Structural Analysis of Laterally Aerated Moving Bed (LAMB) Dryer by using Robot Structural Analysis (RSA) Professional 2018.

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Abstract. The structural design of Laterally Aerated Moving Bed (LAMB) dryer is subjected to buckling effects due to the loads of the paddy bed, self-weight and static pressures by the air blower to overcome the air resistance in the paddy bed, perforated tube and the bed chamber perforated wall. The dryer structural type is a spatial complex structure where the boundary conditions are not very clear, thus the Robot Structural Analysis (RSA) Professional 2018 is used to determine the critical values of loads when the overall structural elements instability occurred to form buckling. The RSA analysed the global buckling of a structure to find the critical coefficient value to be multiply with the case load for the critical buckling load determination. Three different model of dryer structural designs were prepared and analysed by RSA to find the buckling critical coefficient values ($\alpha_c$), displacements (mm), reactions (N) and moments (Nm). All structural design model was designed with similar type of materials, different sizes and geometrical arrangements. The RSA results within the three structural design models were compared. The structural design model with the best buckling coefficient values with minimum displacement had been selected for the actual LAMB dryer structural construction.

1. Introduction
The Laterally Aerated Moving Bed (LAMB) dryer is a new design for paddy rice drying based on the bioreactor concept which have a vertical perforated tube to provide uniform air flow distribution. The principle of the system is to achieve drying uniformity by aerating the paddy bed laterally. The short air flow distance across the paddy bed produces lower aeration energy contributes to the smaller air flow pressure drops. It has many advantages against the existing industrial paddy rice dryers such as good drying uniformity, low labour intensive, less dust pollution, good heat and mass transfer ability which shorten the drying period (Nor Hidayah Kamin and Jidon Janaun 2017).

The structural analysis of the LAMB dryer structure is vital to ensure it has adequate strength to withstand the loads of paddy bed and pressure inside the dryer vessel. The bed chamber perforated wall and tube are the most crucial areas as there have direct contact with the paddy and pressure from the air blower. The structures are prone to instability due to the loads compression where it starts to
change shapes or deflection. Sudden deflection of the structures caused by the compressive load generates the critical stress commonly known as buckling phenomenon (Helbig D., et al. 2016). The structural analysis software such as the RSA is useful to determine the critical values of loads on complicated spatial structures where the boundary conditions are not clear. The structural analysis result obtained by the RSA software is less than 5% difference compared to the result obtained from the analytical way which is acceptable. The critical force, \( N_{cr} \) determined by the RSA is always on the safe way (Chen and Wierzbicki 2000).

The selection of materials for LAMB paddy dryer must considers the abrasiveness of the paddy rice husk. The paddy husk contains high silica that causes excessive wear to parts of processing machine (IRRI n.d.). The fabrication of column paddy dryer, galvanised steel was been used for the dryer construction (Olaniyan and Alabi 2014). The fixed bed dryer (Flatbed & Inclined bed dryers) perforated floor and frames were made of mild steel (Wimberly 1983). The plug-flow fluidised-bed paddy dryer was made of stainless steel and mild steel (Khanali et al. 2012). Thus, the materials selected for the LAMB paddy dryer are stainless steel 304 sheet ASTM A240 for the dryer vessel walls, square hollow steel (SHS) and rectangular hollow steel (RHS) ASTM A500 for the dryer structural frames to reduce the excessive wear problems.

The LAMB paddy dryer’s capacity of 1000kg was selected for this study. Paddy rice drying analysis by the LAMB dryer was performed to determine the parameters needed for the loads analysis such as the heater power, air flow rate, static pressure and the mass of paddy. These load parameters were used in the RSA to determine the buckling critical coefficient values \( (\alpha_{cr}) \), displacements (mm), reactions (N) and moments (Nm).

The RSA is capable to identify any errors on the structural joints due to the nodes instability which is very helpful to detect any design faults of the particular structures. It could analyses the global buckling of a structure to find the critical coefficient values to be multiply with the case load for the critical buckling load determination. In EN1991-1-8 (2005): Eurocode-3: Design of Steel Structures (Part 1-8) standard, the buckling critical coefficient values should be, \( \alpha_{cr} \geq 10 \) (elastic analysis) and \( \alpha_{cr} \geq 15 \) (plastic analysis) (Autodesk Inc. 2012).

The LAMB dryer is consisted of two main structures namely the dryer vessel and support chute. In this research, the dryer structural designs were prepared in three different models and analysed by the RSA for comparison. All model was designed with similar type of materials with different sizes and geometrical arrangement to suit the fabrication and installation processes. The vessel structure design models are shown in the Figures 1, 2 and 3 while the support chute is shown in Figure 4. The RSA final results on buckling coefficient values were compared where the design model with the best buckling critical coefficient values was selected for the dryer structures construction. On the support chute structural design, it is confirmed the RSA results obtained in compliance with the Eurocode-3 buckling critical coefficient value, \( \alpha_{cr} \geq 10 \) (elastic analysis) and \( \alpha_{cr} \geq 15 \) (plastic analysis).

In conclusion, the Robot Structure Analysis (RSA) professional 2018 package is capable to analyse the buckling effects on LAMB dryer structural analysis.

2. **Paddy drying analysis**

This analysis is to determine paddy mass and internal pressure needed for the loads analysis. Given, the Inner pipe diameter, \( D_1 = 0.64 \text{m} \), Paddy Bed diameter, \( D_2 = 1.17 \text{m} \), Outer wall diameter, \( D_0 = 1.97 \text{m} \), Dryer height, \( H = 3.00 \text{m} \), Dryer designed weight capacity, \( W_p = 1000 \text{kg} \), Bulk density of paddy = 495 kg.m\(^3\), Specification for the perforated sheer / wall: Perforate (Aperture), Diameter of one exit hole = 0.003m, Number of holes (Aperture) = 43.1 holes per inch\(^2\) or 66805 holes per m\(^2\), Area of holes = 0.4722 m\(^2\) holes per m\(^2\) of sheet.

2.1. **Paddy mass**

The designed capacity of the LAMB dryer is 1000kg, thus the maximum mass of paddy for the load analysis is 1000kg.
2.1.1. Heater power, blower air flow rate and static pressure

The quantity of heat required to remove moisture content from the paddy was determined by using the following equation (A K Stephen et al 2009):

- Heater Power, \( Q = M_w \times C_p \times \Delta T \)

where, \( M_w = \) Mass of water (kg), \( C_p = \) Specific heat capacity of water (kJkgK\(^{-1}\)) and \( \Delta T = \) Temperature dried grain – Initial temperature of dryer (°C).

2.1.2. Heater power

At \( \Delta T = 35^\circ C \), \( M_w = 236.62kg \) and specific heat capacity of water of 4.182 kJkgK\(^{-1}\). The quantity of heat required to remove moisture content:

- \( Q = M_w \times C_p \times \Delta T = (236.62kg) \times (4.182 \text{kJkgK}^{-1}) \times (35) = 3.50 \times 10^4 \text{kJ} \)
- The quantity of power = Quantity of heat (Q) / time (s) = 3.241 kJs\(^{-1}\) or 3.241 kW
- By giving the heater safety factor of 1.3, the heater power = 4.212 kW

2.1.3. Blower air flow rate

Given, the specific heat of air = 1.005 kJkgK\(^{-1}\), Power of heat on air = Mass Flow Rate of air \( \times \text{specific heat of air} \times \Delta T \),

- Mass air flow rate = \( \frac{(4.0 \text{kJs}^{-1})}{(1.005 \text{kJkgK}^{-1} \times 35)} = 0.11372 \text{kg.s}^{-1} \)
- Density of air at 40°C = 1.127 kg.m\(^{-3}\), Specify volume of air at 40°C = \( \frac{1}{1.127} = 0.88731 \text{m}^3 \text{kg}^{-1} \)
- Air flow rate = Mass flow rate \( \times \) specific volume at 40°C = \( (0.11372 \text{kg.s}^{-1}) \times (0.88731 \text{m}^3 \text{kg}^{-1}) = 0.101 \text{m}^3 \text{s}^{-1} \)
- Converting the value of air flow rate to cubic foot per minute (cfm); \( 1 \text{cfm} = 4.91747 \times 10^{-4} \text{m}^3 \text{s}^{-1} \), thus \( 0.101 \text{m}^3 \text{s}^{-1} = 205.40 \text{cfm} \)

2.1.4. Pressure resistance in the paddy bed

Air flow resistance in the paddy bed is determined using the equation by (ASABE 2011);

\[
\frac{\Delta P}{L} = \frac{aQ^2}{\log_e(1+bfQ)}
\]

where; \( \Delta P = \) Pressure Drop [Pa], \( L = \) Depth of packed bed [m], \( a \) & \( b = \) constants for particular grain

- \( Q = \) air flow, [m\(^3\)/s.m\(^2\)] or [cfm/ft\(^2\)]
- Cross-section of paddy bed = 0.753m\(^2\)
- Air flow, \( Q = \) (air flow rate) / (cross-section area of the bed) = 0.14077 ms\(^{-1}\)
- Given values of, \( a = 2.57 \times 10^4 \) [Pa. s\(^2\)/m] and \( b = 13.2 \) [m\(^2\). s/m\(^3\)] (for rough rice).
- Pressure drop, \( \Delta P_B = [(2.57 \times 10^4) (0.14077)^2(3)] / \log_e \{1 + (13.2) (0.14077)\} = 3.349.765 \text{Pa} \)

The air resistance in the paddy bed = Pressure drop in the paddy bed = 3.35kPa

2.1.5. Air flow resistance through the perforated tube walls

Given, the porosity of the perforated walls, \( f = 46.47\% \). The open area ratio (porosity, \( f \)) to be used on the following equations to find the \( k \) -factor to determine the pressure drop (Idel’chik 1994).

\[
k = [0.707(1 - f)^{0.375} + 1 - f]^2 \frac{1}{f^2} \quad \text{and} \quad \Delta P = k \left( \frac{\rho v^2}{2} \right)
\]
• $f$ = porosity, $\Delta P$ = pressure loss [Pa], $v$ = velocity (m.s$^{-1}$), $\rho$ = density of air at 40°C = 1.125 kg.m$^{-3}$

• $k = [0.707(1-0.46467)^{0.375} + 1-0.46467]^2 [1/(0.46467)^2] = 5.5495$

• $v$ = velocity (m.s$^{-1}$) = Air flow rate / Open area segment of inner pipe = 0.037 m.s$^{-1}$

• Thus, pressure drop, $\Delta P_1 = 5.5595 (1.127 \text{ kg.m}^{-3})(0.037 \text{ ms}^{-1})^2 / 2 = 0.116 \text{ kg.m}^{-1}\text{s}^{-2} = 0.116 \text{ Pa}$

2.1.6. Air flow resistance through the perforated bed wall
Given, $k = 5.5495$, $\rho$ = density of air at 40°C = 1.125 kg.m$^{-3}$

• $v$ = velocity (m.s$^{-1}$) = Air flow rate / Open area segment of paddy bed = 0.0204 m.s$^{-1}$

• pressure drop, $\Delta P_2 = 5.5595 (1.127 \text{ kg.m}^{-3})(0.0204 \text{ ms}^{-1})^2 / 2 = 0.064 \text{ kg.m}^{-1}\text{s}^{-2} = 0.064 \text{ Pa}$

2.1.7. Static pressure
The static pressure of the blower = pressure resistance in the paddy bed + pressure drop on the perforated tube + pressure drop on the bed perforated wall

• Total Pressure Drop, $P_s = \Delta P_B + \Delta P_1 + \Delta P_2 = 3.35 \times 10^3 + 0.116 + 0.064 = 3,350.18 \text{ Pa}$

• Given the safety factor of 1.3, the blower static pressure = 4.36 $\times$ 10$^3$Pa

2.2. Loads analysis
The loads on the dryer vessel frame were contributed by the vertical force due to the mass of paddy and the horizontal forces caused by the internal pressure of the vessel.

2.2.1. Vertical loads
The forces are determined by Newton’s second law ($F = mg$), where $m$ = mass (kg) and $g$ = gravity acceleration (9.8 m/s$^2$). The vertical forces were caused by the load of the paddy mass from (1.1).

• Vertical force, $F_z = 1000 \text{ kg} \times 9.8 \text{ m/s}^2 = 9.8 \text{ kg.m/s}^2 = 9.8 \text{ kN} \approx 10 \text{ kN}$

2.2.2. Horizontal loads
Horizontal forces are determined by $F = PA$, where $F$ = horizontal force (N), $P$ = pressure (Pa or N/m$^2$) and $A$ = surface area (m$^2$).

2.2.2.1. Horizontal load on the inner perforated tube
Perforated tube wall surface area = circular perimeter $\times$ height = 1.005 m$^2$

• $F_{x1} = F_{y1} = (1.005 \text{ m}^2) \times (4.36 \times 10^3) = 4381.8 \text{ N or 4.40 kN}$

2.2.2.2. Horizontal load on the paddy bed wall
Bed perforated wall surface area = circular perimeter $\times$ height = 1.838 m$^2$

• $F_{x2} = F_{y2} = (1.838 \text{ m}^2) \times (4.36 \times 10^3) = 8013.68 \text{ N or 8.01kN}$

2.2.2.3. Horizontal load on the outer wall
The pressure at the outer wall is merely the residual pressure through the bed perforated wall.

• The pressure on the outer wall = $(4.36 \times 10^3) - (3.35 \times 10^3) = 1.01 \text{ Pa}$

• The outer wall area = 9.283m$^2$

• $F_{x0} - F_{y0} = (9.283 \text{ m}^2) \times (1.01\text{Pa}) = 9.376 \text{ N} \approx 0.01 \text{ kN}$
3. Structural analysis

Three structural models were prepared for the LAMB dryer vessel and analysed by the RSA. The RSA results were then compared to select the best structural strength for the LAMB dryer structures construction. Given: the vertical load, \( F_z = 10\, \text{kN} \) and the horizontal loads; \( F_{x0} = F_{y0} = 0.01\, \text{kN} \), \( F_{x1} = F_{y1} = 4.40\, \text{kN} \) and \( F_{x2} = F_{y2} = 8.01\, \text{kN} \). (In the RSA, the horizontal loads shall be in the x and y axis, the vertical loads shall be in the z axis.)

3.1. Model Structure No. 1

The selected materials for model no.1 are RHS 50x25x2.5 and SHS 50x50x3 as shown in Figure 1.

![Model Structure No. 1](image1)

**Figure 1. Model Structure No. 1**

3.1.1. RSA results for Model No. 1

Table 1. Buckling Analysis Results - Values (Model No. 1)

| Case/Mode | Critical coefficient | Precision          |
|-----------|----------------------|-------------------|
| 2/1       | 6.12020e+00          | 3.05759e-04       |
| 2/2       | 6.79447e+00          | 3.37184e-03       |
| 2/3       | 8.51962e+00          | 1.77585e-03       |
| 2/4       | 8.91491e+00          | 3.84918e-03       |

3.2. Model Structure No. 2

The selected materials for model no.2 are RHS 50x25x2.5, SHS 50x50x3 and SHS 25x25x2.5 as shown in Figure 2.
3.2.1. RSA results for Model Structure No. 2

Table 2. Buckling Analysis results - Values (Model No. 2)

| Case/Mode | Critical coefficient | Precision   |
|-----------|----------------------|-------------|
| 2/1       | 3.94137e+00          | 1.12316e-03 |
| 2/2       | 3.94298e+00          | 1.12086e-03 |
| 2/3       | 4.12656e+00          | 1.16044e-03 |
| 2/4       | 4.13121e+00          | 3.29510e-04 |

3.3. Model Structure No. 3

The selected materials for model no.3 are SHS 50x50x3 and SHS 40x40x2.5 as shown in Figure 3.
3.3.1. RSA results for Model Structure No. 3

Table 3. Buckling Analysis Results - Values (Model No. 3)

| Case/Mode | Critical coefficient | Precision |
|-----------|----------------------|-----------|
| 2/1       | 1.67156e+01          | 2.40375e-03|
| 2/2       | 1.67158e+01          | 3.66079e-03|
| 2/3       | 1.88446e+01          | 1.66991e-03|
| 2/4       | 1.88446e+01          | 2.43442e-03|

3.4. RSA for support chute

The support chute is made of S275 steel, CRS 152x102x23.07, SHS 50x50x3, UB 152x89x16 and S275 steel plate of 8mm thickness. The vertical load, \( F_z = 25 \text{kN} \) (total loads of the mass of paddy and maximum weight of the dryer vessel).

![Figure 4. Support Chute Structure](image)

3.4.1. RSA results on the support chute

Table 4. Buckling analysis results values

| Case/Mode | Critical coefficient | Precision |
|-----------|----------------------|-----------|
| 2/1       | 2.08568e+01          | 9.23010e-07|
| 2/2       | 1.13765e+01          | 2.20282e-03|
| 2/3       | 1.15870e+01          | 1.13529e-03|
| 2/4       | 1.16739e+01          | 1.85424e-03|

4. Discussion

Three structural design models for the dryer vessel were analysed by the RSA to find the buckling analysis critical coefficient values. The RSA buckling results obtained on the critical coefficient values for design structural Model No.1 and No.2 as tabulated in Table 1 and 2 respectively are found less than 10. The structural design Model No.3 RSA buckling results on critical coefficient values as shown in Table 3 are found to be in compliance with the EN1991-1-8 (2005): Eurocode-3: Design of Steel Structures (Part 1-8) standard, the buckling critical coefficient values should be, \( \alpha_{cr} \geq 10 \) (elastic analysis) and \( \alpha_{cr} \geq 15 \) (plastic analysis).

The buckling analysis results on critical coefficient values for the Support Chute as shown in Table 4 are also found to be in compliance with the EN1991-1-8 (2005): Eurocode-3: Design of Steel...
Structures (Part 1-8) standard, the buckling critical coefficient values should be, $\alpha_{cr} \geq 10$ (elastic analysis) and $\alpha_{cr} \geq 15$ (plastic analysis).

5. Conclusion
The Robot Structural Analysis (RSA) Professional 2018 package is capable to perform structural analysis for the Laterally Aerated Moving Bed (LAMB) dryer.

The best structural model design for the LAMB dryer vessel is Model Structure No.3 as shown in Figure 3 and Table 3 to be used for the actual construction of the dryer vessel structure.

Further studies and experiments will be carried out upon completion of the LAMB dryer construction for processes validation, cost and performance optimisation, serviceability and sustainability.

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