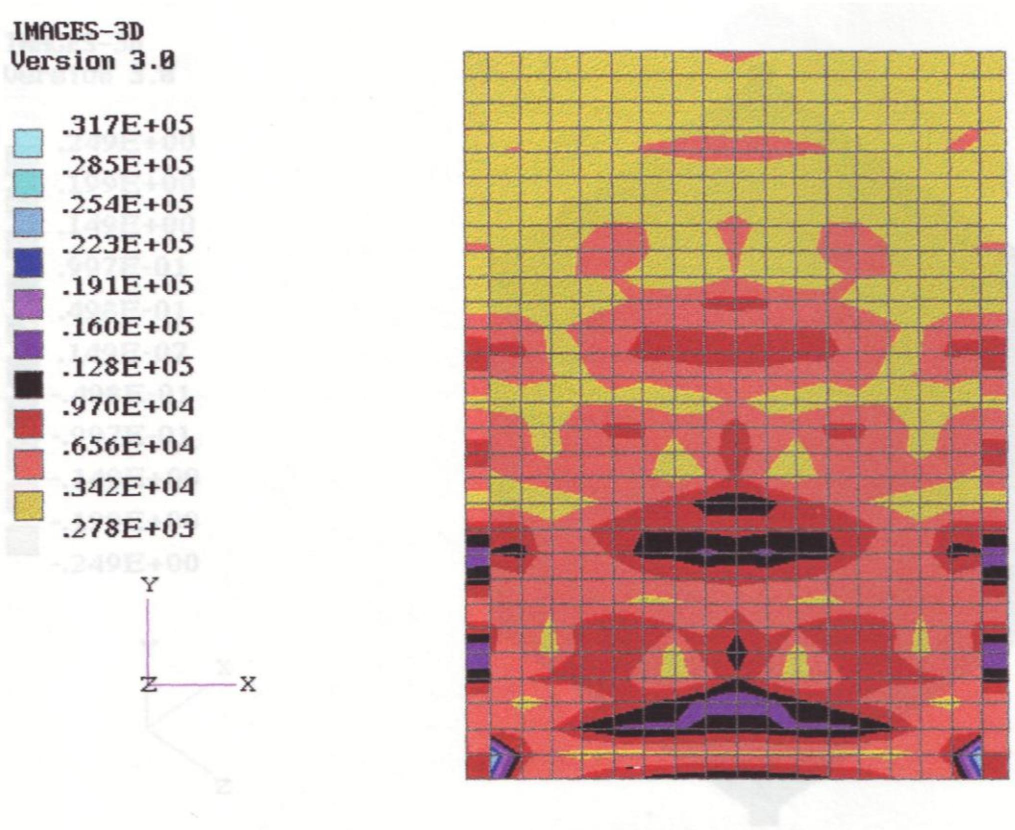


Figure 6. Plot of stress intensity

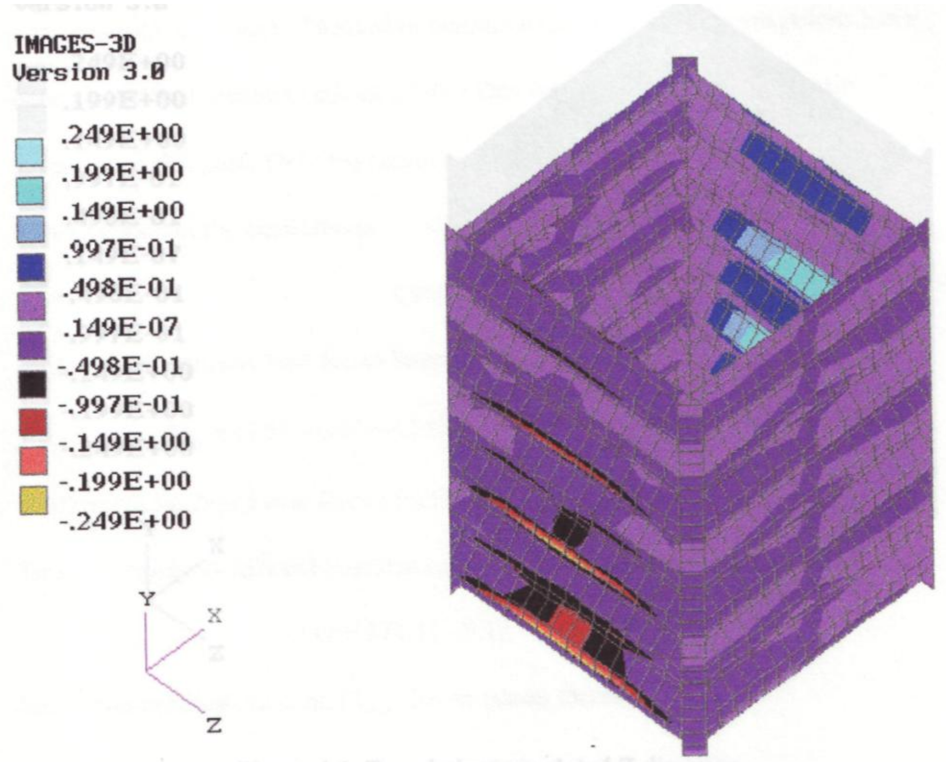


Figure 7. Displacements on global-X direction

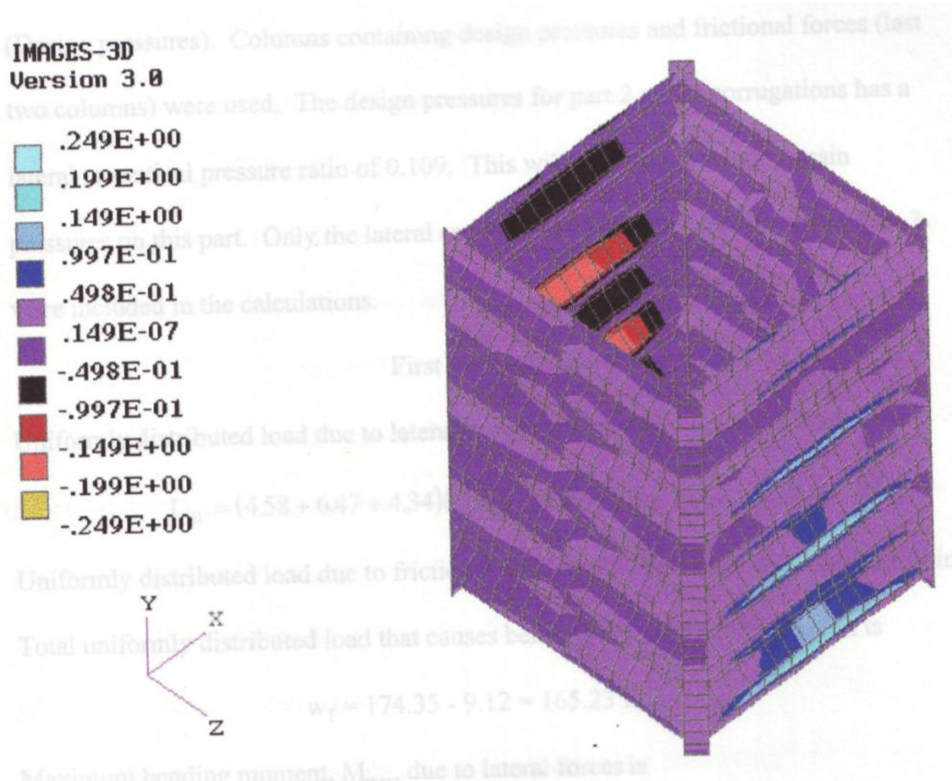


Figure 8. Displacements on global-Z direction

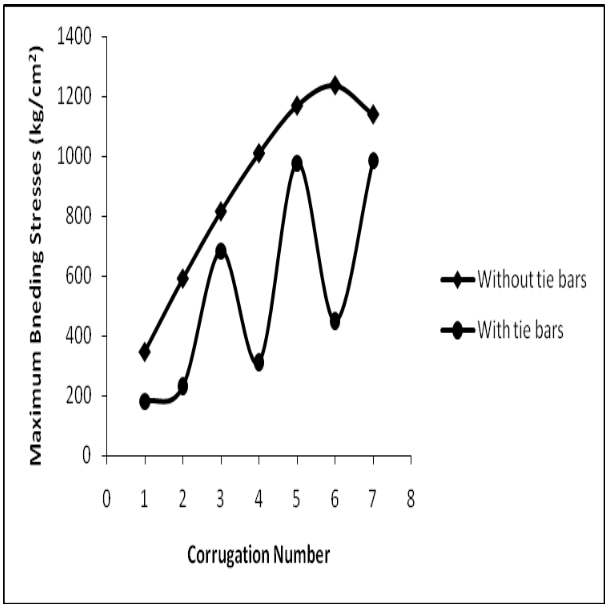


Figure 9. Change in bending stresses

Conclusions

Finite element analysis approach was used in this study to investigate the displacements and bending stresses exerted by shelled corn on a wall configuration made of folded steel plates.

Silo walls panels with trapezoidal corrugations and silo wall loads calculated by using Jansen's equations for pressures in deep bins were considered. Resultant displacements and bending stresses were evaluated by using the plots generated by finite element analysis software. The highest bending stresses occurred at the corner of each wall panel with greater bending stresses occurring around the tie bars. The highest displacements were observed at mid-points of wall span. Corrugations with tie bars had significantly lower bending stresses than the corrugations without tie bars. Using the results of this theoretical work, further studies can be performed for a complete silo model with a roof structure and a hopper bottom and wind forces and the shear stresses can be added to the model. This may give a better interpretation of the theoretical results on real models.

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