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Numerical simulation of reinforcement in steel slender silos having concentric hopper with carbon fiber-reinforced polymer composites (study of the silos filling)

Latifa Louetri *,[1], Djeghaba Kamel [2], Eutiquio Gallego Vasquez [3].
[1]*Department of Civil Engineering, University Badji Mokhtar Annaba,Algeria*
[2] *Department of Civil Engineering, University Badji Mokhtar Annaba,Algeria*
[3] *Department of Agricultural Engineering, Polytechnical university of Madrid,Spain*
Corresponding Author E-mail:latifa_23000@yahoo.fr

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Abstract

This paper presents a numerical analysis of the reinforcement of steel slender silos having concentric hopper with carbon fiber-reinforced polymer (CFRP). The numerical model has been developed using the finite element method, where the stored material was considered to be wheat. The actions of the stored material over the silo wall were obtained by simultaneously modelling the silo wall with shell elements, and the wheat with solid elements. The interaction between both materials was properly simulated by using adequate contact elements. The Drucker Prager elastoplastic criterion was used to define the behaviour of the stored material. The simulations analysed the influence of different reinforcement layers and the placement of reinforcement.
In all cases, the effectiveness of the CFRP use for reinforcing steel slender silos was obtained. Indeed, a significant reduction of the circumferential and meridional stresses, especially for the bin – hopper junction was also obtained. The results shows that up to 50% reduction of stresses are obtained in the silo with five layers compared to a silo with non-reinforced wall. The reinforcement with CFRP can be of interest for silos having suffered damage and alterations that induced a reduction in the thickness of their walls.

1.Introduction

Storage structures, such as silos, which are used for the industrial or agroalimentary sectors, were always needed because of the economic importance of the immediate availability in large quantities of the stored materials. The nature of materials stored in silos (cement, sand, cereals, or sugar, among others) can greatly differ, and the actions caused by them over the silo walls can also be quite different [1-2, 3-4]. However, the interaction between two different materials (stored material and silo wall) makes difficult to address the actions exerted over the silo wall, especially for the discharge process. These actions are usually summarised in normal pressure and friction on the silo walls.

The reinforcement of steel silos usually requires a complete silo discharge and stopping exploitation during the repair works. To address this problem, a solution which is reliable enough and safe to reinforce these silos while significantly reducing the downtime of exploitation is required. Nowadays, the fiber-reinforced polymer composites (FRP) is being used for reinforcing and rehabilitating such kind of structures [5-6, 7], and even for other structures used in civil engineering. This material has several advantages in comparison to the classic method of reinforcement: low density (which means a lower self-weight), a higher strength-to-density ratio and an excellent corrosion resistance. In addition, the application of the FRP composite on the external surface of the wall by using a resin matrix is also easier, and it avoids the need of discharging the silo.

Currently, the actions exerted by the stored grain over the silo walls are obtained from different international standards [8-9,10], and used to design them. The development of the first finite element models in silo research dates from the late 70s and the early 80s [11-12, 13], and they fostered a new period in silos research [14]. Thus, the finite element method (FEM) is being increasingly used to analyse all kind of problems and phenomena in silos because of the possibility of both simulating the real structure and the material stored [15-16, 17-18, 19-20, 21-22].

2. Methodology

2.1. The Composite Material CFRP

The CFRP is in an orthotropic fabric, which may have its fibres oriented in one direction or in two directions. In general, 70% of fibres are placed in the horizontal direction and 30% in the vertical direction, according to ISO 7211[23]. So, the mechanical properties of this material, such as the elasticity modulus, the shear modulus or the Poisson's ratio, have to be defined in two orthogonal directions. The mechanical characteristics of CFRP considered in the developed numerical model are derived from experimental tests that were performed at INSA (Lyon) in a previous work [23], and relates to an orthotropic CFRP of elastic behavior whose mechanical characteristics are shown in (table1).

Table 1. Mechanical characteristic of the CFRP

Circumferential' elasticity modulus (E1)	Axial elasticity modulus (E2)	Shear modulus (G1)	Poisson's ratio (v1)	Thickness (without resin)
105000 MPa	15000 MPa	5800 MPa	0.3	0.43mm

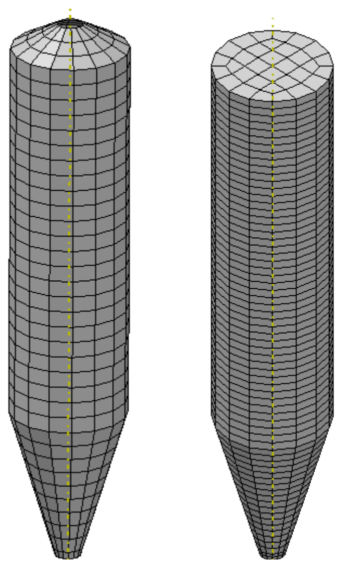
2.2. Test specimens and properties

The finite element methode was used in this work were the actions of the stored material over the silo wall were obtained by simultaneously modelling the silo wall with shell elements, and the stored material with solid elements (Fig.1.). The interaction between both materials was properly simulated by using adequate contact elements. Drucker–Prager criteriom was selected to define the behaviour of the granular material for the plastic part, while a classic isotropic and linear theory was used for the elastic part of the constitutive model.

The circumferential direction has been considered as the preferred direction of reinforcement, and to simplify the modelling of the CFRP bonded to the silo wall, a composite section model (multilayered) based on the perfect adherence hypothesis has been used.

The numerical models were developed by selecting a steel slender silo having concentric hopper (Fig.2), as used by other authors[24], and the stored material was supposed to be wheat, the surface of the solid was treated as level. Table 2 shows the geometric characteristics of the silo modelled, while Table 3 contains the mechanical properties of the ensiled wheat.

The software package ABAQUS[25] is used for the development of the numerical models in this research.



(a) (b)

Figure 1. Modeling of the silo wall (a) and the granular material (b)

3. Results and discussions

3.1. Geometry and characteristics of the model

This section presents the results obtained with the silo reinforced by using CFRP in order to reduce the stresses produced in the silo walls comparatively to those in unreinforced silo. First, some results relating to the reinforcement of the entire silo are shown. Then, the optimal location and number of the CFRP layers to be placed on the silo wall is discussed.

Finally, the stresses ratios curves obtained for the different hopper length ratios is shown in order to assess the most efficient solution for silo reinforcement. The results obtained are related to the silo reinforcement for the filling process.

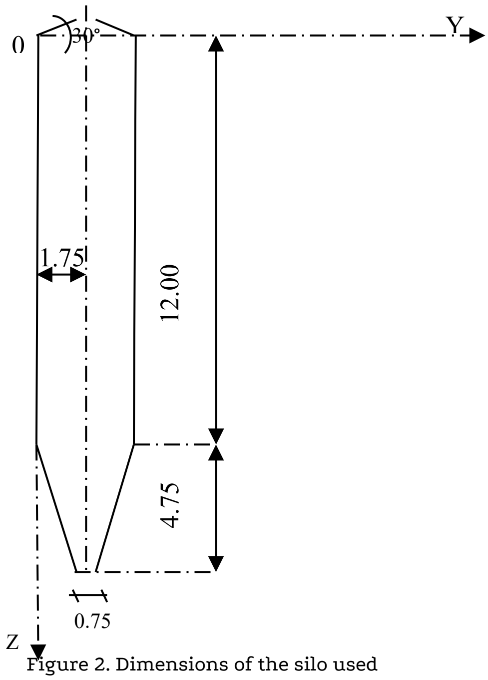


Figure 2. Dimensions of the silo used

Table 2. Dimensions of silo

Parameter	Value (m)
Total height	16.75
Hopper height	4.75
Radius	1.75
Outlet radius	0.375
Thickness	2.5×10^{-3}
Capacity exceeding 100 tons	Silo of class '2' following Eurocode 1 part 4

Table 3. Mechanical properties of the ensiled wheat

Properties	Value
Specific weight (kg/m3)	$\delta = 840$
Elasticity modulus (MPa)	E = 5.129
Poisson's ratio	$\nu = 0.32$
Grain-to-wall friction coefficient	$\mu = 0.2$
Angle of internal friction	$\rho = 25°$
Apparent cohesion (MPa)	$C = 3 \times 10^{-3}$
Angle of dilatancy	$\psi = 17.6°$

3.2. Analysis of a silo completely reinforced with CFRP

First, the normal pressures Fig. 3, and both meridional and circumferential stresses (Fig.4) were obtained in the silo wall from the finite element model developed without reinforcement, these results were also compared to those obtained according to the ones predicted by Eurocode. It can be seen from the curves of the normal pressures and both meridional and circumferential stresses that numerical results are close to the values predicted by Eurocode, especially in the vertical part of the silo. However, for the circumferential ones, a significant decrease can be observed at the transition zone between the vertical silo wall and the hopper for the Eurocode prediction, since this decrease is limited for the FEM model. This circumstance can be explained because in the finite element analysis, both the silo wall and the granular material are modelled, in this case the granular material restrains the horizontal displacements, which limit the stresses decrease.

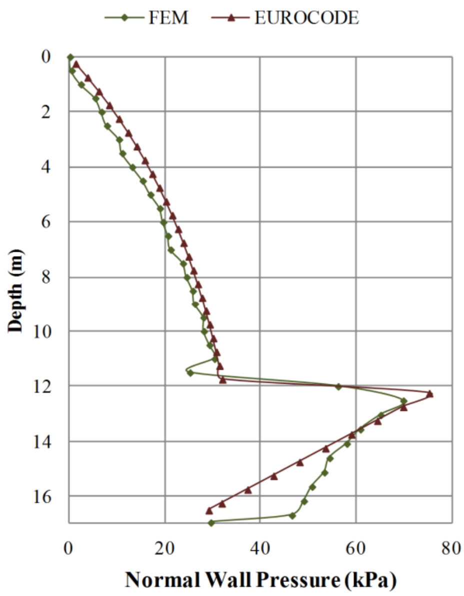


Figure 3. Normal wall pressures predicted by the FEM and the Eurocode

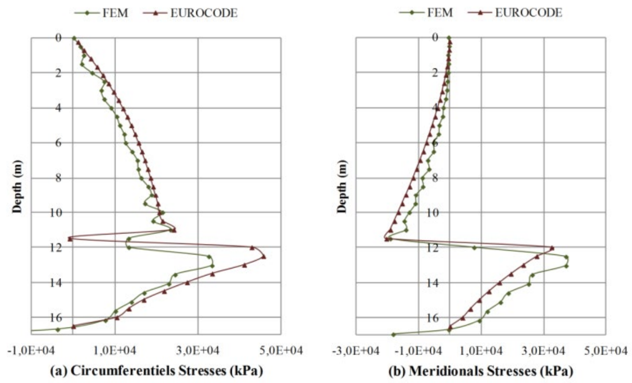


Figure 4. Circumferential (a) and meridional (b) stresses obtained according to pressures predicted by Eurocode and FEM

Different reinforcement layers of CFRP were considered to check the influence of thickness reinforcement on the reduction of wall stresses (Fig.5). It can be observed that the more number of reinforcement layers used, the less of both circumferential (S11) and meridional (S22) stresses are obtained for any part of the silo wall.

Fig.6 shows the percentage reduction in stresses obtained at a silo depth of z = 12.5 m, corresponding to the transition area with regards to different number of reinforcement layers. The reduction of the circumferential stresses (S11) by applying one layer of composite is 12.82%, compared to a non-reinforced wall, and it is up to 55.61% when five CFRP layers are considered. For the meridional stresses (S22), a 15.96% stresses reduction is obtained when only one CFRP layer is applied, while a maximum reduction of 54.6% is obtained when five CFRP layers are considered.

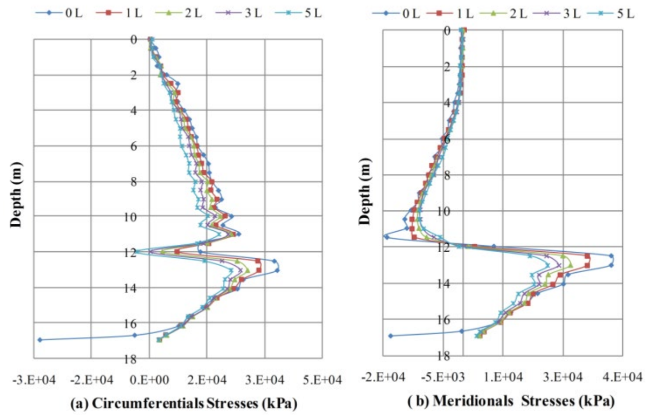


Figure 5. Circumferential (a) and meridional (b) stresses after full reinforcement of silo walls. (0L: results obtained without reinforcement; 1L, 2L, 3L and 5L: results obtained by using the CFRP reinforcing layers specified)

However, it can be seen that the reduction in stresses between one and three layers is about 30%. But when the number of reinforcement layers used increases from three to five, the gained reduction of stresses is only about 15%. This trend indicates that the number of reinforcement layers used in order to reduce the costs can be optimised, and suggests that may be the more adequate number of reinforcement layers would be three.

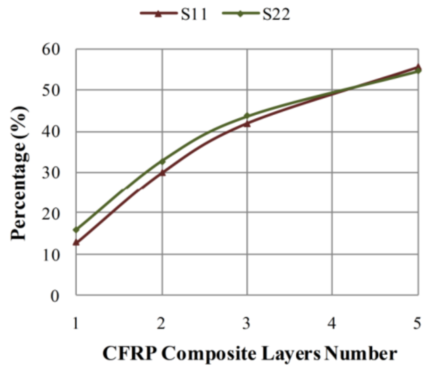


Figure 6. Silo stresses reduction percentage at z = 12.5 m for a completely reinforced wall

3.3. Study of the optimal location for reinforcing the silo wall

Several reinforcement configurations have been simulated to study the effects on the stress reduction. Each configuration considers 0.5 m of reinforced silo wall on the cylinder, and an increasing length of reinforced wall on the hopper side, starting from the transition.

• Location n°1: 0.5 m length on the cylinder and all the hopper length.

• Location n°2: 0.5 m length on the cylinder and 0.5 m length on the hopper.

• Location n°3: 0.5 m length on the cylinder and 1.0 m length on the hopper.

• Location n°4: 0.5 m length on the cylinder and 1.5 m length on the hopper.

• Location n°5: 0.5 m length on the cylinder and 2.0 m length on the hopper.

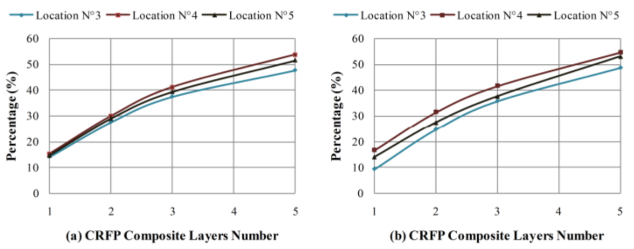


Figure 7. Circumferential (a) and meridional (b) stresses reduction percentage for the locations reinforcement 3, 4, and 5 at z = 12.5 m

Fig.7 shows the circumferential (S11) and meridional (S22) stresses reduction percentages obtained for locations 3, 4 and 5 at a silo depth of z = 12.5 m. The least reduction percentage corresponds to location 3, with independence of the number of reinforcing layers, or the stress type (meridional or circumferential). It is also interesting to remark that location n°4 produces a greater reduction in stresses than location 5. This is an unexpected result, since the hopper-reinforced length is larger for location 4: 2.0 m against 1.5 m. The value of circumferential and meridional stresses reduction for location n°4 is 54.68 and 53.65%, respectively, when five CFRP layers are applied. It can be seen again that the higher stress reduction occurs from one to three reinforcing layers.

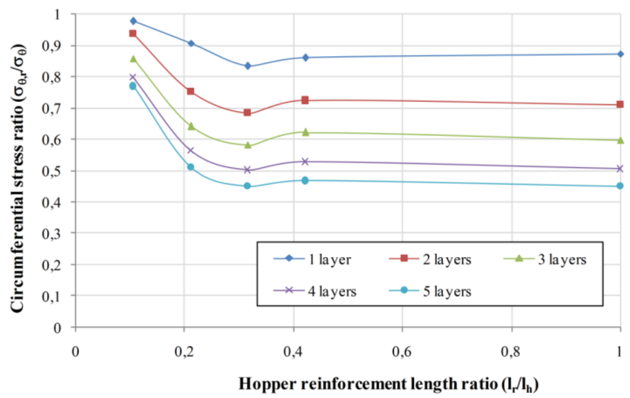


Figure 8. Circumferential stresses ratios for different hopper length ratios

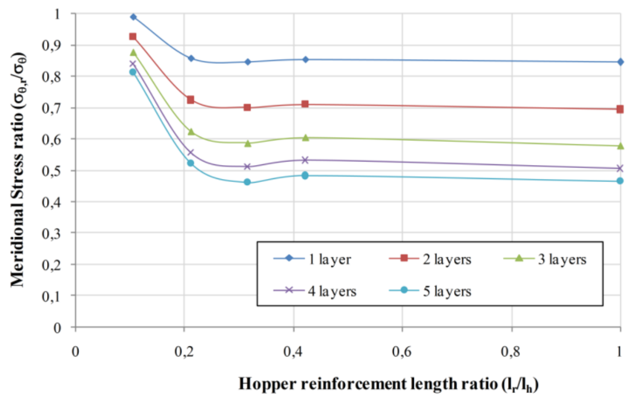


Figure 9. Meridional stresses ratios for different hopper length ratios

The optimal number of CFRP layers and location of the reinforcement can be derived from Fig.8 and 9, which show the circumferential (Fig.8) and meridional (Fig.9) stress ratios ($\sigma_{\theta r}/\sigma_{\theta}$) obtained for the different hopper length ratios (lr/lh) modelled at height z = 12.5 m, where Ir is the reinforcement length (m), Ih is the hopper length (m), $\sigma_{\theta r}$ is the stress obtained in a reinforced wall (kPa) and σ_{θ} is the stress obtained without reinforcement (kPa). It can be seen that both meridional and circumferential stress ratios decrease when the number of the reinforcement layers used increases, which verify the improvement of the silo wall resistance. However, it can be observed that the greatest rate of stress reduction is obtained until three reinforcement layers are used. With respect to the influence of the reinforced hopper length, it can be observed that only a gain in stress reduction is obtained for reinforced hopper length ratios lower than 0.3, which represents the location n°4. The stresses ratio remains almost unchanged for higher reinforced hopper length ratios.The tendency of stress reduction may suggest that an optimum reinforcement would be obtained by using only three CFRP reinforcement layers in only 30% of the hopper length. For this reinforcement configuration, 40% stress reduction would be obtained.

4. Conclusion

the research presented in this paper analyses the effects of reinforcing the walls in steel slender silos having a concentric hopper using CFRP. The finite element model developed takes into account non-linear effects for the geometry (large displacement analysis), the material (using an elastoplastic material model for the bulk solid), and the interaction between the silo wall and the stored material (employing a target-to-surface contact procedure). The results have proved the effectiveness of this kind of reinforcement for the steel silo wall. Indeed, the stress reduction can reach up to 55 and 54.6% for circumferential and meridional stresses, respectively, if the entire silo wall is reinforced by applying five CFRP layers (with respect to the non-reinforced silo wall). In addition, it was found that the significant decrease of stresses appears when up to three reinforcement layers are used. If more than 30% of the hopper wall is reinforced, then around 40% decrease in stresses is obtained when using three reinforcement layers. So, the adoption of three CFRP reinforcement layers instead five has the best ratio of costs with respect to the additional stress reduction gained by using two more CFRP layers (in the five CFRP reinforcement layers solution).

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1.] Colonnello, C., Reyes, L. I., Clément, E., Gutiérrez, G., Behavior of grains in contact with the wall of a silo during the initial instants of a discharge-driven collapse. Physica A: Statistical Mechanics and its Applications398(2014)35–42.

[2.] Couto, A., Ruiz, A., Herráez, L., Moran, J., Aguado, P. J. Measuring pressures in a slender cylindrical silo for storing maize. Filling, static state and discharge with different material flow rates and comparison with Eurocode 1 part 4. Computers and Electronics in Agriculture96(2013)40–56.

[3.] Rotter, J. M., Brown, C. J., Lahlouh, E. H. Patterns of wall pressure on filling a square planform steel silo. Engineering Structures24(2002) 135–150.

[4.] Wójcik, M., Tejchman, J., Enstad, G. G. Confined granular flow in silos with inserts – Full-scale experiments. Powder Technology222(2012) 15–36.

[5.] Batikha, M., Chen, J. F., Rotter, J. M., Teng, J. G. Strengthening metallic cylindrical shells against elephant's foot buckling with FRP. Thin-Walled Structures47(2009)1078–1091.

[6.] Teng, J. G., Hu, Y. M. Behaviour of FRP-jacketed circular steel tubes and cylindrical shells under axial compression. Construction and Building Materials21(2007)827–838.

[7.] Teng, J. G., Yu, T.,Fernando, D. Strengthening of steel structures with fiber-reinforced polymer composites. Journal of Constructional Steel Research78(2012)131–143.

[8.] ACI 313-97 , ACI 313R-97. Standard practice for design and construction of concrete silos and stacking tubes for storing granular materials (ACI 313-97) and Commentary – ACI 313R-97. ACI International., Farmington Hills, USA(1997).

[9.] AFNOR P-22 630. Construction métallique: Silos, BNCM-3., Saint Aubin, France(1992).

[10.] Eurocode 1, part 4. Basis of design and actions on structures. Part 4: Actions in silos and tanks. CEN., Brussels(2006).

[11.] Häußler, U., Eibl, J. Numerical investigations on discharging silos. Journal of Engineering Mechanics110(1984)957–971.

[12.] Jofriet, J. C., Lelievre, B., Fwa, T. F. Friction model for finite element analyses of silos. Transactions of the ASAE20(1977)0735–0740.

[13.] Mahmoud, M. H. Silage–silo interaction using material characterization and finite element analysis (PhD. thesis) (1975). Departement of civil engineering, Ohio State University, Columbus.

[14.] Gallego, E. Numerical simulation of loads exerted by stored materials in silos with non-elastic material (PhD thesis) (2006). Technical University of Madrid.

[15.] Blight, G. Assessing loads on silos and other bulk storage structures. Research applied to practice. London: Taylor & Francis Group(2006).

[16.] Gallego, E., Rombach, G. A., Neumann, F., Ayuga, F. Simulations of granular flow in silos with different finite element programs: ANSYS vs. SILO. Transactions of the ASABE53(2010)819–829.

[17.] Iwicki, P., Wójcik, M., Tejchman, J. Failure of cylindrical steel silos composed of corrugated sheets and columns and repair methods using a sensitivity analysis. Engineering Failure Analysis18(2011)2064–2083.

[18.] Piskoty, G., Michel, S. A.,Zgraggen, M. Bursting of a corn silo – An interdisciplinary failure analysis. Engineering Failure Analysis12(2005)915–929.

[19.] Sadowski, A. J.,Michael Rotter, J. Exploration of novel geometric imperfection forms in buckling failures of thin-walled metal silos under eccentric discharge. International Journal of Solids and Structures50(2013)781–794.

[20.] Vidal, P., Gallego, E., Guaita, M., Ayuga, F. Simulation of the filling pressures of cylindrical steel silos with concentric and eccentric hoppers using 3-dimensional finite element models. Transactions of the ASABE49(2006)1881–1895.

[21.] Wensrich, C. Selected case studies on the silo quaking problem. Bulk Solids Handling22(2002)117–122.

[22.] Wilde,K.,Tejchman,J.,Rucka,M.,Niedostatkiewicz, M. Experimental and theoretical investigations of silo music. Powder Technology198(2010)38–48.

[23.] Draidi, Z.Renforcement et réparation des coques métalliques par matériaux composites (TFC) étude du comportement au flambage, approche expérimentale et numérique(PhD thesis) (2005).INSA de Lyon, France.

[24.] Vidal, P., Gallego, E., Guaita, M., Ayuga, F. Finite element analysis under different boundary conditions of the filling of cylindrical steel silos having an eccentric hopper. Journal of Constructional Steel Research64(2008)480–492.

[25.] ABAQUS. (Version 6.10). User's manual. Hibbitt, Karlsson and Sorensen Inc., Pawtucket, Rhode, (2010). Island, USA.