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Research article

Developing the design of the roller of a roll stone crusher by FEM simulation

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Abstract

Stone crushers are fundamental equipment in size reduction processes across metallurgical, mechanical, and other industrial applications. These machines are produced in a wide range of capacities, typically from 30 to 1000 tons per hour, and are categorized according to both the extent of material fragmentation and the type of force application mechanism. From a mechanistic standpoint, crushers are generally classified into three main types: roll crushers, jaw crushers, and impact crushers. Roll crushers, in particular, are widely utilized for medium- and small-scale stone processing due to their structural simplicity and operational effectiveness. This study focuses on the structural optimization of a roll crusher with an emphasis on its roller component, which plays a pivotal role in determining the system's overall efficiency, performance, and operational cost. The subject of the case study is a roll crusher operating in an iron ore mine located in Yazd Province, Iran. The existing roller design is fully solid, which contributes to excessive weight, reduced mechanical efficiency, and elevated costs associated with maintenance and repair. In response, this research proposes a redesigned roller with reduced weight while ensuring that its mechanical integrity and operational functionality are preserved. The roller is modeled using computer-aided design (CAD) software and subsequently analyzed through Finite Element Method (FEM) simulations. To validate the numerical results, the FEM outputs are compared against the corresponding analytical solutions.

Keywords: FEM simulation, Stone crusher, Mining equipment, Roller design.

1- Introduction

In civil engineering, mining, and construction industries, crushed stone- commonly referred to as aggregates- serves as an essential raw material in various structural and infrastructural applications. Crushing equipment plays a pivotal role in the production of these aggregates by reducing the size of stones or mineral ores, processing construction debris, and enabling material recycling. The principal objective of crushers is to fragment large, solid raw materials into smaller, more manageable particles. Additionally, they facilitate the transformation of waste into reusable or disposable forms, contributing to sustainable construction practices. Crushers can be employed not only for primary size reduction but also in secondary and tertiary stages to produce final product sizes through compressive mechanisms.

Among the various types of crushing equipment, the roll crusher is widely used due to its simple design and effectiveness in specific size-reduction tasks. This type of crusher comprises a robust frame that supports two rotating cylindrical rolls, which move toward each other. Material introduced from the top is compressed between the rolls and discharged from the bottom after fragmentation. Depending on the application, the rollers may be fabricated with smooth surfaces for uniform crushing or with rugged (jagged) geometries to enhance grip and breakage efficiency (Fig. 1).

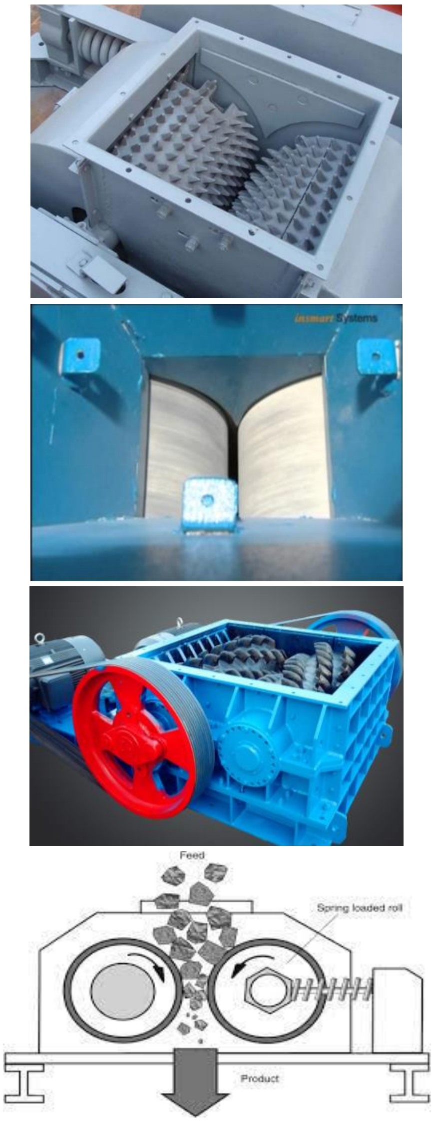


Fig. 1 The mechanism of roll stone crushers and different roller types

Optimizing the energy efficiency of stone crushing systems necessitates careful consideration of various design parameters, including the overall weight and geometric dimensions of the equipment. The application of Finite Element Method (FEM) simulations during the design phase of roll crushers significantly aids in identifying optimal structural and operational configurations. FEM enables predictive evaluation of mechanical behavior and performance characteristics under different loading and boundary conditions, without disrupting the actual production process [1-5]. As such, it serves as a powerful tool for analyzing crushing circuits and establishing optimal working parameters in a cost-effective and non-invasive manner. In this context, a review of relevant literature pertaining to the design methodologies and FEM-based analysis of stone crushers and related crushing mechanisms is presented below:

Terefe et al. proposed the design of an impact-type stone crusher, intended for processing a range of materials from soft aggregates to medium-hard stones and metallic ores. The underlying design was based on the principle of impact loading, which assumes that the natural frequency response time of the system is significantly greater than the duration of force application during particle contact. Due to the high rotational velocity of the hammer, the interaction time between the hammer surface and the particles is minimal, thereby inducing dynamic impact loads. In their analysis, the crusher's shaft was modeled under combined torsional and bending stresses, which are critical for ensuring structural integrity and operational durability [6]. Borse et al. developed and performed a structural analysis of a welding fixture designed for the body assembly of a stone crusher. The fixture functions as a precision work-holding device in manufacturing processes, ensuring accurate positioning and support of components to maintain part conformity and interchangeability. The fixture was modeled utilizing UNIGRAPHICS NX (Siemens NX), a leading CAD software extensively employed in design-driven industries. Finite Element Analysis (FEA) was subsequently conducted using ANSYS to assess stress concentrations and deformation patterns on the fixture's baseplate under applied load conditions. The simulation results were obtained efficiently, demonstrating the capability of ANSYS in delivering precise structural evaluations within a short computational timeframe [7]. Joshi et al. proposed an alternative design and analytical approach for small-scale stone crushers. The primary focus of their work was to optimize the crusher's configuration to efficiently handle stones requiring a crushing force of approximately three tons. [8]. Munyasi proposed a research study aimed at investigating the crushing characteristics of various stones and subsequently developing an optimized dynamic and structural design of a small stone crusher for small-scale entrepreneurs.[9]. Many methods to control the industrial process have been introduced [10]. Gurway et al. employed the Taguchi method to optimize key crushing parameters with the aim of maximizing aggregate production yield. Their study focused on evaluating the influence of critical process variables such as feed rate and eccentric speed of the jaw crusher, as well as the closed side setting and throw in the cone crusher. A Taguchi Design of Experiments (DOE) approach was utilized to systematically investigate these parameters, enabling the identification of optimal operational settings to improve crusher performance and productivity[11]. Numerous additional investigations have been carried out on this subject, with selected key studies cited in the references [12-22].

This study investigates the feasibility of implementing a novel hollow roller design for a roll stone crusher through Finite Element Method (FEM) simulations and analytical validation. The existing crusher, situated at an iron ore mine in Yazd Province, Iran, utilizes solid rollers characterized by substantial mass, which contributes to excessive energy consumption and diminished operational efficiency. Moreover, the high mass complicates the handling and transportation of the crushing equipment. To address these challenges, a lightweight hollow roller design is introduced aiming to enhance efficiency while reducing the overall weight. The mechanical integrity of the proposed design is rigorously evaluated by determining key parameters such as maximum bending stress, contact stress, and strain distributions derived from ANSYS-based FEM simulations.

2- Materials and Methods

In this research, the existing design of the stone crusher roller is introduced and its limitations are identified. Subsequently, a novel roller design is proposed, and its performance advantages are discussed in detail. The new design is first modeled using CAD software, and its mechanical properties are initially assessed through analytical methods. Finally, the roller model is imported into ANSYS software and analyzed using the Finite Element Method (FEM). The FEM results are then validated by comparison with the analytical solutions.

2-1 Material properties

In this study, simulations were conducted using ANSYS software version 2022. The initial model was designed in SolidWorks software. The primary component (the rollers of the stone crusher) was imported as a 3D, deformable part into the ANSYS Part module. Conversely, the stones were modeled as solid and non-deformable. Due to the complex nature and unique characteristics of the stones, direct modeling was challenging. The rollers are made from Hardox-400 steel alloy, an abrasion-resistant steel known for its high hardness. The chemical composition of Hardox-400 is provided in Table 1, while its mechanical properties used in the ANSYS Property module are illustrated in Fig. 2.

Table 1: The Chemical Composition of Hardox-400

Element	Mo	Ni	Cr	S	Mn	Si	C
Wt%	0.6	1.5	2.5	0.01	1.6	0.7	0.32

Mechanical property \ Material	Hardox 400
Elasticity modulus, N/mm^2	190000
Poisson's ratio, -	0.29
Shear modulus, N/mm^2	75000
Density, kg/m^3	8000
Tensile strength, N/mm^2	1250
Yield point, N/mm^2	1020
Coefficient of thermal expansion, 1/K	1.8e-005
Thermal conductivity, W/(m·K)	16
Specific heat, J/(kg·K)	500

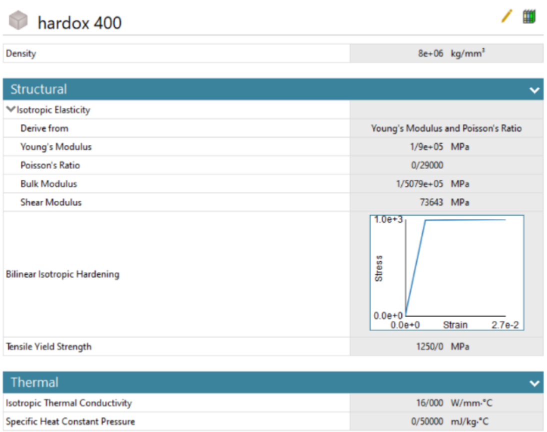


Fig. 2 The Mechanical Properties of Hardox-400 used in ANSYS

2-2- Redesign of rollers

As mentioned, the current solid roller design is inefficient due to its excessive weight. This results in increased energy consumption during roller rotation and higher material costs for manufacturing. Moreover, the maintenance and repair of these solid rollers are challenging and time-consuming. Therefore, the new design proposes the use of hollow rollers, similar in structure to cast tubes, to be implemented in the crusher. Figure 3 illustrates the schematic representation of this redesigned roller.

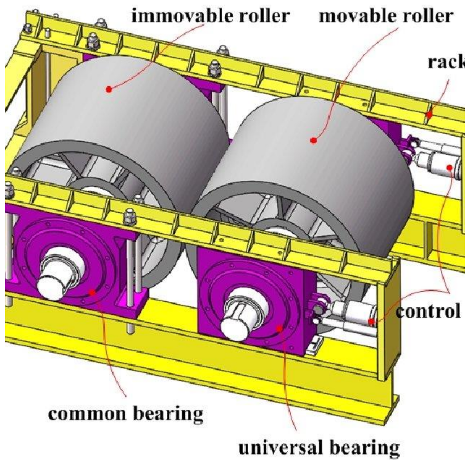
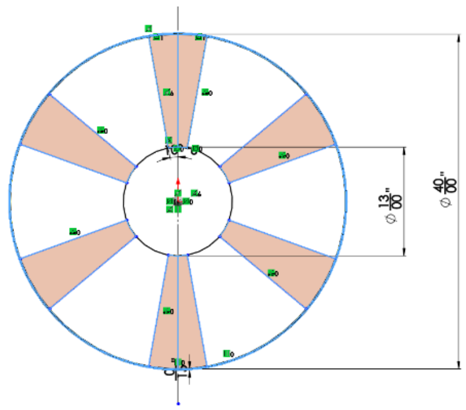
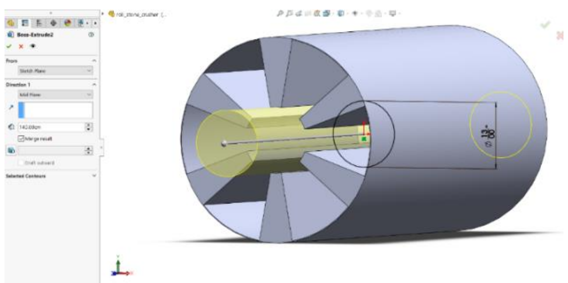


Fig. 3 Schematic of the proposed design





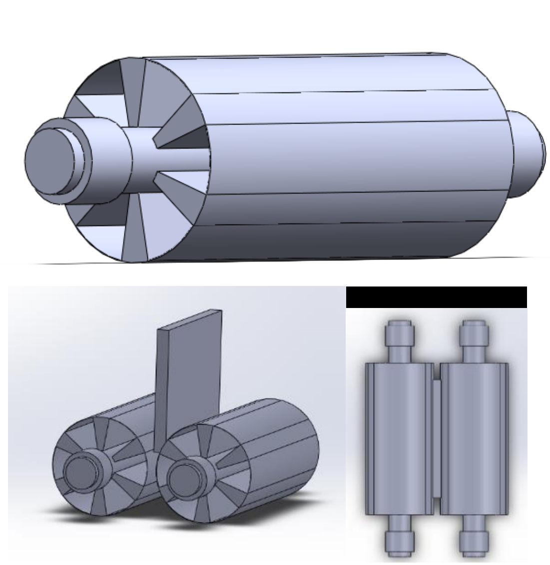


Fig. 4 New design of rollers

According to the new design, the roller wall thickness was set to 120 mm, resulting in an approximate 40% reduction in roller weight, which is a significant improvement.

2-3- Simulation parameters

To simulate this project in ANSYS, the Explicit Dynamics module was utilized. Following the software's workflow ("tree diagram"), all necessary steps for problem-solving are outlined. The crusher operates by applying torque—transmitted from the gearbox—to one end of the rollers. Both rollers must rotate synchronously to efficiently crush the stones. Any difference in rotational speed between the rollers can cause severe surface damage during stone compression. Accordingly, boundary conditions were applied to constrain both rollers to rotate only about their central axes, while all linear displacements were restricted (Fig. 5).

In the next step, the connections among parts in the Connection module should be defined. According to Fig. 6, the coefficient of friction between rollers and slab is assumed 0.3.

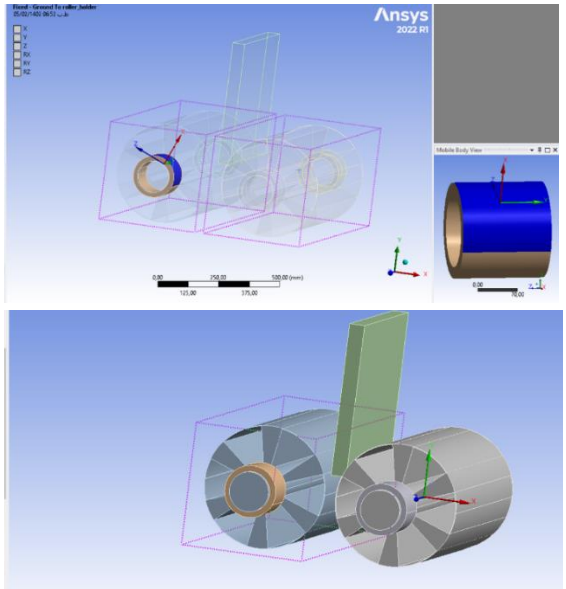


Fig. 5 Constraints for rollers

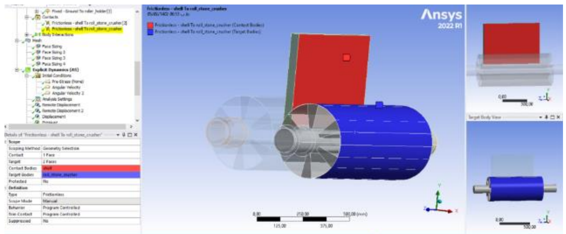


Fig. 6 Connection between rollers and stone

Meshing was defined within the Mesh module. As shown in Fig. 7, a finer mesh was applied to the rollers due to their critical role, whereas a coarser mesh was used for the copper slab representing the stone. Applying a uniform fine mesh throughout the entire model would significantly increase computational time. The mesh size was set to 30 mm with a 2D surface mesh type. Additionally, mesh convergence was evaluated through mesh control. A total of 8000 mesh elements were selected for the final simulation. According to Fig. 8, at a specific point on the part, the stress value was 226 MPa with 3000 mesh elements, and upon increasing the mesh density to 8000 elements (mesh size 30 mm), the stress converged to 470 MPa.

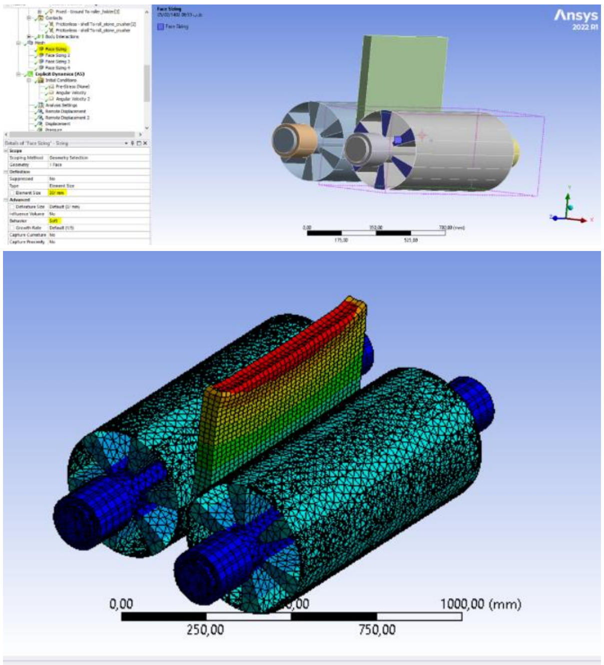


Fig. 7 Meshed part

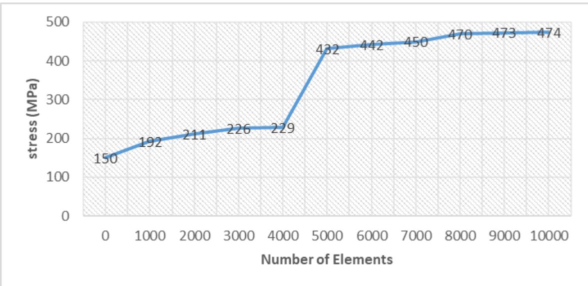


Fig. 8 Convergence of results (stress) by increasing the number of mesh

According to Fig. 9, the rollers rotate at an angular velocity of 250 rad/s, as specified in the manufacturer's catalogue. Additionally, in actual operation, stones are fed onto the rollers by gravity. To simulate this effect in ANSYS, a vertical distributed load of 8kN is applied to the top surface of the slab, based on manufacturer recommendations and the machine's capacity.

3-Results and discussion

This study investigates the feasibility of replacing the roller of a roll stone crusher with a newly designed hollow roller using Finite Element Method (FEM) simulations and analytical solutions.

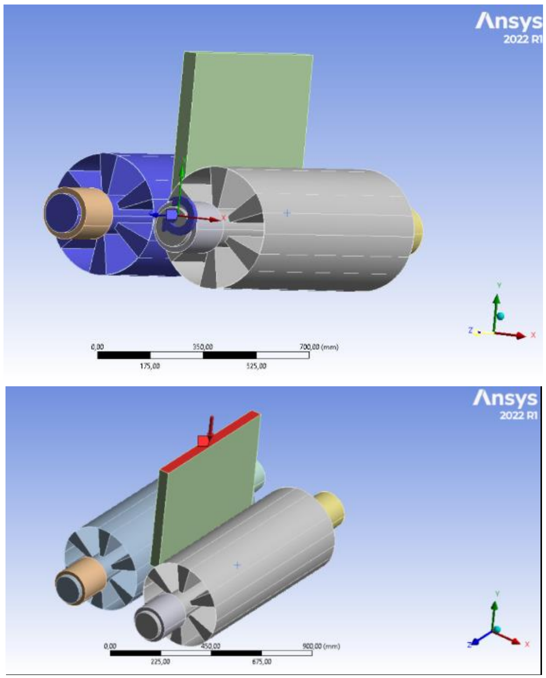


Fig. 9 Running mechanism

The existing roller is solid and heavy, leading to high energy consumption and reduced operational efficiency. The proposed design features a hollow structure that significantly reduces weight while enhancing efficiency. To evaluate the performance of the new design, its mechanical behavior was assessed by calculating the maximum stress, maximum strain, and deformation through simulations conducted in ANSYS software. The results obtained are presented as follows.

3-1- FEM simulation results

According to Fig. 10, the maximum principal stress experienced by the rollers is 939 MPa, which is below the yield strength of the roller material (Hardox 400). The highest principal stress occurs on the roller surface, particularly at the stiffeners or ribs, which play a critical role in the structural integrity of the design. Insufficient stiffener thickness can lead to a significant reduction in roller strength, while over-designing them results in negligible weight reduction, undermining the purpose of the new design.

Additionally, stress concentrations at the bearing sections of the rollers must be carefully considered. Unexpected increases in bearing forces at the journals can cause severe damage, including bearing seizure. In this study, the maximum principal stress at the bearing sections reached 1090 MPa, highlighting the need for careful assessment. It is important to note that the shaft diameter design at the bearing sections was beyond the scope of the current project.

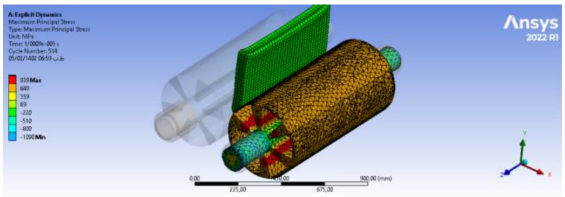


Fig. 10 Principal stresses

Figure 11 illustrates the maximum shear stress distribution on the rollers. Besides the roller surfaces, the stiffeners experience substantial shear stresses, underscoring their critical role in the overall structural performance of the crusher. The maximum shear stress obtained from the simulations is approximately 544 MPa.

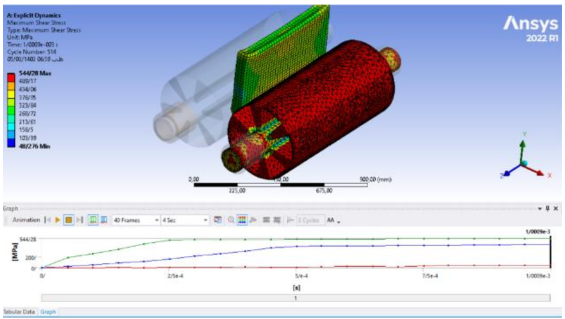


Fig. 11 Shear stresses

According to Fig. 12, the maximum strain observed in the rollers is 0.04 mm/mm. Clearly, the locations experiencing this maximum strain are situated on the surface of the rollers.

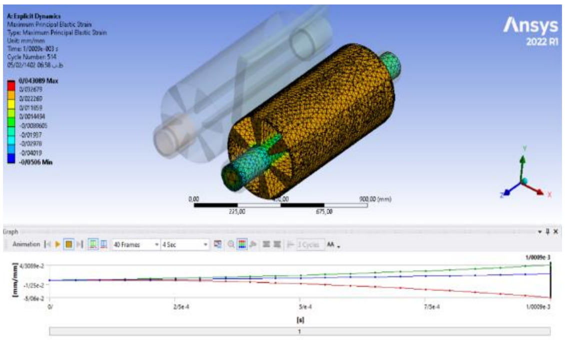


Fig. 12 Maximum strain

Finally, Fig. 13 illustrates the deformation distribution of the rollers. As expected, the maximum deformation is approximately 2 mm, which is attributed to the high elastic modulus of the Hardox 400 material.

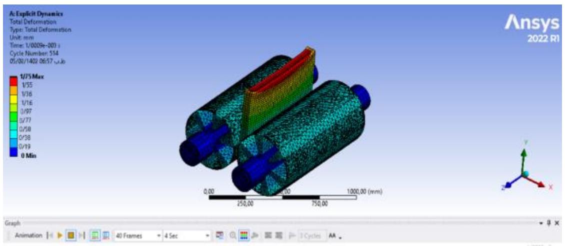


Fig. 13 Total deformation in rollers

3-2- Analytical Solution

According to Fig. 14, to manually calculate the stresses acting on the roller surface, the free-body diagram of the rollers must first be established. At a point on the outer surface of the rollers, two types of stresses are considered: normal stress (pressure) exerted by the stones (slab) and shear stress resulting from the friction between the stones and the rollers.

For calculating the normal (pressure) stress, it is assumed that the stress acting on the roller surface equals the stress required to deform the copper slab, which is 360 MPa. To determine the shear stress, the equations (1) are applied:

$$\tau_{max} = \frac{Tc}{J}$$

$$J = \frac{\pi}{32}(D^4 - d^4) \qquad (1)$$

The output torque from the gearbox is 12,000 Nm, resulting in a calculated shear stress of approximately 420 MPa.

The Von Mises stress is then computed using equation (2) and is found to be about 811 MPa, which shows a 14% deviation from the FEM result of 939 MPa.

$$\sigma_0{}^2 = \sigma_x{}^2 - \sigma_x\sigma_y + \sigma_y{}^2 + 3\tau_{xy}{}^2 \qquad (2)$$

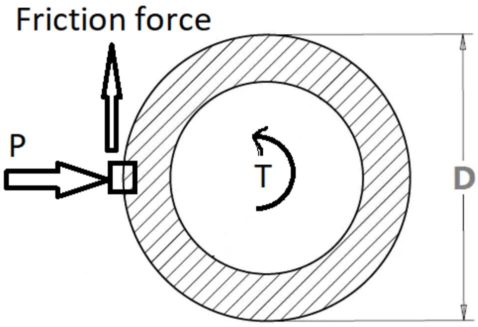


Fig. 14 Free diagram of a roller

3-3- Comparing results

For comparative analysis, the study conducted by Sert et al. was selected as a reference [23]. They conducted a study on the design of a screen roller machine, which shares functional similarities with a roller crusher. As illustrated in their analysis (Fig. 15), they employed a comparable simulation methodology. The maximum stress experienced by the rollers in their study was reported to be 490 MPa, which is in the same range as the results obtained in the present work.

4- Conclusions

In this study, the feasibility of implementing a new design for the roller of a roll stone crusher was evaluated using Finite Element Method (FEM) simulation and analytical solutions. The following key conclusions can be drawn from the present work:

• The maximum principal stress imposed on the roller was found to be 939 MPa, which is below the yield strength of the roller material (Hardox 400), indicating structural safety under the applied loads.

• A maximum principal stress of 1090 MPa was observed at the bearing sections, highlighting a critical region that requires special attention in future design optimization.

• The maximum shear stress obtained from simulations was approximately 544 MPa, concentrated on both the roller surface and the stiffeners, emphasizing the structural significance of the stiffeners in the overall load distribution.

• The maximum strain experienced by the roller was 0.04 mm/mm, occurring on the roller surface, which is within acceptable deformation limits.

• The maximum total deformation was approximately 2 mm, which is attributed to the high elastic modulus of the Hardox 400 material.

• The Von Mises stress calculated through analytical methods was approximately 811 MPa, showing a 14% deviation from the FEM result of 939 MPa, which validates the accuracy and reliability of the simulation.

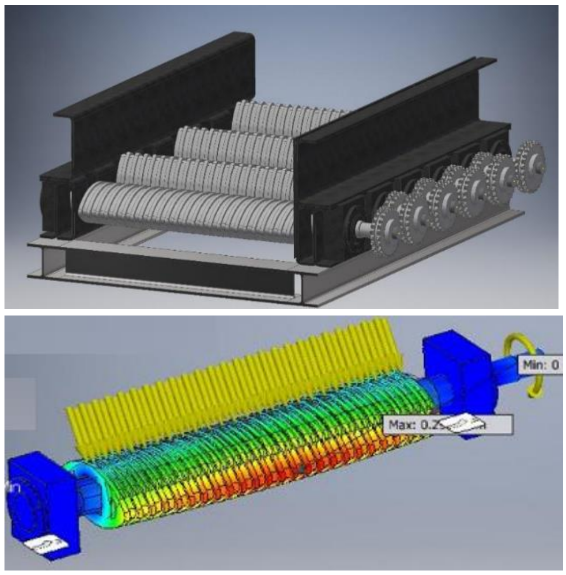


Fig. 15 The results of Sert's study

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