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Abbreviations

EDT=Economic Damage Threshold; EU=European Union; FDA US=Food & Drug Administration; GMP =Good manufacturing practices; IPM=Integrated Pest Managment; IR=Infra-red radiation; HACCP=Hazard Analysis Critical Control Point; IMM=Indian meal moth; UV=Ultra-violet light

Static and Dynamic Stress Analysis of Flat Bottom-Bamboo Reinforced Concrete Silo for Rough Rice Storage

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Abstract

Concrete silos are one of the most robust and reliable structures for grain storage in tropical countries. This study analysed the structural behavior of a low cost, flat bottom bamboo-reinforced concrete (BRC) silo for rough rice storage. This research included the design and development of a BRC silo in accordance with the guidelines mentioned by the Indian Standard (IS) codes. The Finite Element Method was employed to develop the stress profile in the silo walls under "grain at rest" and "grain filling" conditions. The results obtained were further compared with experimental results, classic silo theories (Janssen's theory) and standards of different countries in the world. The numerical technique gave stress magnitudes very close to those of the experimental results. The classic theories as well as the standards of different countries predicted an over estimation of the magnitude of stresses in the BRC silo. This would result in extra cost of construction of BRC silos. The study also suggested that the vertical stresses were most predominant under static and filling conditions. Maximum stresses were developed at the silo bottom. This study is expected to aid the development of economical silos with minimum wall thickness and material requirement which are ideal for on-site construction and use by smallholder farmers.

Keywords: Bamboo reinforced concrete silos, rough rice, finite element method, stress profile

1. Introduction

Food grain silos are highly efficient in storing bulk grains for a long period of time and safe from deteriorating agents such as rodents and insect pests. Modern silos are generally made of materials such as galvanized steel, reinforced cement concrete, painted Aluminum, plastic etc. If designed properly, these structures provide hermetic conditions ideal for safe storage of food grains, ensuring

minimal storage induced losses and improved food security. Bamboo based grain storage structures have been popular among Indian farmers since time immemorial. These include traditional bamboo baskets, mud plastered bamboo bins, bamboo-reinforced concrete bins etc. Bamboo based concrete structures have gained popularity in the present time and have been judged as an environmental friendly and sustainable technology (Holani, 2001).

In spite of several studies being performed on grain storage silos, the structural behavior of certain designs is still unclear. The complexities associated with different types of grain silos can be mainly attributed to the nature of the bulk material being stored (moisture content, internal friction, bulk density, grain shape etc), the nature of the containment structure (material, shape, dimensions etc) and the interactive effects between the stored material and the structure walls. Classic silo theories such as Janssen's and Reimbert's theories fail to address the effect of these critical factors. International standards for silo designs such as the Indian Standard codes, Eurocode and Australian Standards are also designed based on these classic theories. While experimental trials are the most accurate method of studying silo behavior during grain storage, the high cost associated with their construction and automation discourages researchers from utilizing them.

Recent studies have reported numerical methods such as finite element method (FEM) and discrete element method (DEM) as reliable techniques for modelling of grain silo phenomena such as silo filling and discharge (Gallego et al., 2015), granular flow patterns (Wang et al., 2013), buckling (Zaccari and Cudemo, 2016) and development of innovative silo shapes (Anand et al., 2008). While continuum based FEM is ideal for the prediction of stresses developed on silo walls, the discretization based DEM has been found to be suitable for modelling granular flow of grains in and out of silos (Rotter et al., 1998). FEM is highly efficient in developing a realistic elastoplastic behavior of stored grains as a continuum medium and predicting its effect on the silo body. More recent research has occurred applying FEM for modelling stresses developed in silos with different planforms (square, rectangular), construction material (steel, concrete, polymethylacrylate), eccentric discharge, and flat or hopper bottoms. Advances have been made in simulating the interactive effects between grain-silo walls from node-node contact to surface-surface contact algorithms.

This study aimed at designing and developing a bamboo reinforced concrete silo of 1000 kg capacity to be used for rough rice storage at the farm level. A 3D FEM model was developed for the prediction of wall pressures in this intermediate slenderness silo, under static and filling conditions of rough rice. The predicted pressure values have been further compared with the results of classic silo theories, standard codes as well as experimental values.

2. Materials and methods

2.1 Stored granular material

The paddy to be stored inside the BRC silo was procured fresh from the experimental farm of the Agricultural and Food Engineering Department, Indian Institute of Technology Kharagpur. A high amylose, long variety of paddy, IR-36, was chosen for the present study, considering its popularity and ease of availability in the region. The paddy was thoroughly cleaned to ensure the best quality. The paddy was tested for its moisture content prior to storage.

2.2 Experimental determination of FEM input parameters

The results of the finite element method is highly dependent on the input parameters associated with the particles/bodies involved in the system concerned. The physical properties of the granular material was directly obtained from the works done at the Central Institute of Agricultural Engineering, Bhopal (Reddy and Chakraverty, 2004). The poisson's ratio of the paddy was determined from the K_o test (Moya et al., 2002), wherein, K_o, is the lateral pressure ratio. The modulus

of elasticity of the paddy grains were obtained from the triaxial test described by the same group of authors. The values of various parameters used in this study have been tabulated below:

Tab. 1 Input parameters for paddy.

Material parameter	Values	Source
Grain unit weight (kN/m³)	5.638	Experimental procedure
Angle of repose (˚)	42·35	Reddy and Chakraverty (2004)
Wall friction coefficient	0.5	IS 4995: 1974- Part 1
Modulus of elasticity (kPa)	10,000	Moya et al. (2006)
Poisson's ratio	0.2	Moya et al. (2006)

Tab. 2 Input parameters for concrete and bamboo reinforcement.

Material parameter	Values	Source
Concrete (M20 grade)		
Concrete unit weight (kN/m³)	22.55	IS 456:2000
Modulus of elasticity (kPa)	2.23×10^7	IS 456:2000
Poisson's ratio	0.18	IS 456:2000
Bamboo		
Bamboo specific weight (kN/m³)	8.825	Agarwal et al. (2014)
Modulus of elasticity (kPa)	2.44×10^7	Agarwal et al. (2014)
Poisson's ratio	0.28	Agarwal et al. (2014)

2.3 Finite Element Method

Material models

The stress profile developed on the BRC silo walls was developed in ANSYS software (ANSYS, 2018) reproducing the real silo dimensions and geometry. The reinforcing bamboo strips were generated in the design modeler and their properties were assigned. A linear elastic material model was used to describe the concrete as the non-linearity arises only under high levels of stresses. The granular material stored in the silo was described using an elastoplastic material model, wherein the elastic portion was described using the isotropic linear elastic model, while the plastic portion was described by the Drucker-Prager model (Drucker and Prager, 1952). The material parameters involved in these models have been selected according to Gallego et al. (2010). The Coloumb friction model was selected to model the interaction between paddy grains and the silo walls, wherein the wall friction coefficient was the most relevant parameter.

Types of ANSYS elements

The ANSYS elements are highly effective in modelling the physics of the problem and in the present study different elements have been assigned to the individual silo system components. The silo body, made of concrete was assigned the element type SOLID186 while the reinforced bamboo strips were modelled using LINK180 elements. The SOLID186 element is a 3D homogenous structural solid with 20 nodes supporting features such as plasticity, stress stiffening, and mixed formulation capability for simulating deformation of nearly incompressible elastoplastic material. The LINK180 element on the other hand is a 3D spar, tension-compression element with nodes having three degrees of freedom each. The grain body was assigned the element type SOLID187, a 3D 10 node element with the ability to model irregular meshes. The contact algorithm between the silo walls and grains were described using pair based contact elements (CONTA173 and TARGE170). The CONTA173 can model contact and sliding between a 3D rigid body and a deformable body.

Boundary conditions

Only two boundary conditions were employed for modelling the stress profile in BRC silo walls:

- • Fixed support at the silo bottom (constrained rigid body motion) and
- • Bulk unit weight of the stored paddy.

During the filling process, all nodes at the silo bottom were restrained from motion in any direction (Gallego et al., 2010). Prior studies by the same group of authors had reported that progressive filling yields better results than en masse filling. The grain filling process was modelled using the sequential activation of subsequent grain layers through the birth and death feature of ANSYS (Gallego et al., 2015). The Newton Raphson procedure was adopted to solve the set of nonlinear equations during the entire process.

3. Results and discussion

3.1 Description of silo design

An intermediate slenderness, bamboo-reinforced concrete (BRC) silo of 1000 kg capacity as shown in Fig. 1 was developed at the Indian Institute of Technology Kharagpur. It was comprised of a domical roof, silo body and a base support. The grain is loaded from the top opening (40 x 40 cm) on the domical roof and the discharge done through an inclined chute (15 cm φ) at the bottom of the silo wall. The domical roof was made of concrete of 8 cm thickness. The cylindrical silo body was made of a bamboo framework reinforced in cement concrete. The frame work consisted of vertical and circumferential bamboo strips with trapezoidal cross section (2 x 1 x 0.5 cm). The bamboo strips were coated with a layer of araldite and sand spray to ensure better adherence with concrete. The thickness of the silo wall was limited to 12 cm. The entire silo was supported on a circular base of 40 cm height and a diameter of 2 m. This ensured protection from water seepage and inaccessibility to rodents.
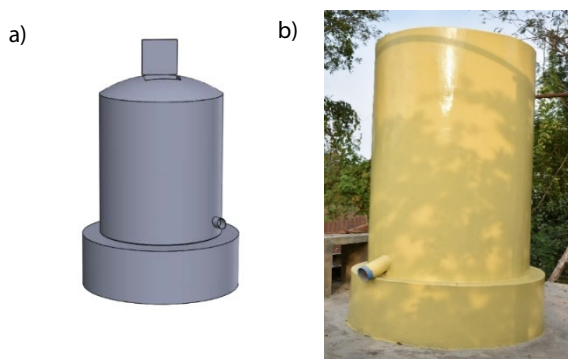

a)   b)

Fig. 1 Bamboo-reinforced concrete silo for rough rice storage: a) 3D representation b) Silo erected on the field.

3.2 Lateral and vertical pressures along the BRC silo walls under static condition

The lateral and vertical pressures prevalent in the BRC silo under static state are depicted in Fig. 2. The wall pressure values predicted by the FEM model were lesser than those estimated using the design codes or Janssen's equation. This could be due to the differences in the input parameters of the material models used. Several studies have reported that the material model adopted has the least effect on the pressures developed in a flat bottom silo. However, the poisson's ratio (ν), lateral pressure ratio (k) and wall friction coefficient (μ) employed in the models significantly influence the pressure profile obtained. For instance, the k values adopted in the Indian standard code and Eurocode (EN1991-4) are 0.5 and 0.63, respectively, while one adopted in the numerical model was 0.47. The pressure values were normalized in order to reduce the redundancy in the data values. Finite element analysis suggested a peak pressure at the silo bottom, which was not accounted for in any other method of estimation. Varying the mesh density at the silo base did not affect this peak

pressure. The results suggested that the wall thickness of 15 cm for concrete grain silos, suggested in the Indian Standard codes, is an over estimation and would result in additional costs for economically constraints farmers. A wall thickness of 10 cm was sufficient to take the grain loads, static and dynamic, which were well within the permissible strength of concrete. However, this finding has to be supplemented with studies related to the life cycle assessment of the BRC silo.
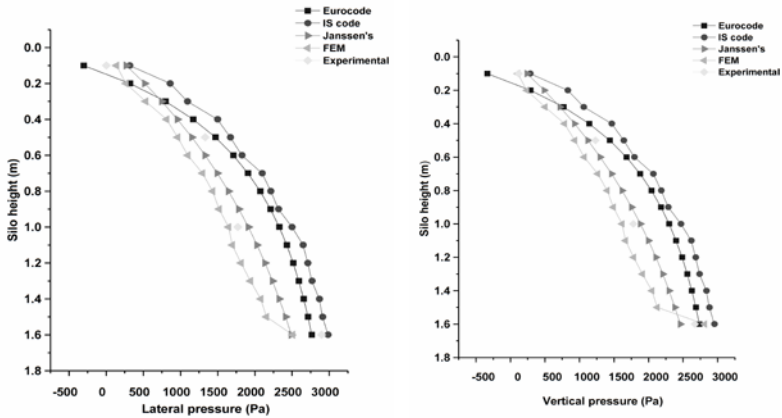

Fig. 2 Lateral and vertical pressures acting on the BRC silo wall under static conditions.

3.3 Lateral and vertical pressures along the BRC silo walls under filling conditions

The pressure profile of the silo walls is illustrated in Fig. 3. Significant distortions were observed in the pressure values predicted by FEM. These values were normalized and the modified values were represented in the chart. These distortion could be a result of numerical issues, roughness of meshes, or differences developed in the subsequent grain layers during filling. Previous studies have reported similar kind of leaps in FE values during grain filling in metal silos (Gallego et al., 2010). These issues needs to be addressed in depth to obtain better pressure distribution profiles in grain silos. The study also suggests that during the filling of grains the vertical stresses are more predominant than the normal pressures.
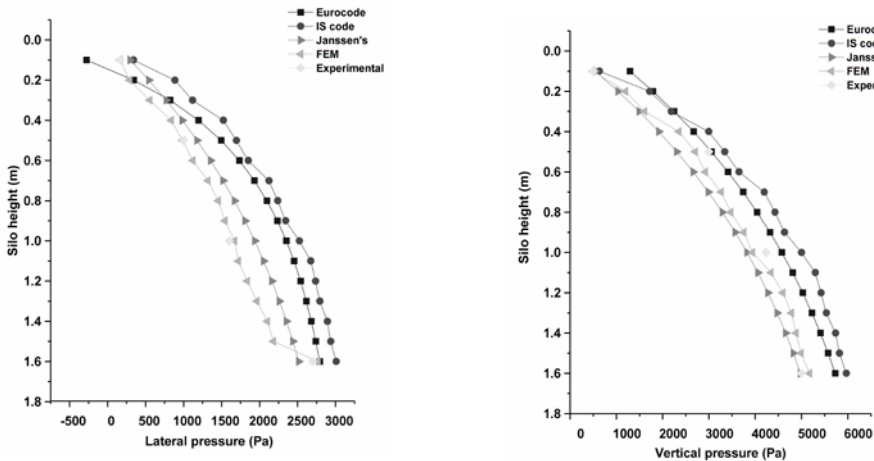

Fig. 3 Lateral and vertical pressures acting on the BRC silo wall during progressive filling of grain.

4. Conclusion

The study dealt with the development of a low cost bamboo reinforced concrete silo for farm level storage of rough rice. The structural safety of the developed structure was analyzed using the finite element method and the results were compared with Janssen's theory and design codes. The numerical method has been adjudged as one of the most reliable and versatile tools for development of innovative structures of various scales. The selection of input parameters for the FE model is a critical process affecting the prediction of the method. Dynamic pressures developed during filling of grains have been quantified in this study.

Acknowledgements

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Increase of Paddy Moisture with Automatic Aeration in a Warehouse Guided by Adsorption Equilibrium Absolute Humidity Equation

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Abstract

An automatic bulk monitoring and aeration controller was programmed with an adsorption equilibrium absolute humidity (CAE)equation and was used to aerate paddy with the aim to increase moisture content (MC)