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Fatigue and Stiffness Analysis of Rotating Drum Composter

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***Abstract*—**All types of farms have a waste problem. Livestock farms have huge amounts of manure and vegetable farms have to deal with inedible parts of vegetables or rotten, damaged and unacceptable vegetable waste. All of this waste needs to be disposed of safely, ecologically, and as quickly as possible. One of the options is composting using bioreactors, which are rotating drum composters. This type of composting allows biodegradable waste to be disposed of quickly and in an environmentally friendly manner, turning it into a useful product such as soil fertilizer or livestock bedding. This paper presents the fatigue and stiffness analysis of a rotating drum composter. The analysis was performed using a 3D finite element model. It was found that the analyzed composter design has good mechanical strength, good fatigue strength for a cylinder, and acceptable fatigue strength for tire rings. The deformation analysis of the cylinder indicated that the front and rear door support mechanisms should allow the positioning angle to be changed to ensure tightness.

***Keywords*—**3D modeling, fatigue, Finite Element Method, Goodman’s diagram.

I. INTRODUCTION

ONE of the challenges facing livestock operations is manure management. The main strategies can be to spread raw manure on the fields or to treat the manure before spreading. The first strategy is cheap but has negative impacts on soil quality: heavy metal pollution, salinization, antibiotics, pathogens, reduction of soil fauna. Manure treatment is usually associated with aerobic composting, biostimulant fermentation, anaerobic digestion, additives and others. The treatment has mainly positive effects on the soil, e.g. aerobic composting reduces heavy metals, salinization, antibiotic contamination and pathogens, increases soil organic carbon content, microbial biomass, genetic diversity and soil fauna [1]. In addition to the benefits of soil enrichment, aerobic composting using specialized equipment is relatively inexpensive if the price of the equipment is excluded, is fast, and can be technologically organized as a continuous flow.

Horticulture and vegetable farms are also interested in ways to quickly dispose of large amounts of waste. Since fruits and vegetables are biodegradable, aerobic composting can be used for managing this kind of waste as well.

Examples of large-scale aerobic rotating drum composters are shown in Fig. 1. Such composters can be used not only for manure treatment but also for composting any kind of organic, biodegradable material. The equipment is basically an insulated large diameter cylinder supported by rollers. The front and rear ends of the cylinder are usually stationary and the moving part is the cylinder itself. The stationary ends are usually equipped with feed openings or mechanisms. Since the rotation speed of the cylinder is quite slow, i.e. several revolutions per hour, the movement can be performed by the electric motor attached to the support rollers, gears, chain and even hydraulic cylinders attached to the ratchet mechanism.

Fig. 1 Examples of large rotary drum composter

This paper presents the structural integrity, fatigue, and stiffness analysis of the rotating drum composter designed for both livestock manure and vegetable composting.

II. MODEL

The size of the composter depends on the amount of waste to be treated. It is recommended that the composting time at 55 °C be at least 72 hours to kill dangerous pathogens [2]. After this time, the compost can be safely used as livestock bedding or

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applied to fields as soil fertilizer.

The drum composter can only be filled to 60% of its total volume for active composting. The remainder of the space must be left for good air circulation to ensure good oxygenation and cooling. For best composting results, the preferred humidity of the waste is between 40% and 60%. Therefore, the manure should be separated to achieve the desired moisture level. According to literature [3], the density of separated manure can be up to 375 kg/m^3. A cow weighing more than 600 kg can produce 7-8% of its own weight in manure. This would be ~50 kg per day (up to 7.3 kg of solid particles). The separated manure to 60% moisture could reach 18 kg per cow per day. Since the composting should not take less than 3 days, the composter could be filled only 1/3 per day. According to all this, in order to manage the waste of 500-550 cows, the working volume of the composter should be ~75 m^3, i.e. the total size of the composting cylinder of the drum should be ∅3 m in diameter and 18 m in length.

In the current stage, the rotating drum composter is designed as a universal composter capable of composting cow manure, vegetable waste and a combination of both. Therefore, the waste density of 700 kg/m^3 is considered in the analysis.

The research object is a rotating cylinder with ∅3 m diameter and 18 m length. The 3D FE model of the cylinder is shown in Fig. 2. It shows all the parts of the model along with the applied loads and boundary conditions. The main parts of the model are

- Cylinder with partially closed ends;
- 9 stiffness rings;
- 2 tire rings with holders used to support and rotate the composter;
- 4 sets of double support rollers;
- Sprocket for chain drive.

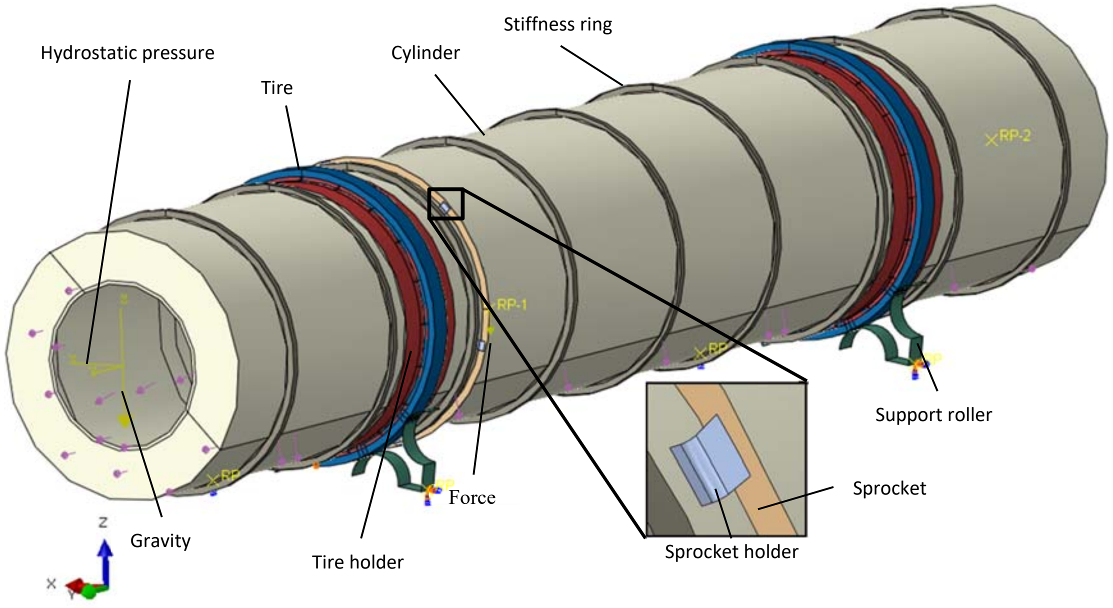


Fig. 2 3D FE model of the rotating drum composter with applied loads and boundary conditions

The model was created using the finite element program ABAQUS v6.11 [4]. It was meshed using several different element types. S4R elements were used to mesh the cylinder, tire holder, stiffening rings, and sprocket holders. S4R are shell type elements with 4 nodes [4]. The support rollers were modeled as rigid elements and meshed with R3D4 shell elements with 4 nodes. The sprocket and tires were modeled as solid 3D parts and meshed with S3D8R elements. These elements are cubic and have 8 nodes. Only the small parts of the tires, where the contact between the tire and the support rollers is expected, were meshed with smaller S3D20R elements, which are solid, cubic, but have 20 nodes. The entire model has 172627 elements and 380625 nodes in total. Different parts of the model were connected using tie type constraints. A tie constraint allows two regions to be fused together even though the meshes created on the surfaces of the regions may be dissimilar [4]. Movement between constrained regions is not allowed, so it can be used to mimic welded joints. On the other hand, motion between tires and support rollers is expected. Therefore, surface-to-surface contacts were created in these regions.

Displacement in all three axes and rotation about the X and Z coordinate axes were constrained for all support rollers as shown in Fig. 3. Rotation about the Y axis was allowed to simulate the rocking action of the supports following the shape of the tire. To limit the movement of the cylinder along its axis, constrained displacement in the Y axis was applied to a point on the tire.

The main loads on the model are the dead weight of the construction, the weight of the composting waste, and the force acting on the sprocket to rotate the cylinder. The dead weight of the construction was evaluated by applying gravity to the model in the negative direction of the Z-axis. The hydrostatic pressure caused by the product was added to the portion of the inner surface of the cylinder in such a way as to simulate 60% filling of the cylinder at a collapse angle equal to 45°. In this way, when the density of the product is equal to 700 kg/m^3, the hydrostatic pressure reaches its maximum value at the lowest point of the cylinder equal to 0.0186418 MPa. The force required to rotate the cylinder with the composting material inside is about 200 kN. The required force was applied to a point on the gear and directed vertically downward (in the direction of the negative Z coordinate). In a real construction, the torque applied by the chain-driven gear will be resisted by the composting material in the cylinder by friction against the cylinder wall. Since the composting material is not modeled, the resistance to the torque is conservatively applied by constraining the rotation of the outer edge of the back end of the cylinder around its axis, i.e., around the X coordinate.

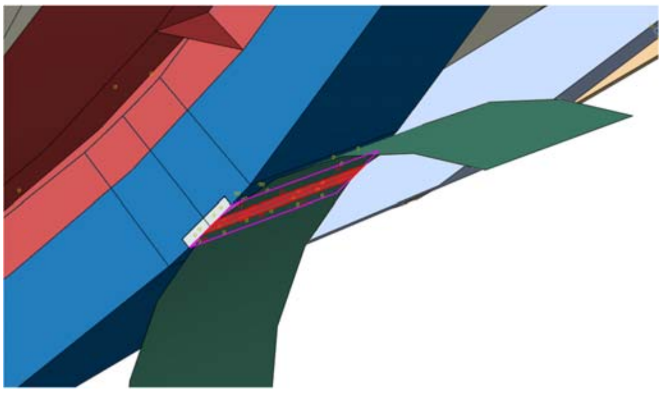


Fig. 3 The area of contact between the tire and the roller

Material properties used for analysis are presented in Table I.

TABLE I
MATERIAL PROPERTIES USED IN FE MODEL

Property	Material grade		
	S355JR	EN10083-3 (DIN0.7225)	S235
Module of elasticity, GPa	210	200	210
Poisson's ratio	0.3	0.3	0.3
Yield strength, MPa	355	550	235
Ultimate strength, MPa	490	800	360
Density, kg/m^3	7800	7800	7800

III. CALCULATION RESULTS

A. Strength Evaluation

The results of the calculation are shown in Fig. 4. The figure shows the equivalent stress distribution in the model. The highest stress in the model is found at the contact area between the tire and the support roller and reaches 475 MPa. Compared to the yield strength of 1.7225 steel, it has a safety factor of 1.15. The stress distribution on the cylinder is shown separately in Fig. 5. As can be seen, the highest equivalent stresses in the cylinder are about 127 MPa. Compared to the yield strength of S355JR steel, the safety factor is about 2.8. However, since the tires together with the cylinder are constantly moving parts, the load should be analyzed as cyclic. Therefore, the maximum equivalent stress level of the tire and cylinder should be checked with the fatigue limit of the material.

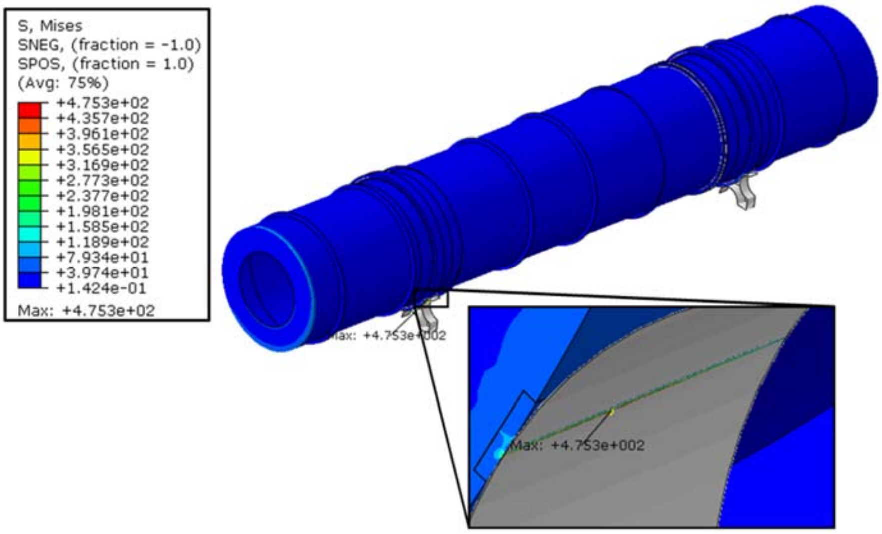


Fig. 4 Equivalent stress distribution in the full model

B. Fatigue Evaluation

According to the researches found in the scientific literature, the fatigue limits are at the stress amplitude of 260 MPa [5] for steel S355JR and 532 MPa [6] for steel 1.7225. The standard fatigue tests are performed at the stress ratio (cycle asymmetry coefficient) R = -1. This means that the loading of the specimen is completely reversed, i.e., the tensile load of the specimens is equal to the compressive load. Fig. 6 shows the equivalent stress distribution along the outer circumference of the tire. Most of the circumference stresses do not exceed 25 MPa. However, there are 4 very distinct peaks. These peaks are located at the contact points of the tire and the support rollers. This shows that in our case the load is close to a pulsating type load, where R ≈

0. In this case, the stress amplitude cannot be directly compared to the fatigue limit of the material. In order to compare whether this load is potentially dangerous, Goodman's diagrams [7] should be constructed. Fig. 7 shows Goodman's diagrams for both the cylinder and the tire. As can be seen, point A, representing the cyclic loading condition, is below the Goodman line in both diagrams. This indicates that no fatigue damage will occur in either the cylinder or the tire. The cycle safety factor can be calculated as follows:

$$CSF = \frac{OB}{OA}. \qquad (1)$$

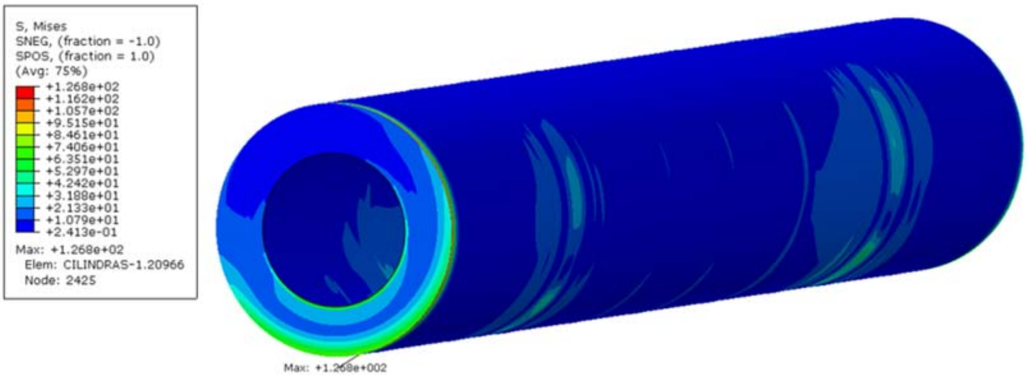


Fig. 5 Equivalent stress distribution in the cylinder

According to (1), the cycle safety factor for the cylinder is $CSF_{cylinder} = 2.67$ and for the tire is $CSF_{tire} = 1.3$.

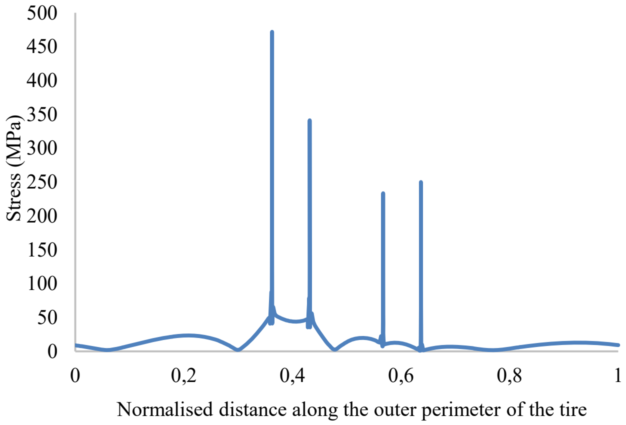
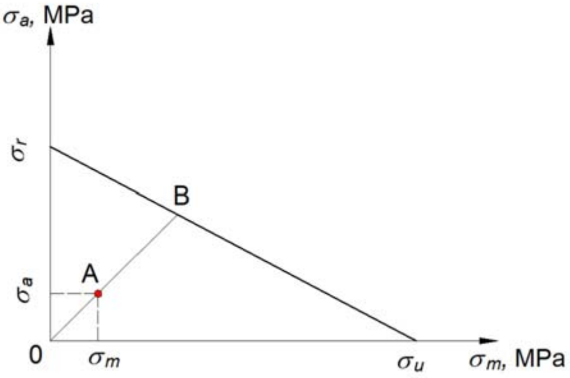
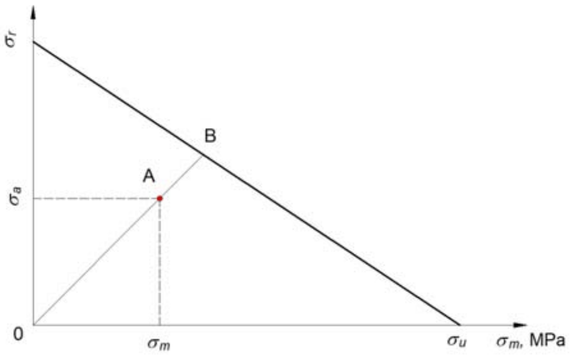


Fig. 6 Equivalent stress distribution along the outer circumference of the tire



(a)



(b)

Fig. 7 Goodman's diagrams for: (a) cylinder; (b) tire

C. *Stiffness Evaluation*

The other important aspect of the design is the stiffness of the cylinder ends. Technologically, the composting process should be a continuous, uninterrupted operation. Therefore, the design of the composter should have stationary doors at the front and back ends with some kind of openings or feeding mechanisms to feed and unload the composting material into the cylinder. The moving part would be the drum. Fig. 8 shows the front end of the cylinder with the opening where the stationary door should be located. To ensure that the gap between the door and the cylinder is well sealed, the edge of the opening should be flat and perpendicular to the axis of the cylinder under load. Any deformation or rotation of the end plane of the cylinder may cause the gap between the doors and the cylinder to open, resulting in leakage of composting material. Fig. 9 shows the displacement of the perimeters of the cylinder openings along the Y coordinate axis, i.e., the axis of the cylinder (Fig. 8). Obviously, since the displacement values of all the perimeter points are not zero, this means that both ends are shifted along the cylinder axis. Also, the somewhat sinusoidal shape of the curve indicates the change in the angle of the planes of the ends of the cylinder. The maximum displacement of the opening point of the cylinder is approximately 8 mm at each end. If the stationary position of the door were fixed at all times, the product would leak from the cylinder. Therefore, the door support mechanism should be designed to allow the angle and position to change.

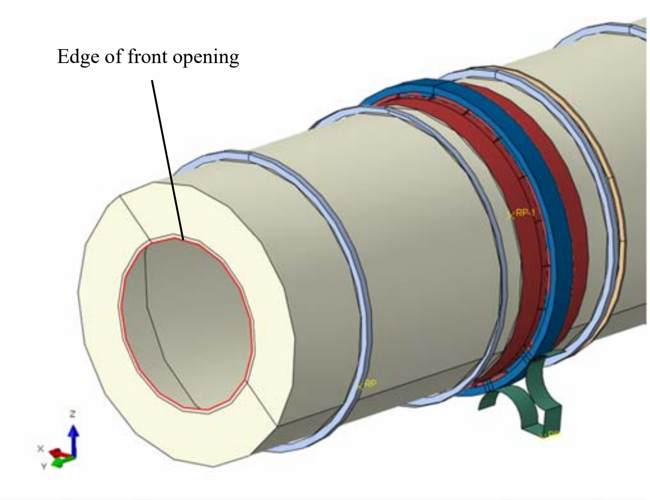


Fig. 8 Front end of the full model

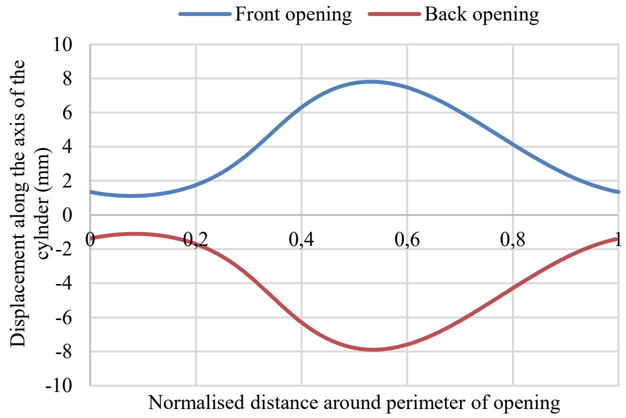


Fig. 9 Displacement of the opening edges of the front and rear ends along the axis of the cylinder

IV. CONCLUSIONS

After performing the fatigue and stiffness analysis of the rotating drum composter, the following conclusions can be made:

- The analyzed design of the drum composter's tire and cylinder has a safety factor of 1.15 and 2.8, respectively, for a static load;
- Since the moving components of the design are subjected to cyclic loading, the fatigue of the design was evaluated by constructing the Goodman diagram. The evaluation showed that the cycle safety factor for a cylinder is CSFcylinder = 2.67 and for the tire is CSFtire = 1.3. Since the safety factor of a tire is low, the following measures should be taken: the loading of the composter should be carefully monitored to avoid overloading, or the tire material should be replaced with a material with a higher yield strength and fatigue limit;
- Cylinder deformation under load analysis showed that the ends of the cylinder can be deformed up to 8 mm. To prevent the leakage of composting material, the design of the support mechanism of the stationary doors must be developed so that the angle and position of the door can be changed.

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